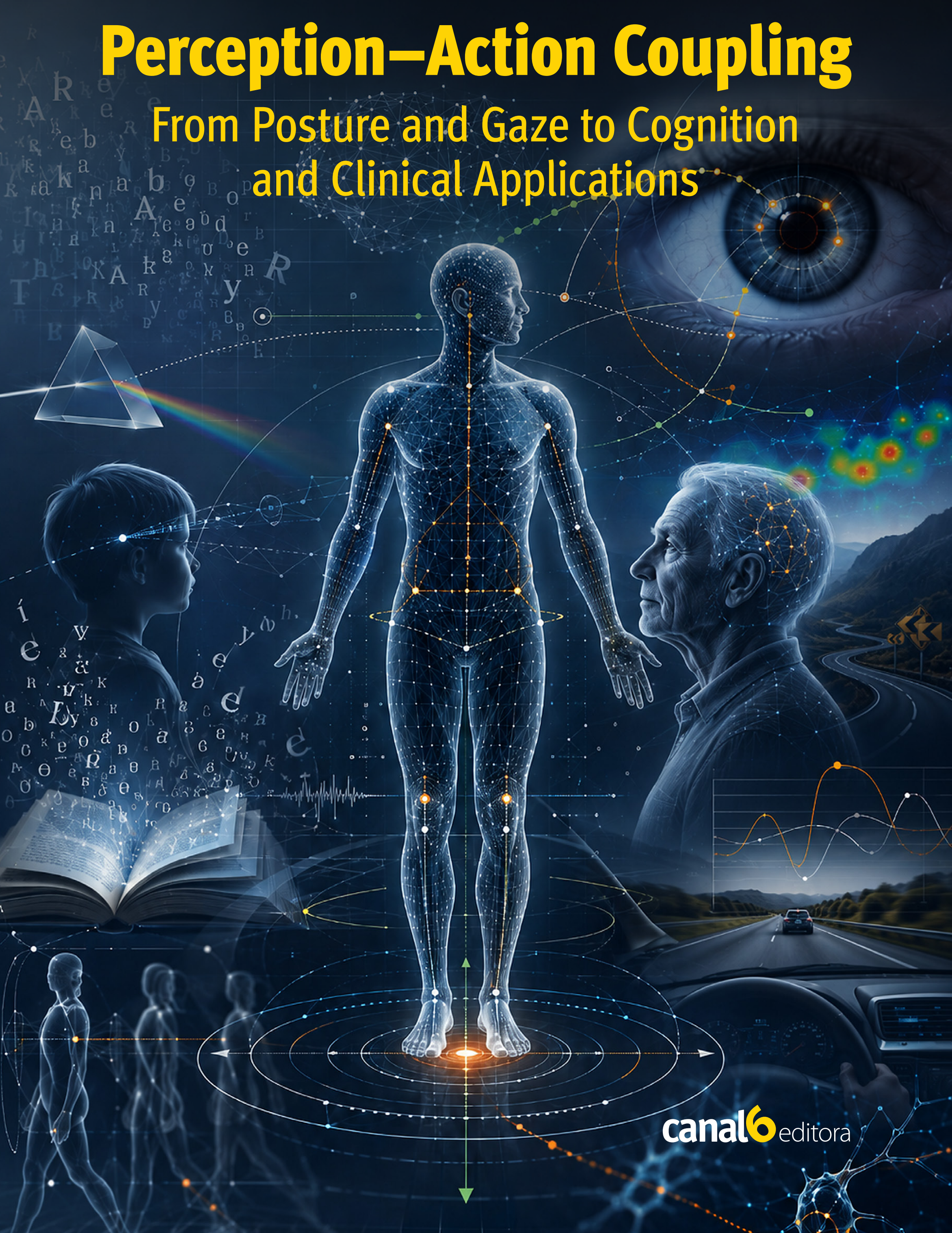
Sérgio Tosi Rodrigues • Cédrick T. Bonnet • José Angelo Barela (orgs.)

Perception–Action Coupling

From Posture and Gaze to Cognition and Clinical Applications



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Foreword

It is a great pleasure to contribute these institutional words to Perception–Action Coupling: From Posture and Gaze to Cognition and Clinical Applications, a volume that brings together the work of researchers from São Paulo State University — UNESP — and the Université de Lille. More than a scientific publication, this book is the expression of a mature and highly productive collaboration between academic communities in Brazil and France.

The CAPES–COFECUB framework has played an important role in consolidating this cooperation, transforming shared scientific interests into sustained mobility, joint research and long-term academic interaction. In this sense, the present volume is not only the result of a research project, but also a visible expression of how institutional support can strengthen collaboration between laboratories, researchers and students.

The significance of this book becomes even clearer when placed within the broader trajectory of cooperation between UNESP and Université de Lille. Our institutional relationship dates back to 2013, when both institutions jointly prepared and successfully secured the Erasmus Mundus IBrasil programme. Since then, this relationship has continued to expand through successive initiatives in research, academic exchange, pedagogical innovation and more structured forms of academic cooperation.

This broader trajectory shows that the partnership between UNESP and Université de Lille has been built progressively, through continuity, trust and a shared commitment to meaningful internationalization. It also demonstrates how cooperation can grow from specific academic encounters into wider institutional agendas, including language education, virtual exchange, scientific literacy, digital technologies, and possible future engagement with broader European collaborative frameworks such as EUGLOH — the European University Alliance for Global Health.

In this sense, the collaboration between UNESP and Université de Lille offers an important example of how international academic cooperation should be developed in the world today. It is a partnership built horizontally, with respect, mutual recognition and a clear understanding of the contributions that each institution and each research community can offer. Rather than following a model in which one partner defines the path for the other, this cooperation has been shaped by joint construction, shared ownership and mutual learning.

This book gives concrete form to that vision. In its pages, readers will find a coherent and interdisciplinary exploration of perception–action coupling, moving from fundamental questions on gaze, posture, balance and cognitive-motor interaction to applied studies involving learning, dyslexia, driving and Parkinson's disease. This breadth is one of the strengths of the volume: it demonstrates how a well-established scientific collaboration can connect basic research with issues of direct relevance to education, health, mobility, human development and society.

On behalf of UNESP's Office of International Affairs, I would like to congratulate Professors Sérgio Tosi Rodrigues and José Angelo Barela, Dr Cédrick Bonnet, and all the Brazilian and French colleagues involved in this initiative. This volume records not only the achievements of a successful research project, but also the value of sustained, respectful and mutually beneficial international cooperation. May it inspire new joint initiatives, deepen the partnership between UNESP and Université de Lille, and open further paths for collaboration between Brazil and France.

Prof. **José Celso Freire Júnior**
Associate Provost for International Affairs
São Paulo State University — UNESP

Foreword

It is a great pleasure for me to contribute to the foreword of this work. This collection is the concrete expression of a deep, enduring and successful collaboration between São Paulo State University in Brazil and the University of Lille in France.

As mentioned by my colleague José Celso Freire Júnior in his foreword, our two institutions have worked together for many years across a wide range of disciplines and in many different ways: international research chairs, European projects, the CAPES-COFECUB framework exemplified by the present work, alongside many others. These projects have brought our two institutions into alignment in terms of approach and priorities, which has led to almost seamless cooperation and easy communication.

As an institutional stakeholder in international relations, I do not always see the output of these collaborations. In my position, I am often present at the beginning to make introductions, suggest potential sources of financing and troubleshoot when there is an obstacle. I am not always involved at the end of the chain when the collaboration has developed and led to tangible results. I am thus even more enthusiastic to see this publication come to fruition.

Another aspect of this project that is particularly noteworthy is the effort on both sides to strengthen and deepen the collaboration to ensure that it is long lasting. The project leaders have built the trust and mutual respect that are vital to this kind of cooperation: these characteristics are important for completing a project, but they must be particularly strong to sustain collaboration over a period of years and to motivate the partners to continue to seek new ways to fund their research, as they have done in this case.

In line with my colleague Professor Freire, I agree that this work represents the product of an exemplary international collaboration that has greatly contributed to our strong institutional links. I hope that this project will endure and also that it will inspire similar future excellent projects between our universities.

Dr. **Kathleen O'Connor**
Vice-President for Europe and International Relations
University of Lille

Contents

Preface

This book represents the culmination of a fruitful and multifaceted collaboration between our research teams in Brazil and France. Our journey began in 2019 at the ISPGR International Congress in Edinburgh, when Prof. José Barela and Dr. Cédrick Bonnet discussed shared scientific interests and immediately envisioned collaborative projects. Early interactions via video meetings allowed us to exchange ideas and to share co-developing projects. By 2021, our first joint publication had emerged, and by June 2022, we had co-authored four international articles. Recognizing our productive collaboration, the directors of international relations at University of Lille (ULille) and São Paulo State University (UNESP) invited us to propose a CAPES-COFECUB project for 2023–2026.

This initiative brought together additional colleagues: on the French side, Dr. Laurent Sparrow and Prof. Séverine Casalis from SCALab, and on the Brazilian side, Prof. Sérgio Rodrigues and Dr. Paula Polastri from LIVIA, along with Prof. Fabio Barbieri from MOVI-LAB. Our successful CAPES-COFECUB proposal, "*Gaze Behavior and Postural Control in Visual Static and Dynamic Environments*", has supported researchers' mobility, enabling multiple short-term and extended visits, fostering shared research projects, and stimulating cross-country collaboration. Furthermore, José and Cédrick received Franco-Brazilian chairs in 2023 and 2026, which further strengthened exchange in both sides. Over these years, our teams have produced eight international publications, two recently submitted manuscripts, thirty-seven oral presentations, nine conference posters, media appearances, and several public outreach chapters. This sustained and prolific collaboration laid the foundation for the present book.

The chapters of this book form a coherent exploration of visual perception, postural control, and cognitive function across diverse populations and experimental paradigms. In chapter 1, Dr. Bonnet opens with an examination of the benefits of active balance control on attention and task performance, demonstrating how posture and movement optimize cognitive engagement. Polastri and colleagues extend this investigation by exploring cognitive–motor interactions during standing under varied visual conditions (Chapter 2), highlighting the adaptive coordination of perception, action, and cognition. In chapter 3, Dr. Rodrigues *et al.* introduced a novel experimental framework to study the coordination between gaze, head, and postural control in a simulated driving task. They also provided preliminary insights into perception–action coupling in dynamic environments. Chapter 4, by Mr. Cuevas *et al.*, addresses the intersection of posture and learning, proposing experimental approaches to study how body position may influence vocabulary acquisition. Dr. de Andrade Silva (Chapter 5) delves deeper by examining pupillary responses as indices of cognitive effort, revealing an embodied interaction between posture and semantic context. Chapters 6 and 7 (Berzghal *et al.*; Virlet *et al.*) shift focus to children and adolescents with dyslexia, investigating visual perception and the effects of prismatic lenses on reading performance. in Chapter 8, Camargo and colleagues demonstrate how proprioceptive interventions enhance visual attention in dyslexic children over extended periods. Finally, Chapters 9 and 10 (Penedo *et al.*; Fukuchi *et al.*) explore visual and oculomotor contributions to postural control in Parkinson's disease, illustrating the translational relevance of our research from basic mechanisms to clinical applications.

Together, these chapters form a continuous narrative: from fundamental mechanisms of gaze and posture, through cognitive and learning processes, to applied and clinical contexts. The coherence of our work reflects the dynamic, productive, and interdisciplinary nature of our collaboration—a collaboration that has not only advanced scientific understanding but also fostered sustained connections between our research communities in Brazil and France.

Benefits of the active control of balance on visual perception and task performance

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Abstract

This chapter examines whether body position - sitting versus standing - affects cognitive performance in modern sedentary societies. As many adults, particularly desk-based workers, spend over eight hours per day seated, reducing sedentary time has become a major public health concern. Sit-stand desks are increasingly used and have been shown to improve health and long-term productivity. However, it remains unclear whether standing directly enhances short-term task performance or whether observed benefits result only from improved general health. A review of more than 100 studies shows that performance while standing is generally equivalent to sitting, and sometimes superior—especially when reaction time is measured. Alternating between sitting and standing appears more beneficial than prolonged sitting. The author argues that improved performance

in standing is not due to posture itself, but to active postural control. Standing requires continuous balance regulation through postural sway, a nonlinear and adaptive process. This active control may enhance perception and attention for three reasons: (1) sensory systems function best with continuous variability; (2) sway complexity adapts to task and environmental demands; and (3) maintaining balance may promote optimal arousal and selective attention. Experimental studies conducted in the SCALab partially support these hypotheses. Analyses show that sway magnitude and complexity predict better attentional and visual performance when standing, but not when sitting. Overall, actively controlling balance - particularly without fatigue - may enhance cognitive performance, with alternating postures representing an optimal strategy.

Introduction about the body position (sitting vs. standing) in our modern society

In most countries worldwide today, and especially in high-income countries, people spend a lot of time in the seating position. In fact, more than half of the word population spend more than half of the waking day, i.e. more than 8 h/d, in the sitting position (Leitzmann, Jochem, & Schmid, 2018). Desk-based workers even spend between 11.2 and 12.8 h/d in the sitting position (Hadgraft *et al.*, 2016; Parry & Straker, 2013). This large time spent seated is problematic as it leads to various health issues such as physiological issues (e.g. premature death, cancer, diabetes, cardio-vascular diseases, ...), psychological issues (e.g., depression, anxiety, ...), cognitive issues (e.g., problems in attention, working memory, executive functions, ...) with problems at all levels (from microscopic to macroscopic issues)

(Bonnet & Barela, 2021; Bonnet & Cheval, 2023; Ekelund *et al.*, 2016; Levine, 2010, 2015). As a consequence, excessive sitting can lead to reduction of efficiency in work productivity (Chandrasekaran, Pesola, Rao, & Arumugam, 2021; Hendriksen, Bernaards, Steijn, & Hildebrandt, 2016; Munir *et al.*, 2015; Puig-Ribera *et al.*, 2015) in relation to the so many, sometimes chronical, healthy issues.

Solutions have to be implemented worldwide to reduce the time spent seated. The use of sit-stand desks is one of the best solutions for desk-based workers (Bonnet & Cheval, 2023). By definition, sit-stand desks can be used either in the sitting or standing position by simply changing the height of the desk by means of up or down electrical buttons or manual crank. The literature already showed that the use of sit-stand desks is i) well accepted by users (Dutta, Walton, & Pereira, 2015; Leavy & Jancey, 2016), ii) is effective in reducing health issues caused by excessive sitting (Dutta, Koepp, Stovitz, Levine, & Pereira, 2014; Zhu *et al.*, 2018) and iii) is effective in increasing work productivity (Chandrasekaran *et al.*, 2021; Hendriksen *et al.*, 2016; Munir *et al.*, 2015; Puig-Ribera *et al.*, 2015). The question still holds whether task performance, evaluated in short periods of time (e.g. min, hours), can be improved by spending more time in the standing position. In other words, is work productivity (evaluated in months and years of work) more effective with sit-stand desks only because general health is improved or because variations in body position can be beneficial in task performance. The question is especially relevant sit-stand desks are largely sold and used in various countries such as in the USA, Canada, Australia, and North of Europe.

Review of the literature on task performance when sitting vs. standing (before fatigue)

Today, more than 100 research studies in human factors engineering have compared task performance when standing and sitting (for reviews, see (Kar & Hedge, 2016; Karakolis & Callaghan, 2014; Rostami, Razeghi, Daneshmandi, Hassanzadeh, & Choobineh, 2022; Sui, Smith, Fagan, Rollo, & Prapavessis, 2019). In these reviews, investigators analyzed task performance in desk-based activities such as typing, computer mouse use, work-related tasks, memory tasks, visual tasks, reading comprehension, mathematics, executive function tasks, creativity, and psychomotor function. Most of the time, task performance when standing was found to be as good as when sitting (Kar & Hedge, 2016; Karakolis & Callaghan, 2014; Rostami *et al.*, 2022; Sui *et al.*, 2019). Thus, one important information is that the standing position is not associated with poorer performance. These non-significant findings especially were found when task performance was analyzed with discrete variables with "0" for failure and "1" for success. When task performance was analyzed with continuous variables, such as the reaction time to perform the experimental task, published results were more discriminative. In fact, some studies used the modified Stroop task and evidenced better task performance (Rosenbaum, Mama, & Algom, 2017; Smith, Davoli, Knapp, & Abrams, 2019) or equivalent (Caron *et al.*, 2020; Caron *et al.*, 2022) task performance when standing. Other studies used the Attention Network Task (ANT) and analyzed three composite variables, i.e. the alerting, executive, an orienting scores (Abou Khalil, Doré-Mazars, & Legrand, 2023, 2024; Barra, Auclair, Charvillat, Vidal, & Pérennou, 2015). These three studies showed that the overall reaction time or the alerting score was significantly shorter when standing than when sitting (cf. Figure 2 of their publication).

Some investigators also tested whether alternating standing and sitting can lead to better task performance than only sitting. Hasegawa, Inoue, Tsutsue and Kumashiro (2001) evaluated participants performing a repetitive task (single-digit multiplications) over periods of 15, 30, 45 or 90 minutes. These investigators found that changing the body position every 10 to 20 minutes over a 60-minute period was the best alternative to improve task performance (Hasegawa *et al.*, 2001). In a remarkable study, van Steenbergen, Wilderjans, Band and Nieuwenhuis (2024) explored whether the alternating position (six blocks of 20 min) could impact cognitive performance and arousal. Participants performed three tasks (flanker task, switch task and 2-back working memory) in each block, each task lasting 6 minutes. Results showed that when alternating sitting and standing, arousal was significantly enhanced, effort cost was significantly decreased and cognitive outcome was significantly improved. Furthermore, Schwartz, Kapellusch, Baca and Wessner (2019) and Schwartz *et al.* (2018) studied participants either alternating sitting and standing or only sitting during two sessions of 150 minutes. Participants were requested to complete five repeated trials (each lasting 25 minutes) of a test battery comprising three tasks. The results showed a significantly higher concentration and work speed when alternating standing and sitting than when only sitting.

Swaying in the standing position as an effective way to succeed in the task performed

In our research team in France, we do not consider that standing per se can explain better cognitive processes and task performance. For us, the body position is a confounding variable. Instead, we consider that having to actively control equilibrium in the standing position is what matter to explain better cognitive processes and task performance when standing. To be clear, we need to mention that when standing, individuals sway at all time and continuously need to control their equilibrium. Individuals even sway by default in a nonlinear, non-stationary and fractal manner (Riley & Turvey, 2002; Stambolieva, 2011). In our hypothesis, we consider that the active process of adapting postural sway to the task perform matters to explain better cognitive processes and task performance. Carefully, we take into consideration that standing in a stationary position – as when standing in front of a sit-stand desk – is rapidly tiring as it can be tiring only after some minutes. As a consequence, here are our two sub-hypotheses: i) for short period of time (before any fatigue), we expect that individuals should better succeed in cognitive tasks when standing than when sitting; ii) for longer period of time (when physical fatigue is coming into play), we expect that individuals should better succeed in cognitive tasks when frequently alternating sitting and standing to spend as much time as possible in the standing position while avoiding fatigue caused by (excessive) standing.

At least three main reasons could explain why individuals should perform better cognitive tasks when swaying and actively controlling balance in the standing position than when passively seated (again before any physical fatigue). Firstly, for optimal perception, our sensory systems have to be continuously stimulated (Davids, Glazier, Araújo, & Bartlett, 2003; Engbert, 2021; Fabre *et al.*, 2021). In fact, effective visual perception depends on continuous eye movements (Montesano *et al.*, 2018). When fixational eye movements are absent, neural adaptation in the visual cortex renders the system functionally blind (Martinez-Conde *et al.*, 2009). In a completely motionless visual field, that is, without ongoing retinal image refreshment, perception would fade (Engbert, 2021). An important information is that constant sensory input – whether auditory, gustatory, or tactile – is perceived only transiently before fading from awareness. This likely explains why human eyes are never perfectly still (Intoy & Rucci, 2020). Probably for this reason and for vision, micro-movements of the eyes – drifts, tremors, and microsaccades – prevent vision from becoming static (Engbert, 2021; Intoy & Rucci, 2020). In the same vein, both body and brain depend on continuous variability to accurately perceive body position and the spatial relationship between body and environment (Kelty-Stephen, Lee, Carver, Newell, & Mangalam, 2021; Riccio, 1993; Riley & Turvey, 2002). From this perspective, postural sway observed during quiet standing appears beneficial rather than detrimental. This interpretation remains relatively rare in the literature – apart from some studies (Doyon, Hajnal, Surber, Clark, & Kelty-Stephen, 2019; Hajnal, Clark, Doyon, & Kelty-Stephen, 2018; Hajnal *et al.*, 2022; Mangalam, Carver, & Kelty-Stephen, 2020; Mangalam, Chen, McHugh, Singh, & Kelty-Stephen, 2020; Mangalam & Kelty-Stephen, 2020; Masoner *et al.*, 2020; Palatinus, Dixon, & Kelty-Stephen, 2013; Palatinus, Kelty-Stephen, Kinsella-Shaw, Carello, & Turvey, 2014) and the broader ecological framework for perception and action (Gibson, 1966; Riccio, 1993; Stoffregen, Yang, & Bardy, 2005; Stoffregen, Yang, Giveans, Flanagan, & Bardy, 2009). In line with this last line of results, we consider postural sway as a functional and adaptive mechanism to best detect information – or stimuli – from the environment.

Secondly, this is not simply swaying that is important for perception and task performance, but adjusting postural sway to the difficulty of the task performed. As a general insight, our surrounding environment is complex, with various irregular, erratic forms, i.e. fractal forms (Xu, Moore, & Gallant, 1993). A fractal form is a complex geometric structure that exhibits self-similarity across different scales and is often generated by repeating a simple process (iteration) infinitely (Xu *et al.*, 1993). In other words, if you zoom in on a small part of a fractal, it resembles, although still different from, the overall shape. Most of the time, our surrounding environment is extremely complex. According to some investigators, this surrounding complexity could be best perceived only in adjusting the complexity of functioning of our perceptual systems (e.g. Mangalam, Carver, *et al.*, 2020). In other words, the complexity of our perceptual systems should be adjusted to the complexity of the surrounding world, to best match it to allow optimal perception. In many of their studies, the research team by Kelty-Stephan, Mangalam and colleagues are testing these relationships. For example, (Mangalam, Carver, *et al.*, 2020) investigated whether the multifractal characteristic of center-of-pressure (COP) sway was associated with perceptual accuracy during effortful touch. These investigators used vector autoregression (VAR) analysis to capture the body-wide interdependencies among multifractal estimates across trials. Their results revealed that i) multifractality in COP dynamics facilitated multifractal fluctuations in hand movements and that ii) the strength of these exchanges in multifractal fluctuations between the COP and the hand predicted perceptual accuracy. Based on these findings, the authors proposed that accurate perception through effortful touch emerges from the coordinated interactions among different body segments mediated by multifractal fluctuations. In other words, perceptual performance may depend not only on the hand's effortful touch but also on the ongoing dynamic regulation of postural control (Mangalam, Carver, *et al.*, 2020). In conclusion, lucky individuals are to sway in the standing position (Bonnet & Cheval, 2023). The message here is that the nature of postural sway can be easily modulated in the standing position, and is indeed adjusted to the task performed (while it may be too imprisoned in the sitting position).

Thirdly, maintaining an upright posture – and consequently controlling balance through continuous postural adjustments – may facilitate the functioning of attentional resources in goal-directed tasks. This idea is based on Chajut and Algom's attentional hypothesis (Chajut & Algom, 2003). According to these investigators, a moderately high level of mental stress can reduce the overall availability of cognitive resources while simultaneously promoting focus on task-relevant stimuli and filtering out irrelevant information. Moderate stress could foster more selective attention in healthy young adults compared with lower-stress (Chajut & Algom, 2003) or lower-load (Lavie, Hirst, de Fockert, & Viding, 2004) situations. Although Chajut and Algom (2003) did not consider body posture as a factor influencing attentional constraints, it has been suggested that the level of physiological or cognitive stress may be too low in the sitting position, while arousal may reach an optimal level in the standing position (Bonnet & Cheval, 2023; Ebara, Kubo, & Inoue, 2008; Kar & Hedge, 2016; Rosenbaum *et al.*, 2017; Smith *et al.*, 2019). Instead of only considering that the standing position per se could higher selective attention, our research group in France suggests that it is the need to actively control balance in continually regulating postural control that may play a critical role to higher selective attention and task performance.

The three aforementioned explanations discussing active postural control as predictor of task performance are not necessarily mutually exclusive; they can instead be complementary. The literature already showed that postural sway is adjusted both at the magnitude level (e.g. amplitude, velocity) and at the nature level (e.g. complexity) to perform and succeed in various tasks (e.g. fixation of a stationary target, free-viewing of a virtual environment, searching to locate target in a virtual environment) (e.g., Bonnet & Baudry, 2016). In our opinion, the brain actively modulates postural sway all together for controlling equilibrium and for adjusting – fitting – the nature and magnitude of postural sway to the task performed. Individuals would be able to maintain their alertness higher and longer when actively controlling their equilibrium than when passively sitting.

As explained earlier, we need to consider that the standing position becomes rapidly tiring and even sometimes painful (Baker *et al.*, 2018; Coenen *et al.*, 2017; Locks *et al.*, 2018). In fact, one additional hour of standing can lead to pain in the back and lower limbs, muscular fatigue, chronic venous problems (Baker *et al.*, 2018). As a consequence, excessive standing should i) cancel the beneficial effects of swaying and ii) should even cause lower task performance when standing than when sitting. In long-lasting tasks, we thus assume that frequently alternating sitting and standing should favor task performance in contrast to only sitting (or also in contrast to the painful only standing condition) (Bonnet & Cheval, 2023).

Studies performed in the SCALab

Studies performed to test if standing and swaying could benefit task performance (vs. sitting)

In our research team in the SCALab, we are conducting studies to test i) if adaptation of postural sway can be used to higher task performance and ii) if task performance can be higher when standing (and swaying) than when sitting. We published various studies since 2022.

In Bonnet, Singh and Barela (2022), our first objective was to test if task performance to locate Waldo in experimental cartoon images (based on the game “where is Waldo”) could be higher when standing than when sitting. Our second objective was to show that postural sway could play a determinant role in the level of task performance. In studies 1 and 2, 32 and 16 young adults performed three visual tasks (searching to locate targets, free-viewing and fixating a stationary cross) either when standing or when sitting. The tasks were displayed in small images (visual angle: 22°). Task performance, eye, head, upper back, lower back and center of pressure displacements were recorded and analyzed. In both studies, task performance in searching was equivalent (and absolutely not worse) when standing than when sitting. Postural sway was smaller in magnitude during the search task (vs. other tasks) when standing but not when sitting. Hence, only when standing, postural control was adjusted to perform the challenging search task. Only in study 2, when exploring images, and searching to locate the targets, head rotation was significantly greater when sitting than when standing. We explained that when sitting, variability in body movement may be lacking to facilitate visual task performance, thus requiring compensatory movements. In this study, results indirectly suggested that the magnitude of body movement could be too limited when sitting to facilitate task performance in a goal-directed visual task.

In Bonnet, Kechabia, Magnani, Polastri, & Rodrigues (2024), our objective was to test if postural sway could provide beneficial effects on goal-directed visual task performance. Twenty-four healthy, young adults performed the incongruent and reversed incongruent modified Stroop tasks in four body position conditions (standing against a vertical surface, and standing freely either in a wide, standard or narrow stance). COP sway, head sway, eye movements, visual attention, and task performance were recorded. We used partial correlation analyses to test relations between body sway and task performance while controlling for the level of visual attention. These partial correlation analyses showed significant positive associations between task performance and some COP and head sway variables. Therefore, higher magnitude of COP and head sway was suggested to be related to higher level of task performance in this modified Stroop task. Bonnet *et al.* (2024) thus showed that the magnitude of postural sway could have an influence on task performance. In fact, partial correlation analyses showed that i) task performance was worse when participants did not need to control their equilibrium – exactly as when sitting on a chair – and that ii) task performance was higher when participants could sway freely in narrow stance.

In Hua *et al.* (2025), our objective was to test if body position (sitting vs. standing) could influence task performance in various visual tasks (reading and understanding a text; answering questionnaires about this text; performing an Attention Network Task (ANT)) and if the presence of postural sway could influence task performance. Seventeen young adults performed three ANT (5 min 35 per ANT) sequentially in both standing and sitting positions: reading a text, answering a questionnaire and performing ANTs. We measured body kinematics from the head, upper back and lower back during the study. We analyzed the velocity and fractal dimension of body sway, reaction times (shorter reaction time indicating better performance) and alerting scores (higher alerting scores indicating better performance) from the ANT. Our results showed that when standing, the complexity of sway was significantly negatively correlated with ANT reaction times and positively correlated with the scores of alerting from ANT. Hence, consistent with our expectation, ANT performance could be higher when standing because participants could actively adjust their postural sway. In contrast, when sitting, there was no significant correlation between body sway and ANT performance. In our discussion, we suggested that the complexity of body sway in the standing position may increase alertness levels, thus leading to better visual task performance.

Study performed to test if alternating body position could benefit task performance (vs. only sitting)

In Cherigui, Guillaume, Rodrigues and Bonnet (2025), we mainly tested if alternating body position (successively sitting and standing) could higher task performance in contrast to only sitting. We also tested if alternating body position could higher task performance especially when participants were standing. Twenty-four participants performed the ANT six times either in alternating sitting and standing or in only sitting. We analyzed the reaction time in the ANT measured by the keyboard and the proportion of blinks measured by our Pupil-labs eye tracker. The proportion of blinks was significantly lower when alternating sitting and standing than when only sitting. We then analyzed significant differences in our dependent variables between the three tasks performed when standing and the three tasks performed when sitting. These analyses were performed either in the same block of 6 trials (within-condition) or in contrast to the other block (between-condition). In both between- and within-condition analyses, the reaction times were significantly shorter when standing than when sitting. Overall therefore, young individuals were more effective (i.e. a shorter reaction time) and had greater visual attention (i.e. less frequent proportion of blinking) when alternating sitting and standing than when only sitting.

Methodological benefits of our international collaboration (CAPES-COFECUB project)

The new use of the linear mixed model

In the literature reports, various studies already used linear mixed models to show that characteristics of postural sway (both linear and nonlinear) to predict task performance in affordance tasks (Doyon *et al.*, 2019; Hajnal *et al.*, 2018, 2022; Mangalam, Carver, *et al.*, 2020; Mangalam, Chen, *et al.*, 2020; Mangalam & Kelty-Stephen, 2020; Masoner *et al.*, 2020; Palatinus *et al.*, 2013, 2014). In 2024, our research team decided to learn how to use the linear mixed model and this work was performed by Dr. De Andrade Silva (Brazilian researchers) who came to France as a post-doctoral fellow in the CAPES-COFECUB project. Dr. De Andrade Silva successfully understood the methodology to use this linear mixed model, he prepared R codes to use it and he even defined and explained this model to SCALab members in a statistical technical course (on October 24th 2024).

First results brought by the linear mixed model

In Butin *et al.* (in preparation), our objective was to test if it was body position or postural sway which could predict change in task performance in ANT. Twenty-four participants were positioned in front of a sit-stand desk and performed three successive ANTs in three body positions: i) in sitting quietly, ii) in free standing and touching the two key boards on the desk with their two preferred fingers and iii) in restrained standing in pushing both forearm on the desk to touch the two key boards with their two preferred fingers. We tested differences in general reaction time and in the three sub-scores of the ANT (alerting network, orienting network and executive control). We expected task performance to be significantly higher than when standing quietly in both other conditions. We also expected task performance to be exactly equivalent when sitting and when standing in the restrained condition because participants did not need to control their posture in both latter conditions. Our results initially showed that task performance was not affected by any type of body position. We then used the linear mixed model to test if the body position and/or characteristics of body sway could predict task performance in the ANT. The model showed that body position was not a relevant variable. It also showed that body sway at the head ($p<0.05$), lower back ($p<0.05$) and almost at the upper back ($p=0.06$) could predict task performance only in the restrained standing condition. A repeated measure ANOVA and post-hoc additionally showed that participants swayed significantly less in the restrained standing condition than when standing quietly but still swayed significantly more in this restrained standing condition than in the sitting condition. Overall, we invalidated our main hypothesis that only postural sway when standing quietly could predict task performance. However, our results were not completely contrary to our initial hypothesis. In fact, participants really swayed in the restrained condition, they swayed more than originally expected and could still actively modulate their equilibrium. May be that results validated our initial hypothesis only in this restrained condition because the restriction eliminated irrelevant variability of postural sway and facilitated the discrimination of relations between characteristics of postural sway and task performance. May be that in including more participants, we could have validated our initial hypothesis with postural sway when standing quietly. In line with this last assumption, the model was almost significant when standing quietly at the lower back level (p = 0.07), upper back level (0.13) and head level (0.14).

In a more recent study performed in the context of the CAPES-COFECUB project (in preparation), our objective was to test if postural sway when standing could predict task performance in a visual search task. Twenty-four participants were either sitting on a chair or standing on a force platform in front of a large screen (dimensions: left-right: 62°; up-down: 38°). The images used were virtual rooms (e.g. kitchen, living room, bedrooms) in various houses composed or few vs. a lot of objects. The experimental tasks were either searching to locate as many target objects as possible (experimental search task), to randomly look at the image without any specific goal (free-viewing control task) or to fixate a stationary target displayed at the center of the screen (basic fixation task). Analyses of results of this study are still not performed but will be computed end of 2025 – beginning of 2026. We will be interested to know if task performance can be predicted by characteristics of postural sway in such an ecological search task. We will also be interested to know how characteristics of postural sway can be changed by the task performed (fixation, free-viewing, searching) and body position (sitting vs. standing).

Interpretation

For recall, in our research team, we consider that the active process of controlling and adapting postural sway to the task perform matters to explain better cognitive processes and task performance. For short period of time (before any fatigue), we expect that individuals would better succeed in cognitive tasks when standing than when sitting because they can adjust their sway when standing. More exactly, we expect that changes in postural sway should predict success in cognitive tasks only when standing. For longer period of time (when only standing can be tiring), we expect that individuals would better succeed in cognitive tasks when frequently alternating sitting and standing instead of only sitting. Exactly as for short periods of time, we expect that changes in postural sway should predict success in cognitive tasks only when standing. Published studies in our research team partially validated these hypotheses, and at least did not invalidate them.

Could active postural control and active adaptation of postural sway explain better performance when standing?

In two studies (Bonnet *et al.*, 2024; Hua *et al.*, 2025), we used – Pearson's and partial – correlation analyses to show possible relations between characteristics of postural sway and the level of task performance. In Bonnet *et al.* (2024), participants were only standing and Partial correlation analyses showed significant positive associations between task performance and some COP and head sway variables, after controlling for the level of visual attention. In (Hua *et al.*, 2025), we found a significant negative correlation between the complexity of postural sway and ANT reaction times (as an important insight, the lower the reaction time the better the performance) and a significant positive correlation between the complexity of postural sway and the score of alerting. In contrast, while sitting, there was no significant correlation between body sway and ANT performance. The results in both studies showed that there was a positive relation between an increase in the quantity and/or complexity of postural sway and higher task performance (Bonnet *et al.*, 2024; Hua *et al.*, 2025). In an earlier study in Bonnet *et al.* (2022), we did not perform any correlation analyses but showed that young participants significantly increased their head rotation from a free-viewing control task to a search goal-directed task when seated but not when standing. We suggested that when seated, participants needed to increase this variability – by means of head rotation – to compensate for the lack of useful variability required to facilitate visual task performance. For us, the increased head rotation in the seated position in Bonnet *et al.* (2022) was a functional sign of adaptability. At least, it could not be a sign of instability as individuals were already stable in the seated position. Furthermore, in the sitting position, there was no reason for participants to get less stable from free-viewing to searching. Butin *et al.* (in preparation) is our first study to test whether active adjustment of postural sway could predict – by means of the linear mixed model – task performance in an attentional task (ANT). In this study, the model was almost significant when standing quietkly at the level of the back marker (p=0.07). Furthermore, linear characteristics of postural sway (dependent variables: path length and ellipse area) predicted task performance when participants were standing in the restrained condition. These results partially validated our initial hypothesis as participants still swayed significantly more in this restrained condition than when seated, thus showing that they still actively adjusted their equilibrium to the task performed.

In our Introduction, we already explained three reasons why active postural control and active adaptation of postural sway in the standing position could predict task performance. These reasons are summarized here again for recall. Firstly, all our perceptual systems detect random stimuli, i.e. nonlinear, non-stationary and fractal stimuli but do not detect constant stimuli. In the visual system, the eyes need to move to best perceive (Montesano *et al.*, 2018) and the absence of stimulation in the eyes make them functionally blind (Martinez-Conde, Macknik, Troncoso, & Hubel, 2009). Accordingly, eyes move continuously with drifts, tremors, microsaccades and saccades. Furthermore, eyes also move randomly because the head and body sway in a random manner, i.e. with nonlinear, non-stationary and fractal properties. In our opinion, randomly swaying in the standing position is an efficient functional manner to best help all our perceptual systems to best perceive stimuli our surrounding environment. Secondly, the adjustment of postural sway to the difficulty of the task performed also matters. As our surrounding environmental is more or less complex, with various irregular, erratic forms, i.e. fractal forms, our perceptual systems have to function in complex ways to best perceive it. More exactly, the more complex our surrounding environmental is and the more complex the functioning of our perceptual systems should be. Remarkably, some investigators already showed that the complexity of postural sway was adjusted to the complexity of the perceptual task performed (Masoner *et al.*, 2020). In our opinion, the complexity of body movement may not be adjusted enough while seated as the body is too much constrained. Thirdly, based on (Chajut & Algom, 2003)'s theory, the fact of having to control balance and adjust postural sway when standing may higher the level of selective attention. The constrained imposed on the body system by actively maintaining balance may be great enough when standing but may be too low when passively seated. Overall, individuals could more easily detect relevant stimuli and avoid focusing on irrelevant stimuli when standing than when sitting (Bonnet & Cheval, 2023; Ebara *et al.*, 2008; Kar & Hedge, 2016; Rosenbaum *et al.*, 2017; Smith *et al.*, 2019).

Is task performance better when standing (before fatigue) or not?

In two of our studies (Cherigui *et al.*, 2025; Hua *et al.*, 2025), we showed that young participants get significantly shorter reaction time in the ANT when standing than when sitting. In other studies, we could not find any significant difference, in reaction time or in task performance (success vs. failure) between the standing and sitting conditions (Bonnet *et al.*, 2024, 2022; Butin *et al.*, in preparation). These results are in line with the literature reports as some studies showed significantly shorter reaction time when standing than when sitting (Abou Khalil *et al.*, 2023, 2024; Barra *et al.*, 2015; Rosenbaum *et al.*, 2017; Smith *et al.*, 2019) or equivalent ones between the two body positions (Caron *et al.*, 2022, 2020; for reviews cf. Kar & Hedge, 2016; Karakolis & Callaghan, 2014). We are aware of a few studies in which participants performed worse when standing than when sitting. However, in all these studies, there were biases as participants were not standing in the standard position but either on one foot (Remaud, Boyas, Caron, & Bilodeau, 2012) or one foot forward the other (Kerr, Condon, & McDonald, 1985; Remaud *et al.*, 2012).

Is task performance better when alternating than when only sitting?

In Cherigui *et al.* (2025), we tested and found that task performance, indirectly evaluated in visual attention to perform the ANT, was significantly better when alternating sitting and standing than when only sitting. In fact, we found that the proportion of blinks was significantly lower in the alternating condition than in the only sitting condition. In other words, the standing position was effective in reducing visual attention. Our results are in line with van Steenbergen *et al.* (2024) who tested participants in three tasks (flanker task, switch task and 2-back working memory; 20 min in total). Participants performed these tasks either in alternating between sitting and standing or in only sitting. van Steenbergen *et al.* (2024) also showed that arousal was significantly enhanced in the alternating condition than in the sitting only condition in the flanker task. So far, we are not aware of any published study showing worse task performance of cognitive processes when alternating between sitting and standing than when only sitting.

Future work to test the hypotheses that task performance can be better when standing

As it should be clear in this book chapter, we assumed that task performance could be higher when actively controlling postural sway in the standing position than when passively sitting. The fact of disentangling which of the standing position and the active control of equilibrium could better explain and predict task performance is possible in two ways. Firstly, we have to use linear mixed model considering both body position (sitting vs. standing) and postural sway as predicting factors in showing that only the variables of postural sway can predict task performance. Secondly, we have to vary the active control of equilibrium in requesting participants to stand either naturally or completely restrained (e.g. standing against a vertical wall). Then, we have to disentangle which of our three aforementioned sub-hypotheses (see introduction for more details) is most relevant to best predict task performance in the standing position. In this vein, various investigators already showed that the two first hypotheses are complementary and closely related (Doyon *et al.*, 2019; Hajnal *et al.*, 2018, 2022; Mangalam, Carver, *et al.*, 2020; Mangalam, Chen, *et al.*, 2020; Mangalam & Kelty-Stephen, 2020; Masoner *et al.*, 2020; Palatinus *et al.*, 2013, 2014). In fact, all these studies showed that postural sway is very complex and that this complexity is adjusted to best perceive and best perform perceptual affordance tasks. Future studies still have to test and disentangle if it is only active postural control or more efficient selective attention that may matter to best perceive and best perform goal-directed tasks. We assume that both active postural control and more efficient selective attention are closely related and come together. Future studies will need to test this new assumption.

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Cognitive–motor interference revisited: Insights from visual manipulations during standing

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Absract

Postural control during quiet standing is a highly adaptive process that emerges from the continuous interaction between sensory information, motor coordination, and cognitive demands. Dual-task paradigms have traditionally interpreted cognitive–motor interference as competition between independent systems for limited resources. However, alternative dynamical perspectives suggest that posture, perception, and cognition form an integrated coordination structure which is adapted to task and environmental constraints. The present study examined how engaging working memory modulates postural control and cognitive performance under different visual environments. Twenty-seven healthy young adults performed a visual 2-back task while standing in a stationary room or in a moving room oscillating at 0.2 Hz and 0.5 Hz. Postural sway was quantified using center-of-pressure (COP) measures, and visuomotor coupling was assessed through gain, phase, and position variability analyses. Cognitive performance was evaluated using reaction time and task accuracy. Repeated-measures ANOVAs and linear mixed-effects models were used for statistical analysis. Postural sway was reduced across all visual conditions by means of increasing cognitive engagement. Visual perturbation increased visuomotor coupling, particularly at 0.5 Hz, and this effect was amplified during the cognitive task condition. Behavioral results revealed a dissociation between accuracy and reaction time: accuracy remained largely stable, whereas mixed-effects models revealed a context-dependent association between postural sway and reaction time only under the most demanding visual condition. These findings indicate that cognitive–motor interactions are not linear and competitive but emerge selectively as the perception–action system reorganizes to meet environmental demands. Postural sway should therefore be understood as a functional component of behavior, whose role depends on context rather than variability to be minimized.

Introduction

The study of postural control has long served as a window into the organization of perception and action in humans. Although quiet standing might appear as a static and automatic process, it is in fact a highly adaptive behavior that emerges from the ongoing integration of sensory information, motor coordination, and cognitive regulation (Horak, McPherson, 1996; Nashner & McCollum, 1985; Huxhold *et al.*, 2006). When individuals stand upright, they continuously update their body orientation relative to the environment. This process depends not only on vestibular and somatosensory inputs but also on the structure of visual information available in the surrounding scene (Peterka, 2002; Stoffregen & Riccio, 1988; Polastri *et al.*, 2012; Assländer & Peterka, 2014). At the same time, higher-level cognitive operations, such as maintaining information in working memory or engaging executive monitoring, can influence how sensory information is selected, weighted, and used to guide postural behavior (Freitas, Barela 2004; Mitra e Fraizer, 2004; Fraizer, Mitra, 2008; Rougier & Bonnet, 2016; Bonnet & Baudry, 2016a; 2016b).

Dual-task paradigms became a central tool for investigating cognitive–motor interference. By requiring individuals to maintain balance while simultaneously engaging in a cognitive task, these paradigms showed that cognitive activity can either destabilize or reorganize postural control, depending on task demands and sensory context (Woollacott & Shumway-Cook, 2002; Huxhold *et al.*, 2006; Fraizer & Mitra, 2008; Belizario Brito *et al.*, 2023). Despite decades of research, this interaction continues to challenge our understanding of the mechanisms linking cognition and postural control (Fraizer & Mitra, 2008; Yogev-Seligmann *et al.*, 2008). Some studies have shown that posture is not merely a background condition for action but instead an active component of perception–action coupling, continuously adapting to what the task requires and to the information available in the environment. For example, in Bonnet, *et al.* (2024), healthy young adults stood freely while performing visual search tasks (modified Stroop task) designed to engage selective attention and goal achievement. Task difficulty was manipulated by systematically increasing cognitive conflict:

in the incongruent condition, word meaning and ink color conflicted (e.g. the word green colored in another color such as yellow, black, red…), requiring inhibition of automatic reading; and in the reversed-incongruent condition, participants had to follow an inverted rule, responding to word meaning instead of color, which further increased executive demands (e.g. if the word green was colored in pink, the participant had to imagine that he was seen the word pink colored in green). Participants performed the tasks under four body configurations: standing against a wall with full trunk support, standing freely with a wide stance, standing freely with a standard stance, and standing freely with a narrow stance. No external perturbations were applied to any condition. The results revealed that greater postural sway was positively associated with higher visual task performance, particularly when participants stood freely. It suggested that postural variability facilitated cognitive performance (Bonnet *et al.*, 2024).

Hence, posture could be viewed as an active component of perception–action coupling, continuously adapting to what the task requires and to the information available in the environment. This idea aligns closely with dynamical systems approaches, which propose that coordinated patterns of behavior emerge from interactions among multiple degrees of freedom (Kelso, 1995; Latash, 2008). In the present chapter, we continued revisiting the concept of cognitive–motor interference from a perception–action perspective, emphasizing the central role of environmental information and treating cognitive and sensorimotor processes as integrated components of a unified coordination system. In the present study, young adults performed a 2-back working memory task while standing quietly under different visual conditions, including a stable environment and a moving-room frequency manipulation that perturbs optic flow (see Lee, Lishman, 1975, Dijskstra *et al.*, 1994; for more details). This combination allowed us to examine how cognitive engagement reorganizes postural control when visual information is experimentally altered. Specifically, this study aimed to understand how engaging working memory influences the organization of postural control under different visual conditions, and whether interactions between cognition and posture reflect simple interference or an adaptive reorganization of postural control within a perception–action framework. We hypothesized that under visual perturbation, postural sway at different frequencies of the moving room would be systematically associated with cognitive performance, indicating functional coupling between postural dynamics and task execution.

Methods

Participants

Twenty-seven young adult university students participated in the study (mean age = 22.2 ± 2.29 years; mean body mass = 66.8 ± 12.3 kg; mean height = 1.68 ± 0.06 m). Inclusion criteria were: age between 18 and 35 years; normal or corrected-to-normal visual acuity (Snellen 20/20–20/25); and cognitive test scores within the normal range (scores between 27 and 30). Exclusion criteria included musculoskeletal (e.g., fibromyalgia, injuries), physical (e.g., prostheses), and sensory impairments (e.g., dizziness, vertigo, severe visual problems, among others) that could compromise performance on the proposed tests. Participants were informed about the experimental procedures and, after agreeing to participate, signed a written informed consent form approved by the Ethics Committee of the School of Sciences – UNESP, Bauru Campus (CAAE: #04406818.0.0000.5398).

Procedures

Data collection was conducted at the Laboratory of Information, Vision, and Action (LIVIA) at UNESP – Bauru Campus. Initially, participants completed a questionnaire to gather qualitative information regarding their profile and medical and family history. Subsequently, the Mini-Mental State Examination (MMSE), a clinical test used to assess cognitive status, was administered. Body mass, height, and visual acuity (Snellen test) were then measured.

Participants were positioned in an upright stance on a force platform located at the center of a moving room. The force platform (AMTI – AccuGait) consisted of a plate with four electrical sensors that measure horizontal and vertical force components (Fx, Fy, and Fz) and the corresponding moments (Mx, My, and Mz), which were subsequently used to calculate center of pressure (COP) displacements. The moving room was used to manipulate participants' optical flow and increase body sway corresponding to the visual stimulus parameters, without prior knowledge of this manipulation. The apparatus consisted of an aluminum structure measuring 2.1 × 2.1 × 2.1 m (height, width, and length). Its inner walls were painted white with alternating black vertical stripes to increase environmental contrast. The structure was mounted on silicone wheels positioned on rails fixed to the floor, allowing continuous forward and backward movement independently of the floor. Movements were generated by a controller (Parker Compumotor – Model 6k8) and a stepper motor (Model PL06) attached to the back wall of the room. Movement parameters (amplitude, velocity, and frequency) were controlled by specific computer programs (Compumotor – Motion Architect) written in a programming language. Room displacement was measured by a sensor mounted on the side wall of the room, which is part of a magnetic motion analysis system consisting of a receiver, a transmitter, and a control unit (Flock of Birds Magnetic System). A multimedia projector (EPSON PowerLite W6) mounted on the ceiling of the room was used to project the visual task onto the front wall. The sampling frequency of all equipment was 60 Hz. Figure 1 illustrates the experimental setup of the study.

Participants were instructed to stand upright with their feet parallel, remain as still as possible, keep their arms relaxed alongside the body, and hold a mouse in the dominant hand (100% of participants used the right hand), positioned parallel to the thigh. Participants were instructed to use the mouse without touching any part of their body. Two cognitive task conditions were performed: with and without a visual 2-back task, named Task (T) and No Task (NT) condition, respectively; under three visual environmental conditions: a stationary environment (ST), in which the room remained stationary, and a moving-room environment, in which the room oscillated at frequencies of 0.2 Hz and 0.5 Hz, with a constant velocity of 0.75 cm/s. The higher frequency was used to increase the demands on postural control.

Participants performed two trials in the stationary room condition, two trials with the moving room at 0.2 Hz, and two trials with the moving room at 0.5 Hz, resulting in six trials in the Task condition and six trials in the No Task condition, for a total of 12 trials. Each trial lasted 60 seconds. In the first two and the last two trials (Task and No Task conditions), the room remained stationary. Trials order was counterbalanced and randomized to avoid order effects. Between trials, participants were given a rest period of approximately 60 seconds to minimize physical and/or mental fatigue.

Figure 1. Experimental set-up with an adult standing on the force plate, inside the moving room.

The 2-back task consisted of viewing a sequence of numbers projected onto the front wall of the room, directly in front of the participant, at eye level. Whenever the participant identified that the number presented on the screen was the same as the number presented two numbers earlier, they were instructed to press the left mouse button as quickly as possible. If this congruency did not occur, participants were instructed to memorize the number without pressing the mouse button and wait for the next number to appear on the screen.

The task began with a blank screen displayed for 1.2 milliseconds (ms), followed by the appearance of a white circle that remained at the center of the screen for 750 ms Participants were instructed to fixate on this target until it disappeared, after which a number appeared on the screen and remained visible for 909 ms. After the number disappeared, the sequence restarted and was repeated continuously over 60 seconds, resulting in a sequence of 21 numbers. This task required sustained attention and working memory and was characterized by a moderate level of difficulty. Figure 2 illustrates the experimental design of the study.

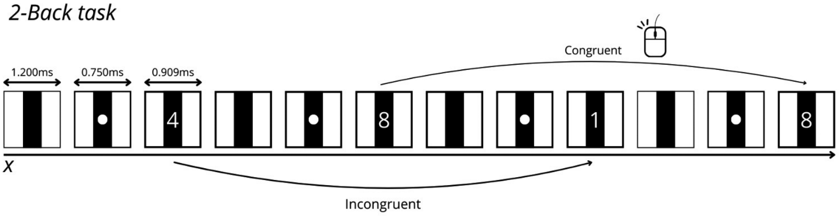

Figure 2. Experimental design showing the sequence of numbers and the duration of each stimulus.

Both the numbers and the circle had a diameter of 3 cm. The white circle preceding the appearance of the numbers was used to ensure that all participants were fixating on the center of the screen at the moment the numbers appeared and could respond as quickly as possible to the presence or absence of congruency. This task was programmed using PsychoPy software in the Python programming language. Six different programs were created, one for each stationary and moving-room trial, to avoid task learning effects. Before data collection began, participants received standardized instructions regarding the 2-back task and completed a familiarization session with the experimental procedures to ensure full understanding. However, participants were not informed about the visual manipulation provided by the moving room so as not to influence the behavior to be observed (Freitas & Barela, 2004). The onset of the cognitive task was synchronized with the other equipment in each trial by means of an external trigger and a 2.4 GHz wireless keyboard.

Data analysis

Data obtained from the force plate and the magnetic sensor were processed and analyzed using MATLAB software (2023). Initially, the data were filtered using a second-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. To quantify the variability of COP displacements across experimental conditions, mean amplitude was calculated from the standard deviation of the COP trajectory after subtracting the mean COP position within each trial, along the anteroposterior (AP) axis (the direction of room movement).

To quantify the coupling between COP displacements and the room movements (visual stimulus), a Frequency Response Function (FRF) analysis was performed. This function consisted of dividing the Fourier transforms of the COP trajectory by the Fourier transforms of the room trajectory at the same stimulus frequency, yielding a complex-valued function for each trial. This analysis was computed on a cycle-by-cycle basis, separately for each visual stimulus frequency (0.2 Hz and 0.5 Hz). From this analysis, the following variables were calculated: (a) Gain – obtained from the magnitude (absolute value) of the complex FRF values. This variable indicates the coupling between the amplitude of room movement and the amplitude of COP displacement in the AP direction (direction of room movement). Gain values close to 1 indicate that the amplitude of COP displacement matched the amplitude of room movement; (b) Phase – obtained from the argument of the complex FRF values, converted from radians to degrees. This variable indicates the temporal relationship between the visual stimulus (room movement) and COP displacement. Positive and negative values indicate that COP displacements led or lagged behind the room movements, respectively.

In addition, COP position variability was calculated for the trials in which participants were exposed to room movement. This variable differed from the overall amplitude, as it represented the variability of COP displacements under the effect of visual manipulation, reflecting how stable the coupling between COP displacements and the visual stimulus provided by the moving room was. To calculate this variable, the standard deviation of the residual COP trajectory was obtained after removing the signal component corresponding to each room movement frequency. Therefore, this variable represented the variability of COP displacements at frequencies different from those of the room movements adopted in this study (0.2 Hz and 0.5 Hz).

Cognitive variables

Data generated by the PsychoPy software were stored in ASCII format. To quantify cognitive task performance (accuracy and processing time) across the different experimental conditions, the number of correct responses and reaction time (RT) were computed. A correct response was defined as pressing the mouse button when the presented number matched the number shown earlier (congruency). The total number of correct responses per trial was computed for each participant. These values were normalized by dividing the number of correct responses obtained by the total number of possible correct responses for each trial and multiplying by 100. Mean values for each condition were then extracted for each participant. Reaction time (RT) was defined as the time interval between the appearance of the number on the screen and the mouse button press during the trial. RT was computed only for correct responses in the number sequence. Then, mean RT values were extracted for each trial and condition for each participant.

Statistical analysis

Shapiro–Wilk tests were conducted to assess data normality, and data were transformed when necessary. To investigate the effect of the cognitive task on posture under different visual environment manipulations, a two-way repeated-measures ANOVA (2 × 3) was performed with task (Task and No Task) and visual environment (stationary, 0.2 Hz, and 0.5 Hz) as within-subject factors. The dependent variable was the mean amplitude of COP displacement in the anteroposterior (AP) direction. Another set of two-way repeated-measures ANOVAs (2 × 2) was conducted to examine the effects of task and room movement frequency (0.2 Hz and 0.5 Hz) on visuomotor coupling. The dependent variables were gain and phase between COP displacements and room movement, as well as COP position variability. To examine participants' performance on the cognitive task, a one-way repeated-measures ANOVA was conducted with visual environment (stationary, 0.2 Hz, and 0.5 Hz) as the within-subject factor for the reaction time variable. In addition, post hoc tests with Bonferroni adjustments were performed when necessary. A nonparametric Wilcoxon test was used to examine differences between environmental conditions for the percentage of correct responses.

Finally, a linear mixed-effects model was used to examine the association between task performance and postural measures across experimental conditions. Reaction time was entered as the dependent variable, condition (Stationary, 0,2 Hz, and 0,5 Hz frequencies) was treated as a within-subject factor, and the postural variable (i.e., mean amplitude in Task condition) was included as a continuous covariate. Random intercepts were specified for participants, and an autoregressive covariance structure (AR(1)) was used to account for within-subject dependencies. Models were estimated using restricted maximum likelihood (REML). A second linear mixed-effects model was conducted to examine whether postural measures were associated with task accuracy. The percentage of correct responses was entered as the dependent variable, condition as a within-subject factor, and mean amplitude of COP displacements in the Task condition as a continuous covariate. The same random and covariance structures were applied as in the reaction time analysis. All statistical analyses were conducted using SPSS software (version 21.0), and the alpha level was set at 0.05.

Results

Mean amplitude of COP displacements

The results showed a main effect of task ($F_{(1,36)} = 34.27$, $p < .0001$, $\eta^2 = .546$) and a main effect of visual environment ($F_{(2,52)} = 15.50$, $p < .0001$, $\eta^2 = .374$), but no interaction between task and visual environment ($p > .05$) for the mean amplitude of COP displacement. Post hoc tests indicated lower COP displacement variability in the anteroposterior (AP) direction in the Task condition ($p < .0001$) and lower variability in the stationary room condition compared with the moving-room condition at frequencies of 0.2 Hz ($p < .0001$) and 0.5 Hz ($p < .003$). Figure 3 (A-D) shows the results for the mean amplitude of COP displacement in the AP direction (Figure 3A), in the Task and No

Task conditions, under the stationary room condition, and at room movement frequencies of 0.2 and 0.5 Hz.

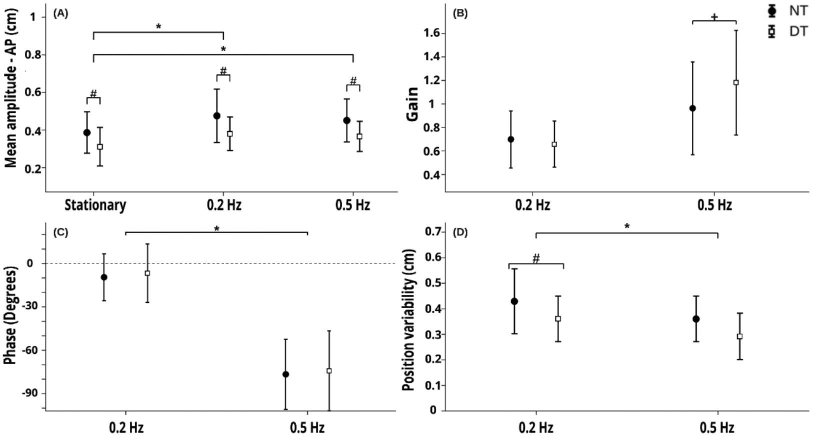

Figure 3. Mean values and standard deviations of the mean amplitude of COP displacement (A), gain (B) and phase (C) between COP displacements and room movement, and COP position variability (D), under the stationary room condition, the moving-room condition at 0.2 Hz, and the moving-room condition at 0.5 Hz, in Task (T) and No Task (NT) conditions. The symbol * indicates a main effect of environment/frequency, # indicates a main effect of task, and + indicates an environment × task interaction.

Coupling between COP displacements and room movements

The results indicated that participants' COP displacements were induced by the movements of the room, with frequency peaks corresponding to the room movement frequency. Figures 4 and 5 present examples of time-series and spectral data of COP displacement and room movement throughout a trial from one participant, in Task and No Task conditions, at room movement frequencies of 0.2 and 0.5 Hz.

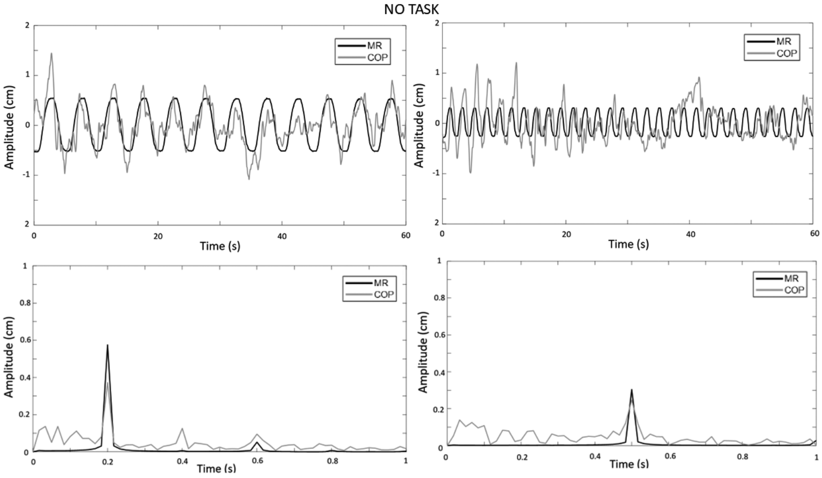

Figure 4. Examples of time series of COP displacements (top panels) and amplitude spectra of COP displacements and moving-room motion (bottom panels) at frequencies of 0.2 Hz (left panels) and 0.5 Hz (right panels), in the anteroposterior (AP) direction, during the No-task condition. The black line represents the moving room (MR), and the gray line represents COP displacements.

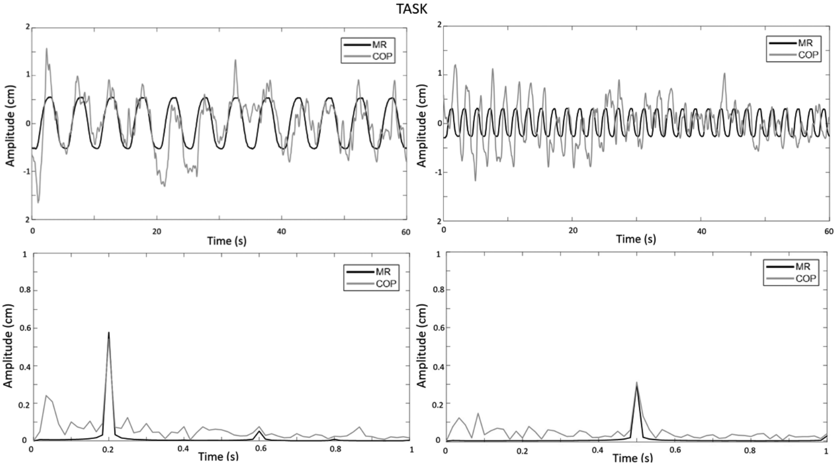

Figure 5. Examples of time series of COP displacements (top panels) and amplitude spectra of COP displacements and moving-room motion (bottom panels) at frequencies of 0.2 Hz (left panels) and 0.5 Hz (right panels), in the anteroposterior (AP) direction, during the Task condition. The black line represents the moving room (MR), and the gray line represents COP displacements.

The ANOVA indicated a significant interaction between task and room frequency for gain (F($_{1,26)}$ = 12.91, $p < .001$, $\eta^2 = .332$), as well as a main effect of task (F($_{1,26)}$ = 6.61, $p < .002$, $\eta^2 = .192$) and a main effect of frequency ($F_{(1,26)} = 51.53$, $p < .0001$, $\eta^2 = .665$). Post hoc tests for the main effects indicated higher gain values in the Task condition ($p < .02$) and at the 0.5 Hz frequency ($p < .0001$). However, the interaction revealed that gain values were significantly higher only during the Task condition at the 0.5 Hz frequency ($p < .0001$) (Figure 3B). For the phase variable, the ANOVA revealed a main effect of frequency ($F_{(1,26)} = 165.66$, $p < .0001$, $\eta^2 = .864$). Post hoc tests indicated negative phase values at the 0.5 Hz frequency, indicating that COP displacements temporally lagged behind room movements at 0.5 Hz compared with 0.2 Hz ($p < .0001$) (Figure 3C). For COP position variability, the ANOVA revealed a main effect of task ($F_{(1,26)} = 37.04$, $p < .0001$, $\eta^2 = .588$) and a main effect of room frequency ($F_{(1,26)} = 45.33$, $p < .0001$, $\eta^2 = .636$), but no interaction between task and frequency ($p > 0.05$). Post hoc tests indicated lower values of COP position variability in the Task condition ($p < 0.0001$) compared to the No-Task condition, and at the 0.5 Hz frequency ($p < 0.0001$) compared to 0.2 Hz (Figure 3D).

Cognitive task performance

Regarding performance on the 2-back task, the results showed no differences across the stationary room condition, the moving-room condition at 0.2 Hz, and the moving-room condition at 0.5 Hz for reaction time ($F_{(2,52)} = .089$, $p > 0.05$, $\eta^2 = .003$). With respect to task accuracy, nonparametric Wilcoxon tests indicated a lower percentage of correct responses only in the moving-room condition at 0.5 Hz compared with the stationary room condition ($p < 0.02$).

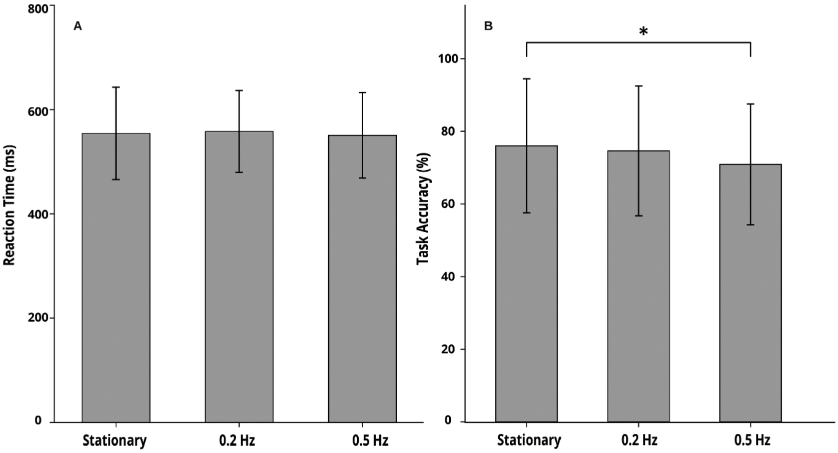

Figure 6. Mean values and standard deviations of the reaction time (A) and percentage of correct responses (task accuracy), under the stationary room condition, the moving-room condition at 0.2 Hz, and the moving-room condition at 0.5 Hz, in the task condition. The symbol * indicates a main effect of environment/frequency.

Mixed model ANOVA

The mixed model revealed a significant main effect of condition on reaction time ($F_{(2,\ 50.1)} = 4.15$, $p < .03$). A significant interaction between condition and postural measure was also observed ($F_{(2,\ 50.2)} = 3.84$, $p < .03$). Post hoc inspection of the fixed effects indicated no association between postural sway and reaction time in the static condition. In contrast, a significant positive association emerged in the most demanding condition (room motion at 0.5 Hz frequency), with higher mean amplitude values associated with longer reaction times (Figure 7). The mixed model revealed no significant effects of condition ($F_{(2,\ 42.1)} = .67$, $p = .515$), postural sway ($F_{(1,\ 68.5)} < 0.01$, $p = .984$), or their interaction ($F_{(2,\ 42.4)} = 0.44$, $p = .650$) on task accuracy. These results indicate that accuracy remained stable across conditions and was not influenced by postural demands.

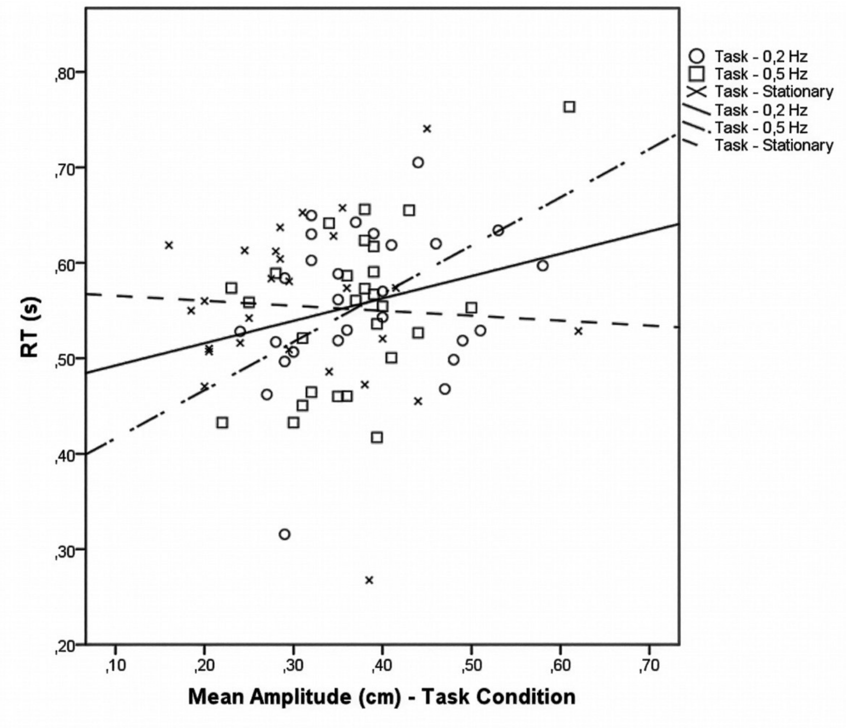

Figure 7. Interaction between the mean amplitude of COP in the task condition and reaction time across experimental conditions. Regression lines are shown separately for each condition. The association between postural sway and reaction time was insignificant in the stationary condition and increased in the more demanding condition, reaching significance in the room movement at 0.5 Hz condition.

Discussion

The present study was design to put forward a perception–action perspective, in questioning the cognitive-motor interference, in examining how engagement in a working memory task reorganizes postural control under different visual environments. Using a combination of repeated-measures approaches and linear mixed-effects modeling, we showed that the relation between cognition and posture depends on context, emerging from the specific informational demands imposed by the task and the environment instead of interacting in a single or strictly competitive manner. The fact that the association between postural sway and reaction time was only observed under the most demanding visual condition (0.5 Hz) indicates that cognitive-postural coupling emerges as a function of task constraints.

Postural reorganization under cognitive engagement

Our results showed a robust main effect of task on COP displacements, with reduced COP variability during the cognitive task across all visual environments. This finding aligns with previous studies showing that cognitive engagement can stabilize posture, often interpreted as a shift toward a more constrained control strategy (Huxhold *et al.*, 2006; Fraizer & Mitra, 2008). It is interesting to note that this stabilization effect occurred regardless of whether visual information was stable or perturbed, which suggests that the cognitive task imposed a general constraint on postural control. Previous experimental studies have consistently shown that engagement in cognitive tasks leads to reduced postural variability, even under altered sensory conditions (Stoffregen *et al.*, 2007; Fraizer & Mitra, 2008). From an ecological perspective, such reduction does not reflect improved stability per se, but rather a functional reorganization of postural degrees of freedom in response to task demands (Newell, 1986; Stergiou *et al.*, 2006). It is consistent with the notion that posture adapts proactively to anticipated task requirements (Stoffregen et al, 2000), and further indicates that postural behavior emerges from the continuous interaction between perceptual, cognitive, and motor processes under varying task and environmental demands.

Visual perturbation and visuomotor coupling

The analyses of visuomotor coupling provide further insight into how postural control adapts when visual information is altered. As the frequency of room movement increased, gain values also increased, indicating that postural sway more closely followed the visual stimulus. This effect was particularly pronounced during the cognitive task, especially at 0.5 Hz. Such an interaction suggests that as visual perturbations become more demanding, participants rely more strongly on visual information to regulate posture, and this reliance is amplified under cognitive load. In parallel, phase analyses revealed systematic temporal lags at the higher frequency, pointing to constraints in the sensorimotor system's ability to track rapidly changing visual input. Together, these findings indicate that postural control under visual perturbation reflects a functional coupling to visual information, which is modulated by both the dynamics of the environment and the cognitive demands of the task (Stoffregen et al, 2000; Genoves *et al.*, 2016; Aguiar *et al.*, 2014).

Cognitive performance: stability of accuracy and selective cost in timing

Behavioral performance on the cognitive task revealed a clear dissociation between accuracy and reaction time. Accuracy remained largely stable across visual conditions, showing only a small reduction at the highest room movement frequency (0.5 Hz). Although this reduction reached statistical significance, it did not appear to have functional relevance, since the participants remained highly accurate even under the most demanding condition. This result may reflect that the system was operating closer to its functional limits, while still maintaining overall task success. Reaction time, in contrast, did not differ across conditions in the repeated-measures analysis, suggesting that average reaction time alone lacks the sensitivity to capture subtle interactions between cognitive processes and postural control. These results suggest that participants prioritized response accuracy even as postural and visual demands increased, while allowing response timing to remain more flexible.

The linear mixed-effects models, however, revealed clear evidence of context-dependent cognitive–motor coupling. When reaction time was examined in relation to postural sway, the analyses showed a significant interaction between task condition and visual environment. No association between the mean amplitude of COP displacement and reaction time was observed in the stationary condition, indicating that under stable sensory conditions, postural control operates largely independently of cognitive timing. In contrast, under the most demanding visual perturbation (0.5 Hz), greater postural sway was associated with longer reaction times, suggesting that posture and cognition became functionally linked when the environment required active sensorimotor regulation.

This pattern cannot be explained by a simple interference account in which postural demands uniformly degrade cognitive performance. Rather, it indicates that cognitive–motor interactions emerge selectively as the perception–action system reorganizes to meet increasing environmental constraints. Importantly, the absence of any association between postural measures and task accuracy in the second mixed-effects model reinforces this interpretation, showing that cognitive–motor interference manifested primarily in the temporal domain of performance, while outcome accuracy remained stable. Such selectivity is difficult to reconcile with capacity-sharing models alone, which would predict more generalized performance costs, but it is well aligned with dynamical approaches emphasizing flexible, context-dependent reorganization of the perception–action system (Kelso, 1995; Newell, 1986; Woollacott & Shumway-Cook, 2002; Mitra & Fraizer, 2004).

Taken together, the results challenge the traditional view that cognitive and motor processes operate as separate systems that compete for limited CNS resources, leading to a deterioration in the performance of one or more tasks (postural, visual, and memory tasks) (Woollacott & Shumway-Cook, 2002). Instead, they are more consistent with the idea that assumes posture, perception, and cognition as components of a flexible coordination structure that adapts to task and environmental constraints (Belizário Brito et al, 2023; Bonnet *et al.*, 2024; Hua et al, 2025). From this perspective, postural sway is no longer viewed as meaningless variability to be minimized, but a functional aspect of behavior that can either support or limit task performance depending on the context.

The present findings extend this perspective by demonstrating that the emergence of posture–cognition coupling depends critically on the informational properties of the environment, particularly the dynamics of visual input. Specifically, higher-frequency visual perturbations appear to push the system toward tighter functional coupling, revealing relationships between postural dynamics and cognitive timing that remain hidden under stable sensory conditions (i.e., a stationary room). This sensitivity to context highlights the need to consider both environmental information and system dynamics when interpreting interactions between cognition and movement.

Limitations and future directions

Despite its contributions, this study has some limitations. First, the sample consisted exclusively of healthy young adults, limiting the generalizability of the findings to older adults, children, or clinical populations, whose perception–action systems may exhibit different coordination dynamics. Second, only a single level of cognitive load (2-back task) was employed, restricting insights into how varying cognitive demands influence postural reorganization. Future studies should incorporate increasing cognitive loads and tasks of different cognitive domains (e.g., spatial, verbal, etc) for different populations.

Conclusion

In conclusion, this study demonstrated that cognitive–motor interactions during standing are best understood as adaptive reorganizations of perception–action systems, rather than as fixed interference effects. Cognitive engagement stabilized posture globally, but under demanding visual conditions, postural dynamics become functionally linked to reaction time, revealing a selective and context-dependent form of interference. These findings underscore the importance of considering environmental information, task demands, and system dynamics when interpreting cognitive–motor interactions in both experimental and applied settings.

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An experimental paradigm proposal for perception-action coupling during driving on a winding road while sitting or standing: Preliminary results on gaze, head and center of pressure displacements

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Abstract

Heading perception is a fundamental component of spatial navigation through the environment, necessary to succeed in driving. It is achieved through the coordination of gaze, head, and whole-body posture. This chapter offers a novel approach to characterize this complex coordination process in response to standardized visual input and motor task requirements, while driving a car through a simulated winding road, allowing a protocol to test perception-action coupling among gaze, head, and posture elements in distinct populations and conditions. As a first step of investigation towards such approach, exploratory analyses on gaze, head and posture sway were conducted. Eighteen young adults, all licensed drivers, divided into expert and novice groups had their center of pressure, head, and gaze displacements in the anterior-posterior and medio-lateral axes recorded while driving for two minutes on a highway with a sinusoidal path, at a constant speed of 100 km/h, avoiding committing traffic violations, in body positions of standing and sitting. The dependent variables of standard deviation of car lateral position, mean amplitude, coherence, and gain of center of pressure, head, and gaze displacements in both axes were preliminarily discussed in terms of perception-action coupling.

Introduction

The perception of locomotion direction (i.e., self-motion) through the environment is a fundamental component of spatial navigation, so-called heading perception (Ali, Decker, & Layton, 2023; Bradley *et al.*, 1996; Warren & Hannon, 1988), necessary to succeed in tasks such as driving, cycling, and walking. Heading perception is achieved through the coordination of gaze, head, and whole-body posture (Gibson, 1979) and is affected by a variety of interrelated factors, such as the role of gaze behavior in the perception of optical flow (Jörges, Bansal, & Harris, 2024; Sun *et al.*, 2024; Warren & Hannon, 1990) and the effects of sitting or standing on postural and cognitive performance (Cherigui *et al.*, 2025; Hua *et al.*, 2025). This chapter offers a novel approach to characterize this complex coordination process in response to standardized visual input and motor task requirements, while driving a car through a simulated winding road, allowing a protocol to test perception-action coupling among gaze, head, and posture elements in distinct populations and conditions. As a first step of investigation towards such approach, exploratory analyses on gaze, head and posture sway were conducted. In the present book chapter, we briefly present foundations of this experimental paradigm and its method, followed by preliminary results.

Vision and heading perception while driving a car in curves

When navigating a winding road, the control processes that facilitate vehicle conduction are often overlooked; the driver's contribution appears so effortless and automated that the task rarely penetrates conscious awareness. However, its significance becomes immediately apparent when drivers close their eyes, even for a moment, as a collision can occur rapidly.

The appropriate control of vehicle heading requires highly precise information regarding the future course of the road, obtained more or less continuously on a short time scale. While a general impression of the scene is insufficient, a complete three-dimensional reconstruction of the environment ahead is rarely necessary (Land, 1998). A variety of relevant questions arise from such a context: What information does vision extract from the road ahead? From which part of the road or surrounding scenery does this information originate? How is this information transformed into muscular commands to control vehicle steering? What are the latencies in this transformation?

Land (1998), based upon the models of Donges (1978) and Godthelp (1986), suggested that driving involves a double control system, as illustrated in Figure 1. This double control comprises a feedback system for error correction and an anticipatory (feedforward) control based on the view of the road further ahead, spanning a time and distance greater than the half-second interval involved in feedback. The anticipatory signal refers to the future curvature of the road, which is directly transformed into the steering wheel angle, as it can be converted into the curvature of the vehicle's trajectory. However, since the anticipatory signal pertains to road curvature well ahead of the vehicle, it is necessary to delay the steering response by an appropriate interval. In Donges' model, this delay was approximately 1 second. Similarly, MacAdam's 1988 model (cited by Land, 1998) presented more varied delays between 0.8 and 3.0 s, while Land (1998) reported delays between 0.8 and 0.9 s.

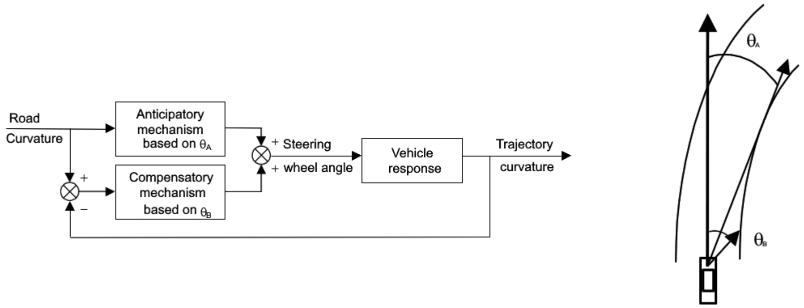

Figure 1. Control diagram of the driving mechanism proposed by Land (1998). Road curvature is determined by the difference between a road feature and the current trajectory direction at a convenient look-ahead distance (θ_A), serving as a *feedforward* signal. Deviations from the appropriate lane position are measured by the near-angle between the lane edge and the vehicle (θ_B), which serves as a *feedback* signal to correct residual errors from the *feedforward* subsystem.

In short, while driving in a winding road, continuously steering to the right and to the left, both mechanisms of feedback-based compensations and anticipations of road information ahead account for controlling the desired trajectory of the vehicle. This requires collective contributions of gaze, head, and posture to the heading perception simultaneously to proper arm movements to control the driving wheel, the topic under investigation in the present research proposal.

Perception-action coupling in postural control applied to driving context

Within this general framework of driving and in addition to the questions above, what are the role of eye movements, head and postural sway in this process? A possibility of integrating all these elements arises from an approach resulting from manipulating visual information to study postural control. Lee and colleagues (Lee & Aronson, 1974; Lee & Lishman, 1975; Lishman & Lee, 1973) experimentally manipulated visual information by moving a suspended "room". This apparatus, known as the "moving room" consisted of side walls, a ceiling, and a front wall, and can be moved anteriorly and posteriorly (Barela, 2000). In their study, Lee and Aronson (1974) showed that when this moving room was in motion, adults and children stood within this room produced corresponding body sway. Even more strikingly, for abrupt displacements of the moving room, the maintenance of upright stance was compromised, occasionally resulting in falls (Lee & Aronson, 1974). This manipulation of visual information to produce alterations in the maintenance of postural orientation was adopted and refined to analyze posture more systematically within a dynamical systems approach (Warren, 2006), particularly when participants are not aware of the visual manipulation, characteristic of a sub-threshold stimulation (Schoner, 1991).

In a similar vein, the present proposal uses an oscillatory visual stimulus generated by the sinusoidal trajectory of the vehicle in the winding road created by the driving simulator environment in order to analyze the relationship between this visual input and movements of the eyes, head and the center of pressure, when participants are conscious of visual stimuli. The descriptions of this perception-action coupling are made in terms of measures of coherence, the strength of the relationship between visual pattern and motor component involved, and gain, ratio between amplitudes of visual stimulus and motor response.

Influences of sitting or standing on body sway, cognition, and attention

Although conventional automotive transport is predominantly associated with a seated posture, some classes of vehicles allow a standing position (e.g., electrical scooters, offshore fishing boats). This standing configuration often serves to enhance the operator's field of vision, maneuverability, balance control among other aspects.

The debate on sitting or standing positions while driving a vehicle or other behaviors is also associated with more general health issues. For instance, office work usually involves long hours in the seated position, exposing workers to sedentary behavior, which may lead to various health hazards, such as increased mortality risk and cardiometabolic disorders (Lavie *et al.*, 2019; Van Uffelen *et al.*, 2010). Several interventions can be employed to mitigate sedentary behavior; one strategy that yields favorable outcomes is the implementation and utilization of sit-stand desks (Bonnet & Cheval, 2023; Commissaris *et al.*, 2016). Occupational productivity is central to this debate on performance when sitting vs. standing. On one hand, relevant literature has shown that the level of performance in a variety of desk-based tasks was equivalent when sitting vs. standing (Karakolis & Callaghan, 2014). In these studies, the research method usually involved the use of binary variable such as failure/success (Karakolis & Callaghan, 2014). On the other hand, when task performance was measured with subtle, continuous variables, such as the reaction time, literature has indicated that the level of task performance was better when standing than when sitting (Cherigui *et al.*, 2025; Rosenbaum *et al.*, 2017; Smith *et al.*, 2019). Shorter reaction times when standing has been found in Attention Network Task (ANT) (Abou Khalil *et al.*, 2023; Barra *et al.*, 2015) and the Stroop test (Rosenbaum *et al.*, 2017; Smith *et al.*, 2019). We still need to mentioned that equivalent reaction times between standing and sitting were found in other studies (Bantoft *et al.*, 2016; Caron *et al.*, 2020, 2022). Cherigui *et al.* (2025) focused on determining the effect of alternating the body position between standing and sitting on task performance and visual attention in the ANT as compared to a sitting-only condition. Their results showed that the proportion of blinks was lower in the alternating condition than in the sitting-only condition and revealed shorter reaction times when standing than when sitting. Authors interpreted these findings as indicative that humans may be more effective and have greater visual attention in an alternating condition than in a sitting-only condition.

Manipulating postural requirements in combination with perceptual-motor tasks may further reveal complexities of heading perception and control. Higher complexity of postural sway while standing is predictive of perception of action possibilities (Masoner *et al.*, 2020). Thus, the implementation of more complex environments for the study of postural control appears advantageous, as it allows for a deeper understanding of the postural stabilization process. In this regard, perceptual-motor tasks, such as driving, may assist in further elucidating this process and its effects.

A novel experimental paradigm for perception-action coupling in driving

The current research proposal brings novelty to both the debate on the comparison between sitting and standing postures and the complexity of driving behavior, emphasizing the perception-action coupling among gaze, head, and balance components. Our new paradigm applies a very simplified version of a simulated driving task, involving solely the driving wheel adjustments under constant velocity, while having visual input from a sinusoidal road trajectory, with no need of regulating clutch, brake, and gas pedals, but preserving fundamental perception and action characteristics of natural context. The aim of our study was twofold: (i) to introduce this experimental paradigm proposal for perception-action coupling during driving on a winding road while sitting or standing; (ii) to present preliminary results on gaze, head and center of pressure displacements, as well as results on driving performance. Although driver's experience and body position are relevant and well-established factors to affect, respectively, driving behavior and postural control, these variables were exploratorily manipulated within this set of preliminary results, with no hypotheses defined in terms of effects on amplitude, coherence, and gain of the relationship between center of pressure, head, and gaze displacements with visual input.

Methods

Participants

Eighteen young adult volunteers, all licensed drivers, participated in this study. All participants had normal or corrected-to-normal vision (glasses or contact lenses), without any sensorimotor or neurological deficits. Approval from the local ethics committee was obtained (CAAE: 67952423.0.0000.5398), and participants signed an Informed Consent Form before beginning their participation in the study. Participants were divided into two experimental groups (Expert, Novice), with mean age of 29.2 (SD = 2.7) years and 25.0 (SD = 5.0), respectively. The classification of drivers was adapted from the study by Lehtonen *et al.* (2014). A participant who reported driving up to 15,000 kilometers was considered a novice driver, and a participant who reported driving more than 15,000 kilometers was considered an expert driver. The mean distances driven by expert and novice groups were, respectively, 79,416 (SE = 33,456) and 4,653 (SE = 4,233) kilometers.

Equipment and software

An eye tracker (SMI Glasses, 120 Hz) was used to record the gaze location and a head tracker (Ascension, model Flock of Birds, 60 Hz) was used to record tri-dimensional head position and orientation of the participants during the driving task, which was performed in the STISIM Drive M100 simulator (version 3.14.01) equipped with a Logitech G29 steering wheel. A height-adjustable table (Office DT900 Table) was used, where the TV monitor (46” LED) was positioned in front of the participant, along with the force platform (AMTI, 60Hz), positioned under participant's feet in order to record the center of pressure (COP) during the simulation in the sitting position (on a seat on the platform) and standing position (directly on the platform), as shown in Figure 2.

Figure 2. Representative pictures of the experimental setup with a participant in the positions of standing (left) and sitting (right)

Experimental Design and Tasks

After a period of familiarization with equipment and task, experimenting with basic control mechanisms while driving for three minutes, participants of expert and novice groups were required to drive for two minutes on a highway with a sinusoidal path, at a constant speed (100 km/h), avoiding committing traffic violations (e.g., not using turn signals when overtaking, colliding with other vehicles), in two conditions of body position (standing and sitting), totaling two trials per participant. The order of the experimental conditions was counterbalanced to avoid order effects.

Procedures

Data collection was carried out at the Information, Vision and Action Laboratory (LIVIA), located in the Department of Physical Education at UNESP – Bauru. Upon arrival, participants were greeted by the experimenter and instructed to carefully read and sign the Informed Consent Form. Visual acuity was assessed by the Snellen test, followed by the experimental tasks as previously described.

Data Analysis

Raw data regarding the participants' center of pressure (COP), head, and gaze displacements in the anterior-posterior (AP) and medio-lateral (ML) axes were obtained and processed through a script in a Matlab environment (The Matworks Inc., 2010 – version 7.10.0.499) specifically written to calculate the following dependent variables: standard deviation (SD) Car lateral position (cm), mean amplitude, coherence, and gain of COP, head, and gaze displacements (all in AP and ML axes). Coherence indicates the dependency ("strength") between body oscillation and visual stimuli; coherence values vary between 0 and 1, indicating none or full dependency. Gain the ratio between the amplitude of visual stimuli and body oscillation amplitude; gain values close to 1 indicates a stronger coupling between visual stimuli and postural oscillation. Raw data regarding the participants' lateral vehicle position were obtained through the driving simulator, that provided the calculated value of variability (standard deviation) of the vehicle's lateral position throughout the entire trial.

Statistical analysis

Data of each dependent variable were subjected to analysis of variance (ANOVA) of Group (Expert, Novices) by Position (Standing, Sitting), repeated measures for the last factor. SPSS software (IBM SPSS Statistics, version 25) was used for the necessary statistical analyses. The significance level adopted was 0.05 for all analyses. Pairwise comparisons (post-hoc) were performed using Tukey's LSD test. Bonferroni probability adjustments and Greenhouse-Geisser degrees of freedom adjustments were used as needed (Maxwell & Delaney, 1990).

Results

The SD of the car lateral position was not affected by group, position or group by position interaction. Mean SD of car lateral position was .459 (SE = .034) cm (Figure 3). In the AP axis, COP mean amplitude was higher in the sitting position (M = .230, SE = .031) than in standing position (M = .128, SE = .013), F(1,16) = 12.15, p = .003, η_p^2 = .432. COP mean amplitude was higher for the novice group (M = .219, SE = .026) than the expert group (M = .139, SE = .026), F(1,16) = 4.91, p = 0.042, η_p^2 = 0.235 (Figure 4 top, left). In the ML axis, COP mean amplitude was higher in the standing position (M = .208, SE = .020) than in sitting position (M = .156, SE = .012), F(1,16) = 12.15, p = .003, η_p^2 = .432 (Figure 4 top, right). In the AP axis, head mean amplitude was higher for the novice group (M = .413, SE = .040) than the expert group (M = .287, SE = .040), F(1,16) = 4.97, p = 0.040, η_p^2 = 0.237 (Figure 4 middle, left). In the ML axis, group by position interaction affected head mean amplitude, F(1,16) = 7.46, p = 0.015, η_p^2 = 0.318. Post-hoc analyses revealed that, in the standing position, head mean amplitude was higher for the novice group (M = .377, SE = .031) than the expert group (M = .282, SE = .031). In the sitting position, head mean amplitude was also higher for the novice group (M = .428, SE = .042) than the expert group (M = .235, SE = .042) (Figure 4 middle, right). In both axes, gaze mean amplitude was not affected by group, position or group by position interaction (Figure 4 bottom, left and right).

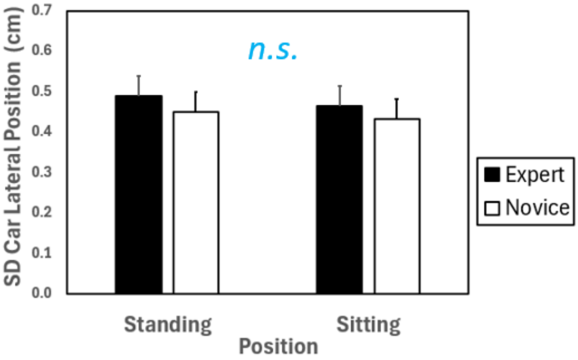

Figure 3. Standard deviation (SD) of the car lateral position (cm) in the standing and sitting positions for the expert and novice groups.

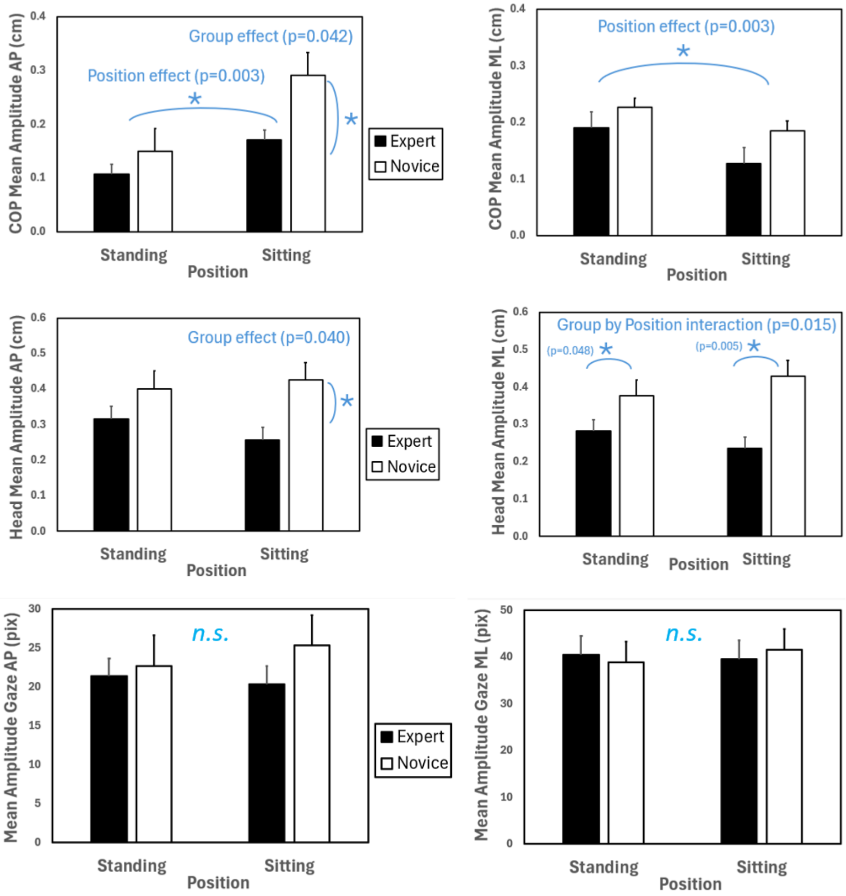

Figure 4. Anterior-posterior [AP] (left column) and medio-lateral [ML] (right column) mean amplitude (cm) of center of pressure [COP] (top row), head (middle row), and gaze (bottom row) in the standing and sitting positions for the expert and novice groups.

In the AP axis, COP coherence was higher in the sitting position (M = .836, SE = .051) than in the standing position (M = .663, SE = .066), F(1,16) = 8.25, p = 0.011, $\eta_p^2 = 0.340$ (Figure 5 top, left). COP coherence in the ML axis and head and gaze coherence in both axes were not affected by group, position or group by position interaction (Figure 5). In the AP axis, COP gain was higher in the sitting position (M = .012, SE = .003) than in standing position (M = .005, SE = .001), F(1,16) = 11.09, p = 0.004, $\eta_p^2 = 0.409$ (Figure 6 top, left). In the ML axis, COP gain was not affected by group, position or group by position interaction. In the AP axis, head gain was higher for the novice group (M = .022, SE = .003) than expert group (M = .010, SE = .003), F(1,16) = 6.11, p = 0.025, $\eta_p^2 = 0.276$ (Figure 6 middle, left). In the ML axis, head gain was higher for the novice group (M = .022, SE = .003) than expert group (M = .009, SE = .003), F(1,16) = 8.96, p = 0.009, $\eta_p^2 = 0.359$ (Figure 6 middle, right). In both axes, gaze gain was not affected by group, position or group by position interaction (Figure 6 bottom, left and right).

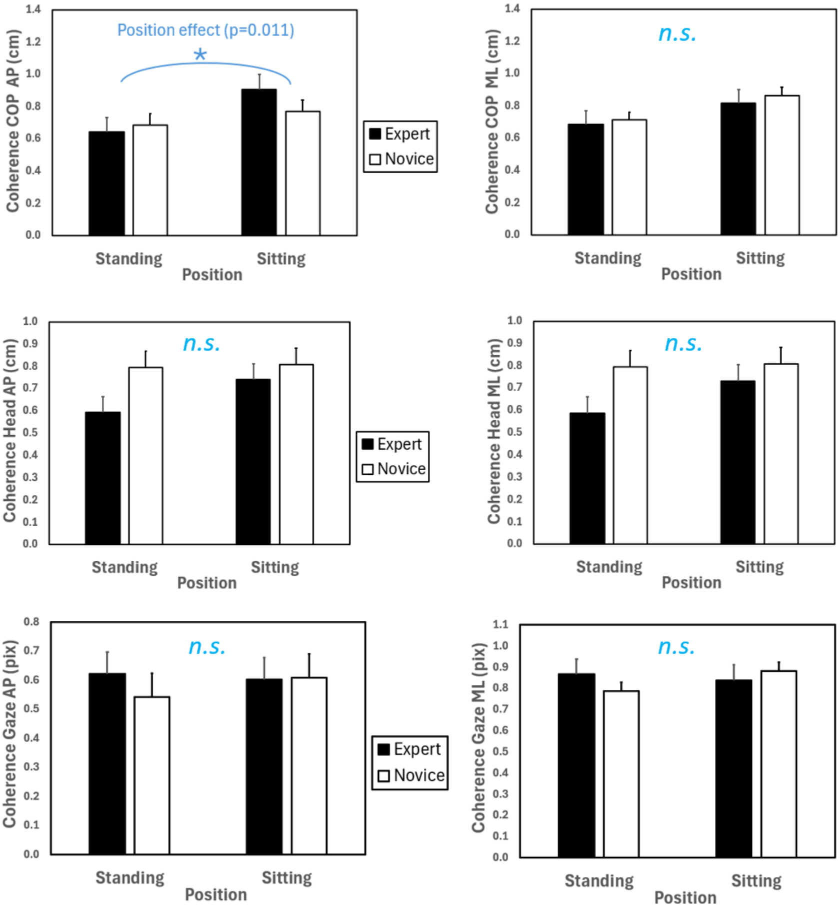

Figure 5. Anterior-posterior [AP] (left column) and medio-lateral [ML] (right column) coherence of center of pressure [COP] (top row), head (middle row), and gaze (bottom row) in the standing and sitting positions for the expert and novice groups.

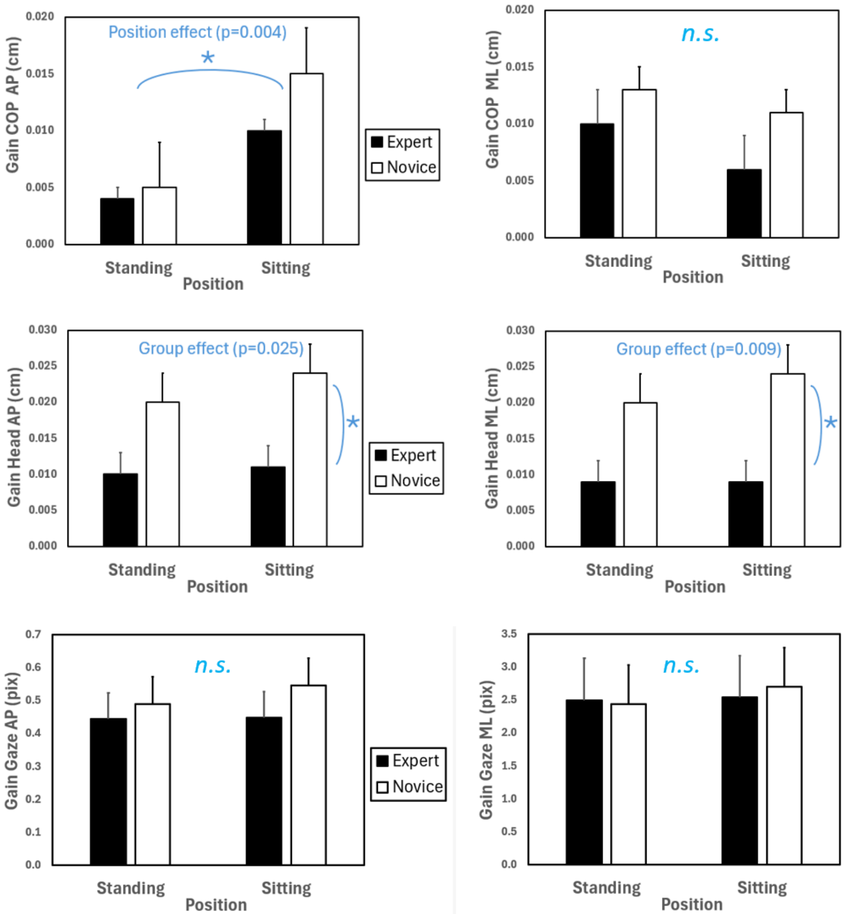

Figure 6. Anterior-posterior [AP] (left column) and medio-lateral [ML] (right column) gain of center of pressure [COP] (top row), head (middle row), and gaze (bottom row) in the standing and sitting positions for the expert and novice groups.

Discussion

The first purpose of this study was to present an experimental paradigm proposal for perception-action coupling during driving on a winding road while sitting or standing. We wanted to offer theoretical and methodological organization to future research. Similarly to the present context, Schoner (1991) brought the moving room paradigm to a dynamic view of perception-action patterns, emphasizing the importance of the theoretical concept of temporal stability of coordination patterns, which means "the ability to return to a coordinated movement pattern after perturbations and to sustain the coordination pattern in the face of a fluctuating environment" (Schoner, 1991, p. 455). In terms of the presented driving paradigm, new investigations could manipulate a variety of dependent variables (e.g., driver's experience and body position, as done in the present study, or distinct aspects of visual stimuli such as velocity and frequency, applied to different populations, as people with Parkinson's disease, dyslexic children, or diabetic elderly) to consistently test the adaptation to particular perturbations of interest to the coordination of posture, head, and gaze patterns. Additionally, Schoner (1991) highlighted the concept of behavioral information (Schoner & Kelso, 1988) which was used to express "the ability of coordination systems to adapt to environmental, memorized or intended constraints in terms of required coordination patterns" (Schoner, 1991, p. 456). For our driving paradigm, to set stimulus conditions in terms of behavioral information, we assume that our perceptual system provides a relevant parameter of the optic flow, the expansion rate of a perceptual scene (Lee, 1976), arriving from the sinusoidal path of the vehicle throughout the road curves in our case.

The second purpose of this study was to present preliminary results on gaze, head and center of pressure displacements, as well as results on driving performance. Here, results are discussed in terms of exploratory analyses conducted. Driving performance was not affected by driver's experience and body position in this study. The variability of the lateral position of the vehicle is a landmark of driving performance (Land & Tatler, 2009). The magnitude of the observed SD seemed not exaggerated, considering the sinusoidal road trajectory as drivers usually attenuate the trajectory of vehicle with respect to the road curvature (Land, 1998). The relatively low level of difficulty of the driving task (visually detecting the road curvature and moving the driving wheel accordingly in constant velocity) justifies the absence of significant effects on this variable.

COP amplitude was affected by body position in both axes. The results showed that the amplitude of AP COP sway was higher in the sitting condition while the amplitude of ML COP sway was higher in the standing condition. This finding is probably related to the lateral direction of the driving wheel rotations, affecting the COP response when standing with additional freedom to move laterally. Additionally, novices presented larger COP displacements than experts in the AP axis, in accordance with the expected effects of expertise on postural performance (Paillard, 2019). A similar trend of higher displacements of less experienced participants was found for head movements in challenging postural contexts due to driving skill level (e.g., Rodrigues, Gotardi, & Aguiar, 2024).

Coherence measures, in general, were not affected by driving experience or body position. Exception was the significantly higher coherence of COP in the AP axis during sitting, as compared to standing position. Coherence measures express the level of dependency between body movement and visual stimuli, varying between 0 and 1. All coherence observed values were closer to 1 (around .6 and .9), revealing a relatively high dependency of the movement responses to visual input. Head and gaze coherence values seemed higher than those from COP; also, coherence values appeared higher in the ML axis, as compared to AP axis.

In terms of gain measures and independently of group and body position, very weak coupling for COP and head measurements, in both AP and ML axes (values lower than .1). Gaze gain measurements revealed considerably stronger perception-action coupling in the AP axis (mean values around .5) than in the ML axis (mean values higher than 1, around 2.5).

Furthermore, gaze measures of amplitude, coherence and gain were not affected by group, body position or interaction, presenting a more invariant pattern with respect to visual stimuli. Independently of group and body position, it is worth of note that drivers exhibit a gaze strategy towards the tangent point in a curve while driving (Paschoalino *et al.*, 2019). This may reflect particularities of gaze behavior constraints due to the need of higher visual acuity for specific visual cues in the environment (Land & Tatler, 2009).

In summary, these preliminary results provide an initial analysis of distinct contributions of COP, head, and gaze controls to the coordination process. The proposed experimental paradigm for studying perception-action coupling in driving and its initial results bring a variety of aspects of complexity to debate, considering the temporal stability of coordination patterns due to the proposed continuous driving task on a winding road; also, it accounts for the need for behavioral information as created visual input meaningful for the perceiver, making available time to contact or other information in a curvilinear trajectory from the optical flow, following the bases suggested by Schoner (1991).

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Body position and vocabulary learning: An experimental proposal

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Abstract

Nowadays, people across the world spend a large proportion of their waking hours in a seated position. One solution that has been suggested is encouraging people to stand more during the day, for example by using sit-stand desks. These desks can be adjusted to allow users to work either sitting or standing up, and they are becoming increasingly popular around the world. While the health benefits of this approach are becoming more widely recognised, the cognitive consequences of this shift are not as well understood. Some studies have shown that standing can have a positive effect on cognitive functioning. One question that arises, then, is whether standing enhances word learning or at least does not hinder it. To address this question, a study was conducted at UNESP in Bauru, Brazil, as part of the LIVIA–SCALab collaboration within the CAPES–COFECUB project framework.

This methodological chapter outlines the aforementioned study's design, in which adult native speakers of Brazilian Portuguese learnt 27 rare words in their mother tongue, with body position and word presentation systematically manipulated. While the analyses are underway, the authors present their hypothesis, proposing the study as a means of expanding our understanding of how body position influences cognitive processes, particularly word learning. This study could be a first step towards answering this question and may provide valuable insights into theory and practice in education and cognitive science.

Body position in daily life

Nowadays, across the world, people spend a large proportion of their waking time in a seated position, particularly during office work, study hours, commuting and leisure activities when these allow it (Leitzmann, 2023). Such widespread sedentary behavior has been linked to multiple cardio-metabolic health risks such as obesity, deficient blood pressure, high levels of cholesterol, reduced cardiorespiratory fitness (Bull *et al.*, 2020), among other health and psychological issues (e.g., Bonnet & Cheval, 2023; Levine, 2015). This also has been reported to be the case even for children (Saunders *et al.*, 2014). Furthermore, high levels of sedentary time have been associated with reduced brain health, dementia and lower academic performance (Bueno *et al.*, 2022; Lima *et al.*, 2019; Voss *et al.*, 2014).

Sedentary behavior is defined as any waking activity performed while sitting, reclining, or lying with an energy expenditure of ≤1.5 metabolic equivalents (METs) (Tremblay *et al.*, 2017, p. 9). Common examples of sedentary behavior include working at a desk, watching television, or travelling in a motor vehicle. High-income countries, in which desk-based employment is prevalent, tend to exhibit the highest sitting times. Recent analyses estimate that more than 30% of European and U.S. adults sit for up to ten hours per day (Bullock *et al.*, 2017). Middle-income regions, such as Latin America, are also experiencing increasing sedentary behavior, with reports indicating an average of about seven hours of daily sitting (Luis de Moraes Ferrari *et al.*, 2019).

Recommendations clearly state that any reduction in sedentary time can provide measurable health benefits (Bull *et al.*, 2020). Bonnet and Barela (2021) and Bonnet and Cheval (2023) even suggested that people should avoid sitting for more than 8 hours per day. One way to spend more time in the standing position during the day is to use sit-stand desks, both for adults in desk-based jobs and for children and adolescents in schools. Sit-stand desks are, by definition, adjustable desks that can be used either in a sitting or standing position by simply changing the desktop's height.

Implementation of sit-stand desks

Children and adolescents typically spend most of their day in a seated position, especially in classroom settings, where they endure prolonged periods of sitting. There is evidence suggesting that children and adolescents spend more time sitting during school hours than outside of school (Abbott *et al.*, 2013). This is noteworthy because it has been found that sedentary habits start at these young ages (Biddle *et al.*, 2010).

In response to excessive sedentariness among young populations, the implementation of sit-stand desks in schools started all over the world and will move on positively at least until 2030 (*Standing Desks Market Size, Share & Growth Report*, 2030, n.d.). The use of these sit-stand desks is intended to reduce the time spent sitting in schools. Consistently, in their systematic review of school-based interventions measuring sedentary time, Hegarty *et al.* (2016) reported significant decreases in sedentary time following the use of sit-stand desks in schools. Two additional reviews confirmed beneficial effects (Minges *et al.*, 2016; Sherry *et al.*, 2016), showing that sit-stand desks in schools significantly increased energy expenditure and standing time of school learners by 60 minutes. This finding aligns with evidence from adult studies in desk-based jobs showing a reduction of 77 minutes per eight-hour workday when using sit-stand desks (Neuhaus *et al.*, 2014).

Overall, these findings suggest that sit-stand desks effectively encourage and lead to a reduction in sitting time. However, their widespread use raises important questions about how body position might impact cognitive processes and performance, both for adults in the workplace and for children in educational settings.

Body position and cognitive tasks

The effects of standing desks on health start to be established but far less is known about the cognitive consequences of this shift (For reviews see Sherry *et al.*, 2016; Silva *et al.*, 2025). More precisely, although studies show that sit-stand desks are an effective way of addressing health issues, further research is needed to establish whether posture affects cognitive aspects such as attention, perception and memory processes, which ultimately shape learning outcomes in educational contexts, for example. Some studies suggest that standing enhances cognitive control and selective attention (Rosenbaum *et al.*, 2017; Smith *et* *al*., 2019), whereas others report no significant effects (Caron *et al*., 2022; Straub *et al*., 2022). Additional findings further suggest that posture influences task performance differently, with sitting proving most effective for arithmetic tasks and standing for cognitive control (Abou Khalil *et al*., 2024). In their study, Rosenbaum *et al*. (2017) investigated young adults performing a Stroop task either when standing or when sitting. In the Stroop task, participants are shown mismatched words and colors (e.g., the word "red" printed in blue ink) and are asked to inhibit the conflicting information when demanded to say the color of the ink, for example. In experimental studies, the Stroop effect is widely used to test cognitive control. The authors found a significant difference in performance between sitting and standing body positions; participants completed the task faster when standing compared to sitting. Similarly, Smith *et al*. (2019) observed significantly increased focus and reduced errors in task-switching and search visual paradigms when participants were standing. These findings led to the conclusion that standing could significantly enhance selective attention and, consequently, cognitive performance. Some explanations for this phenomenon have centered on the physical effort required by standing. This body position is thought to induce a state of increased arousal, supported by heightened alertness or even a fight-or-flight–like response, which may enhance cognitive functioning (Smith *et al*., 2019).

This is in line with a further study by Mehta *et al*. (2015) who found that high school students using sit-stand desks exhibited improvements in executive function, working memory, and increased prefrontal cortical activation measured via functional near-infrared spectroscopy (fNIRS). The authors took these results as initial evidence that sit-stand desks may influence frontal brain function, which is closely tied to learning.

Furthermore, in students with attention difficulties, there is some evidence that non-sedentary positions positively influence in-seat behavior (i.e., how students remain physically engaged in their seating), academic engagement, and attention (Rollo *et al.*, 2019).

At the same time, other published studies did not show any significant effect – neither positive nor negative – of body position on cognitive task performance. For example, Caron *et al.* (2022) used the Stroop task, task-switching and the visual search tasks paradigms but found no meaningful effects of body position on performance. Moreover, in their meta-analysis, Straub *et al.* (2022) found no evidence that body position influenced performance in the Stroop task, even when applying more sensitive analyses to control for individual differences. In school context, Dornhecker *et al.* (2015) also reported no significant differences in academic engagement between classrooms using sit-stand desks and those using traditional seated desks.

All in all, no study to date has reported negative effects of sit-stand desks on academic outcomes. Thus, consistent with other reviews (Sherry *et al.*, 2016; Straub *et al.*, 2022), dynamic sit to stand interventions appear to be a simple and feasible health strategy in educational settings, given that they can reduce sedentary time without deteriorating student learning. Indeed, Straub *et al.* (2022) emphasized that if the effects of body position on cognition were consistently beneficial, possible applications could be considered, among others, in educational contexts. For example, postural strategies that facilitate focus on specific elements of information may enhance learning conditions in classrooms. Considering that standing reduces sedentary behavior and can increase engagement during learning without adverse consequences (Dornhecker *et al.*, 2015; Sherry *et al.*, 2020), it is worthwhile continuing to investigate whether body position influences not only attentional or arithmetic tasks but also more fundamental processes such as learning.

What about language learning?

If standing or other non-sedentary body positions have beneficial effects on cognition in general, could they also enhance the learning of new vocabulary, or at least not hinder it? This question is particularly important because language learning is a core component of education. It is also timely, given the growing implementation of sit-stand desk in schools worldwide, with studies being conducted in several high-income countries (e.g., Australia, Canada, North Europe, USA) to evaluate their impact.

Vocabulary is widely recognized as a cornerstone of language learning and literacy development. It underpins reading comprehension, supports the acquisition of additional vocabulary and enriches communication in both oral and written modalities (Beck *et al.*, 2013; Cain *et al.*, 2001; Perfetti & Stafura, 2014). A robust vocabulary has also been associated with broader academic success, as it facilitates the comprehension of increasingly complex texts encountered in middle and high school (Castles *et al.*, 2018). Consequently, exploring how vocabulary is acquired, and whether body positions such as sitting or standing modulate this process is of high educational relevance.

How do we learn words?

Children typically learn new words incrementally, first grasping approximate meanings and then refining these through additional encounters in varied contexts (Carey, 2010; Nation, 2017). In adults the process is not completely different as we keep learning words during all our lives (Brysbaert *et al.*, 2016). Word learning involves then both the initial mapping of form to meaning and the gradual integration of new lexical items into the learner's mental lexicon (Davis & Gaskell, 2009). Research in psycholinguistics has demonstrated that repeated exposure, attention allocation, and memory consolidation mechanisms all contribute to such process (Clay *et al.*, 2007; Wagner *et al.*, 2007).

Experimental paradigms have often focused on controlled word-learning tasks, where learners are presented with novel words under different instructional or environmental conditions. Such paradigms have facilitated the identification of variables that have been demonstrated to be significant for word learning, including frequency of exposure, semantic richness and contextual support. Across studies, outcomes are typically measured using recognition or recall tasks, which provide indices of how effectively new vocabulary has been encoded and retrieved (Frishkoff *et al.*, 2008). Of importance here is that word learning is not an independent process, it draws on attention, working memory, and long-term memory. Thus, any factor that influences these processes, such as body position, might reasonably be expected to affect vocabulary acquisition.

The role of context

Context provides semantic information that helps learners infer meaning, strengthens associations with prior knowledge, and encourages deeper processing, all of which enhance long-term retention (Nation, 2017). A number of experimental studies have explicitly compared context-rich versus context-poor learning conditions both in mother tongue (Nation & Snowling, 1998; Wang *et al.*, 2011) and second language learning (Elgort, 2011;

Webb, 2008). In their study, Webb (2008) investigated incidental vocabulary learning among Japanese learners of English and found that target words presented in meaningful sentence contexts were recalled and recognized more successfully than those provided in word lists. Similarly, Elgort (2011) demonstrated that context facilitates the transition from initial form-meaning mapping to integration into the mental lexicon, allowing learners to use new words productively rather than merely recognizing them.

On one hand, Nation and Snowling (1998) found that contextual facilitation was particularly beneficial for children with dyslexia, as they rely on contextual cues to compensate for poor decoding skills. On the other hand, poor comprehenders benefit less from context than typical readers. Which suggests that a good level of reading is necessary to benefit from context. Similarly, Wang *et al.* (2011) showed that context facilitated learning of irregular novel words, indicating that contextual information is especially valuable when decoding alone is insufficient for normal readers. More recently, Norman *et al.* (2023) examined how contextual diversity affects word learning. Participants studied eight pseudowords in either diverse contexts (sentences on different topics) or non-diverse contexts (sentences on the same topic). Although diversity did not influence word form recognition, transfer differed by condition. Non-diverse contexts enhanced performance in familiar settings, while diverse contexts supported better generalization to new, unfamiliar contexts. These findings point to diverse contexts as a factor to promote flexible, decontextualized representations meaning that rich context has a key role in supporting robust vocabulary acquisition.

Further evidence comes from studies of reading and listening comprehension, in which context helps learners infer meanings of unfamiliar words and reinforces retention (Hulme *et al.*, 2022; Van Den Broek *et al.*, 2022). In these studies, context seems to facilitate word retention by reducing memory load and guiding learners toward more efficient encoding strategies.

An experimental proposition

If context supports vocabulary acquisition by enhancing attention and memory processes, body position may interact with this effect. The standing position has been associated with heightened alertness and selective attention in some tasks (Rosenbaum *et al.*, 2017; Smith *et al.*, 2019). Given that vocabulary learning depends on both attention and memory consolidation, it is plausible to hypothesize that body position might modulate the benefits of context. Specifically, the standing position could amplify the advantages of meaningful context, leading to improved recall and recognition compared to the sitting position.

At present, however, no study has directly examined how body position affects vocabulary learning. The central question remains: are the benefits of meaningful context preserved, amplified, or diminished when learners are standing rather than sitting?

To address this gap, a study was conducted at UNESP in Bauru, Brazil as part of the LIVIA – SCALab collaboration within the framework of the CAPES–COFECUB project. We wondered whether body position modulates the effects of context on word learning. Based on the evidence at hand, we expected that learners acquire words more effectively when standing and when presented within meaningful context, compared to when sitting and presented with unmeaningful context. This hypothesis lies on two bodies of evidence. First, studies suggesting that standing may enhance alertness and certain cognitive functions, and second, research showing that meaningful context facilitates vocabulary acquisition. Together, these literatures raise the possibility that body position and context may both complementarily support word learning.

Design

The experiment employed a 2x2 factorial design, with two independent variables: body position (sitting vs. standing) and word presentation (with meaningful context vs. with unmeaningful context). This design allowed for the examination of main effects of body position and context, as well as their interaction.

Participants

The study recruited eighteen adult native speakers of Brazilian Portuguese. All participants were adults (M age = 21.5; SD = 2.8), with normal or corrected-to-normal vision and no reported language or reading disorders. They provided informed consent in accordance with ethical standards of UNESP.

Materials

Stimuli were drawn from LexPorBR, a lexical database of Brazilian Portuguese (Estivalet & Meunier, 2015). The targets were 27 words selected based on frequency (M = 0.10; SD=0.19), word length (M=10.07; SD=0.26), and semantic properties (i.e., not belonging to a single semantic category). Each target word was embedded in six sentences, three providing a meaningful context and three other offering no supporting semantic information. Two stimulus lists were created to counterbalance context presentation. In list A, half of the target words appeared in meaningful contexts and the other half in non-meaningful contexts; in list B, this assignment was reversed. Sentence order was randomized for all participants. Thus, participants were exposed to both context conditions and both body position conditions (sitting and standing). Specifically, participants assigned to List A or List B completed the task in both positions, ensuring that each context type was experienced under both postural conditions.

Apparatus

Stimuli were presented on a computer screen connected to a Tobii eye-tracking system. The system recorded gaze behavior allowing for measurement of fixation and saccade metrics. Participants either sat in a standard chair or stood in front of the screen, with table and lighting adjustments made to ensure comparable visual conditions across positions.

Procedures

At the beginning of the session, participants were provided with detailed instructions in Portuguese, explaining the task and ensuring comprehension. After that, they were positioned in front of the screen on which stimuli were presented. Following the first calibration of the eye tracker, the sentences with the embedded target words were presented for the exposition phase. Depending on the condition, the sentences either provided sufficient context to infer the words' meanings or did not. Each participant performed the tasks in both sitting and standing positions in a counterbalanced order.

After exposure, participants completed two recall and one reading tasks designed to assess learning outcomes. In the recall tasks, they were asked to orally produce and write the target without any cue. In the reading task, they saw the words in the center of the screen and were required to read them as fast as possible without making any error.

Throughout the entire experiment, gaze behavior toward the words was continuously recorded with calibration conducted at the beginning of each task. Each experimental session lasted approximately 1 hour and 30 minutes per participant. To date, the study has been completed, and all data has been collected and securely stored on an external hard drive. No analyses have yet been conducted.

Planned analyses

Data will be analyzed using Linear Mixed Models (LMMs), through the software Jamovi (The jamovi project, 2024). We will account for both participant- and item-level variability (Baayen *et al.*, 2008). The primary dependent variables related to the learning of vocabulary will include fixation behavior during exposition and the reading task as well as accuracy in the recall and reading tasks. Latency in all the testing tasks will also be considered.

The focus of the analysis is the interaction effect between body position and context. Specifically, analyses will seek to determine whether the benefits of context on word learning are moderated by body position.

Theoretical and practical contributions

Numerous studies have already demonstrated that context plays a decisive role in supporting word learning. Learners are more likely to remember words embedded in meaningful sentences than those presented in isolation (Elgort, 2011; Webb, 2008). This context effect has been consistently observed across modalities, including reading, listening, and incidental learning, and is widely regarded as a cornerstone of effective vocabulary instruction (Beck *et al.*, 2013; Perfetti & Stafura, 2014). Yet the question remains whether this robust effect of context persists in changing body positions. In other words, does standing enhance or interfere with the benefits of meaningful context for word learning? Such a question is relevant since vocabulary acquisition is a foundational component of literacy development and that an increasing number of classrooms worldwide are integrating sit-stand desks.

The present chapter began with a review of the growing literature on body position and cognition, paying particular attention to the educational context. If body position can modulate attention or arousal states, it is plausible that it could also affect the way learners engage with and learn new words. However, within this literature of language learning, the use of sit-stand paradigms in learning domains in schools remains underexplored. The experimental proposition developed here addresses this gap by testing whether body position interacts with context during word learning.

In our study conducted at UNESP in Bauru, Brazil we manipulated both body position (sitting vs. standing) and contextual information during word presentation (meaningful vs. unmeaningful context) while monitoring eye movements through eye-tracking technology. By combining methodologies from psycholinguistics (contextual information provided during vocabulary acquisition) and cognitive ergonomics (sitting vs. standing), the study aims to open a way at the intersection of language learning and the impact of body position on cognition.

The expected contributions of this work target both theoretical and practical domains. Theoretically, the study is bridging two domains of research: research on body position and cognition, and research on vocabulary learning. The former has largely focused on attention and executive functions, and the latter plays an important role in literacy. Furthermore, a theoretical contribution of this work is the expansion of our understanding of how body positions can shape learning. The integration of our results might provide a novel perspective on how to approach vocabulary teaching. If body position is found to moderate context effects, it would also be a good pathway to continue implementing research with non-sedentary desks in schools. Practically, our study would be valuable by informing classroom practices related to the use of non-sedentary positions for learning. If sit-stand desks were recognized to influence language learning outcomes, educators and policymakers would more strongly support their adoption and design instructional strategies that consider body position. For example, teachers might intentionally schedule vocabulary or reading activities during standing periods, while reserving other tasks for seated conditions, thereby aligning bodily states with cognitive demands.

Conclusion

Our study is seeking to expand our understanding of how body position participates in cognitive processes, more specifically word learning. While much is known about the role of context during word learning in seated learners, extending this inquiry to different body position will open new perspectives on language learning. Our study described here offers a first step toward answering this question, with the potential to inform both theory and practice in education and cognitive science. If our hypotheses are validated, the findings would suggest that physical body position can modulate language acquisition processes, with potential implications for educational practices. Future studies could expand beyond vocabulary to other aspects of language learning, such as reading comprehension, or bilingual word learning.

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Semantic context and body position shape pupillary effort in word acquisition

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Abstract

Language processing and learning are cognitively demanding activities that engage significant mental effort. Body position, specially standing, has been associated with increased cortical activation and attentional control. This study investigated whether body position influences the effort required to learn low-frequency words from context. Seventeen young adults read 168 Brazilian Portuguese sentences containing 28 low-frequency nouns (10–15 letters), each presented in six contexts (3 rich, 3 neutral), while either sitting or standing. Eye movements were recorded at 120 Hz, and task-evoked pupillary response (TEPR) was defined as baseline-corrected mean pupil diameter during reading of the target noun word. A linear mixed-effects model predicted TEPR from Body Position (sitting, standing), Text Context (rich, neutral), and their interaction, controlling for standardized word length and word index, with by-participant random intercepts and a random slope for context. Preliminary results showed that the standing body position significantly increased TEPR relative to sitting; and an interaction between body position and text context showed that TEPR was highest at the standing-rich and lowest at the sitting-rich. These findings suggest that cognitive load during word learning might be modulated by body position, with standing increasing mental effort as indicated by TEPR. While rich semantic context typically reduces effort, this supportive effect was diminished (or even reversed) when participants were standing, suggesting that postural demands may interfere with the benefits of contextual support.

Introduction

In psycholinguistic research, various evidence has highlighted the role of cognitive effort and attentional demands in language comprehension. Studies have shown that increased syntactic complexity and lower lexical frequency elevate processing demands, as reflected in physiological and behavioral indicators of effort. For instance, Chapman and Hallowell (2021) found that more syntactically complex sentences elicited heightened cognitive effort during comprehension tasks, particularly in populations with aphasia. Similarly, Häuser *et al.* (2019) demonstrated that sentence predictability influenced attentional load, with unexpected continuations requiring greater mental resources. Other research has shown that lexical characteristics such as frequency and word length modulate effort during auditory processing (McLaughlin *et al.*, 2022; Schmidtke, Bsharat-Maalouf, & Degani, 2024). Notably, many of these studies employed pupillometry as a sensitive, real-time index of cognitive effort and attentional fluctuations during linguistic tasks (Schmidtke, 2018; Ryan, Hamrick, & Miller, 2017). The convergence of findings suggests that linguistic complexity and lexical properties systematically shape cognitive resource allocation during language processing.

Beyond linguistic variables, recent research has begun to explore how motor and body position impact cognitive workload. Body position refers to the physical orientation or configuration of the body such as sitting, standing, or balancing i.e. varying degrees of musculoskeletal control and stability. Maintaining postural control while standing when compared to sitting, requires continuous sensorimotor coordination and can increase cognitive demands, especially under conditions of instability or sensory restriction (Kahya *et al.*, 2018; Rosker *et al.*, 2024; Strauch *et al.*, 2022). In fact, standing on unstable surfaces, performing unipedal stances, or having visual feedback occluded, led to greater pupil dilation, i.e. higher mental effort compared to more stable or less demanding postural conditions, such as standing on firm ground with full visual input. These findings highlight that body position and/or the maintenance of stance themselves can act as modulators of cognitive load. The study of the effects of alternating between sitting and standing body positions on cognition, recently has emerged as a relevant area of research (Cherigui *et al.*, 2025; Bouquet *et al.*, 2025). Alternating body positions has been discussed as relevant with respect to concerns over the health risks associated with sedentary behavior and the potential for simple interventions to enhance workplace productivity and well-being (Wilkerson *et al.*, 2023).

A few studies have investigated whether body positions, such as sitting versus standing, affect cognitive effort during linguistic learning tasks. Given that standing has been associated with increased cortical activation and attentional control (Kahya *et al.*, 2018), it raises the question of whether body position may impact on contextual richness in word learning, thereby impacting the cognitive cost of acquiring new words. To our knowledge, no research has yet combined task-evoked pupillary response of word learning with manipulations of both linguistic context and body position. The present study addresses this gap by investigating whether body position (sitting vs. standing) influences the acquisition of words presented in phrases with rich versus neutral contexts, using pupillometry (pupil diameter on TEPR) as the primary measure of cognitive effort. By examining how body position and linguistic context jointly affect word learning, this work aims to shed light on the embodied dimensions of cognitive load during language acquisition and the potential interplay between body position and semantic processing efficiency.

Literature background

Linguistics

Lexical frequency

The difficulty associated with recognizing a word is inversely related to its frequency of occurrence, a phenomenon already indexed by pupil dilation (Kuchinke *et al.*, 2007; Schmidtke, 2014; Shechter & Share, 2021). Research publications using tasks such as the Lexical Decision Task (LDT) demonstrated that low-frequency words elicit significantly greater pupil dilation than high-frequency words (Haro *et al.*, 2017; Kuchinke *et al.*, 2007; Kuchinke *et al.*, 2011; Rojas *et al.*, 2024). This result suggests an effect of lexical processing that is independent of response execution mechanisms accessory to the LDT (Haro *et al.*, 2017; Rojas *et al.*, 2024).

For reading, cognitive effort is crucial because proficiency hinges on effortless word recognition, allowing the limited resources of the processing system to be allocated primarily toward comprehension (Perfetti, 2007; LaBerge & Samuels, 1974). The degree of effort invested in reading is highly sensitive to lexical characteristics (Shechter & Share, 2021; Chapman & Hallowell, 2015). In visual word recognition tasks, cognitive effort is modulated by the familiarity of the stimuli (Shechter & Share, 2021; Shechter, Hershman, & Share, 2022).

Syntactic complexity

In sentence processing, historically, the reading of sentences structured with greater syntactic complexity has been linked to larger pupil sizes compared to sentences of equivalent length but simpler syntactic structure (Just & Carpenter, 1993; Schluroff, 1982). Meanwhile, when younger adults listened to sentences varying in syntactic complexity (subject-relative vs. object-relative) for later recall, they demonstrated a significant increase in mean pupil size during the retention interval for the more syntactically complex object-relative sentences (Piquado *et al.*, 2010). This main effect of syntax reflects a larger mean pupil size, and thus greater cognitive effort, for object-relative than subject-relative sentences (Piquado *et al.*, 2010).

Word length

The physical or structural dimensions of a word, such as its length, are consistently found to influence cognitive effort, especially when processing unfamiliar items. Some published studies already showed that cognitive effort was interacting with word familiarity (real words vs. pseudowords) (Shechter & Share, 2021; Shechter *et al.*, 2022).

Previous studies have confirmed a general pattern that more cognitive effort is invested in pronouncing longer letter strings (i.e., a sequence of characters that represents a text) (Shechter & Share, 2021). This effect is often significantly magnified for unfamiliar strings. Researchers predicted and confirmed a strong familiarity-by-length interaction: the length effects on pupillometric measures were consistently stronger for pseudowords than for real words (Shechter & Share, 2021; Shechter *et al.*, 2022). This outcome holds across different populations (skilled adult readers and school-age children) and modalities (oral and silent reading) (Shechter & Share, 2021; Shechter *et al.*, 2022). For example, among university students, relative changes in pupil size were significantly larger for five-letter strings than for three-letter strings, with a markedly greater length effect observed for pseudowords (Shechter & Share, 2021).

Within this context of processing auditory novel words (pseudowords), the number of syllables also significantly modulates pupillary activation, with tetrasyllabic pseudowords producing significantly larger pupil dilations, suggesting significantly greater cognitive effort required for their short-term retention in the phonological loop (López-Ornat *et al.*, 2018). These converging results support the hypothesis that reading unfamiliar strings, particularly longer ones, relies on effortful, sequential letter-by-letter processing (Shechter & Share, 2021; Shechter *et al.*, 2022).

The index of effort in novel words

Efficient word recognition is characterized not only by speed but also by minimal effort (Shechter & Share, 2021; Shechter *et al.*, 2022). As such, studies showed that processing unfamiliar lexical items demands significantly more cognitive resources than familiar words. For instance, tasks requiring the reading of pseudowords (unfamiliar letter strings) elicit larger and more sustained pupillary responses compared to real, familiar words in both adults and children, reflecting greater cognitive effort (Shechter & Share, 2021; Shechter *et al.*, 2022).

Rich versus neutral context for word learning

Word learning often occurs incidentally through reading or listening. The semantic, syntactic, and discourse contexts surrounding a novel word contribute to its acquisition (Bolger *et al.*, 2008; Frishkoff *et al.*, 2008; Nagy *et al.*, 1987). Learning new words based on rich context (i.e., providing strong cues or associations) versus neutral context (i.e., providing minimal or ambiguous cues) inherently varies the cognitive effort required for semantic activation and integration (Cain *et al.*, 2004; Rapaport, 2003, 2005).

Published studies have shown that the pupil response was sensitive to the difficulty of semantic processing. Processing low-frequency words requires greater dilation (Haro *et al.*, 2017; Kuchinke *et al.*, 2007). Similarly, tasks requiring semantic activation (e.g., judging semantic relatedness) showed greater pupil dilation for weakly related pairs than for strongly related pairs, demonstrating sustained cognitive effort in handling uncertain semantic relations (Geller *et al.*, 2019; Haro *et al.*, 2023; Rojas *et al.*, 2024). This principle suggests that a neutral (low-cue) context during word learning should generate greater sustained effort (larger dilation) than a rich (high-cue) context. Complementarily, the increased cognitive demand has been shown to be associated with syntactic complexity (Just & Carpenter, 1993; Piquado *et al.*, 2010).

Body position

Pupillometry as an index of postural demand

In various studies, small changes in pupil diameter were used to capture real-time cognitive effort during language processing and learning (Beatty, 1982; Kahneman, 1973; Krejtz *et al.*, 2018; van der Wel & van Steenbergen, 2018). In these studies, the Task-Evoked Pupillary Response (TEPR) protocol was used to contextualize pupil size changes related to goal-oriented tasks, thus, tracking the dimension of attention, as mental effort activates the sympathetic system, causing corresponding pupil dilation (Eckstein *et al.*, 2017; Kahneman, 1973; Shechter & Share, 2021).

Postural stability, particularly during bipedal standing, requires continuous cognitive resources, a need that is intensified when the balance task becomes more challenging (Kahya *et al.*, 2018; Kahya *et al.*, 2022; Rosker *et al.*, 2024; Woollacott & Shumway-Cook, 2002). Studies confirmed that increased balance task intensity is associated with a corresponding increase in pupil dilation, reflecting greater cognitive workload. Manipulations that increase postural instability or complexity consistently demonstrate this effect, for example, in visual occlusion i.e. challenging postural control by means of visual occlusion (standing with eyes occluded) is associated with a significantly greater cognitive workload (indexed by the Index of Cognitive Activity, ICA) in healthy young adults compared to standing with eyes open (Kahya *et al.*, 2018; Kahya *et al.*, 2022). These results suggest that removing visual feedback leads to additional neural processing to maintain posture. Additionally, the manipulation of the surface (i.e. foam vs. rigid surface) and the stance complexity (i.e., parallel stance vs. single-leg stance) elicit a measurable increase in the steady-state pupil diameter (Rosker *et al.*, 2024). This steady-state dilation is linked to tonic alertness, enabling the necessary sensorimotor integration of proprioceptive, vestibular, and visual information required for preparing corrective movements during increased instability (Peterka & Loughlin, 2004; Strauch *et al.*, 2022).

Body position in the context of cognitive tasks (sitting vs. standing)

Some studies indicate that standing may enhance selective attention and cognitive control in tasks like the Stroop test (Rosenbaum *et al.*, 2017; Smith *et al.*, 2019). In comparisons of workplace performance, sitting has been associated with greater accuracy and lower omission errors in attention tests compared to standing (Rostami *et al.*, 2022).

The present study aimed to investigate how body position influences cognitive effort during word learning and whether this effect interacts with the semantic richness of the linguistic context. Specifically, we examined whether adopting a standing posture, compared to sitting, modulates task-evoked pupillary responses (TEPR) during the acquisition of novel words presented in rich versus neutral linguistic contexts in brazilian portuguese sentences. This research contributes to the embodied cognition framework by exploring how physical postural states affect the allocation of cognitive resources during language processing. It was hypothesized that standing, due to its greater demands on postural control and attentional regulation, would increase cognitive workload relative to sitting. Additionally, it was predicted that semantically rich contexts would reduce cognitive effort during word acquisition, as they provide stronger cues that facilitate semantic integration and learning.

Methods

Participants

Seventeen participants voluntarily participated in this study and were recruited among undergrad and graduate students attending courses at Sao Paulo State University. Eleven of them were male while seven were female. Measurements of body mass (74,5 ± 3,1 kg), height (1,74 ± 0,1 m) and age (21 ± 2,5 years) were noted. None of the participants reported neurological or musculoskeletal diseases nor vestibular problems or recurrent dizziness. All the participants had normal or correct to normal vision. Each participant signed an informed consent to this study.

Apparatus and design

For each experimental session, eye movements were recorded using a Tobii Pro Fusion eye tracker hardware (120Hz of sample rate) that was magnetically mounted on a Dell 21” flat screen display (Figure 1A). The luminance of the environment was controlled and standardized throughout all experimental sessions to i) avoid display environmental light reflections; ii) guarantee the same light conditions for pupil measurements; iii) control as much as possible the environmental lighting effects on participant’s pupil diameter. The display was positioned on a standing desk which could have its height simply adjusted, by pressing buttons (up and down arrows, raising or lowering the desk at 0.1 cm pace) (Figure 1B). A stull with 90 cm of height was used for the sitting body position conditions and it was removed accordingly whenever needed and placed back at the same position for sitting condition.

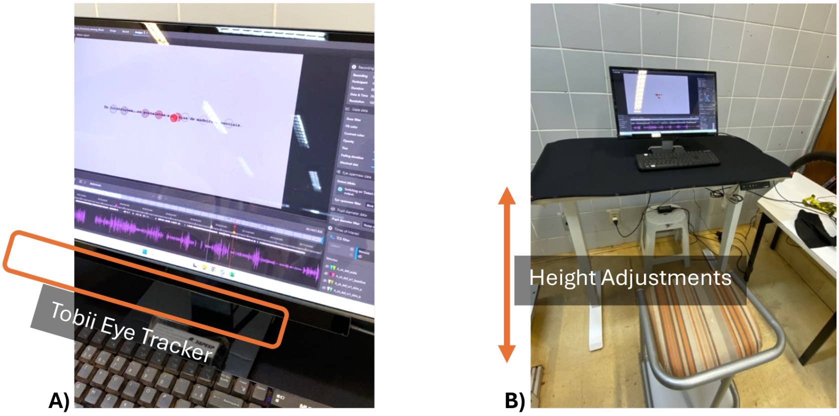
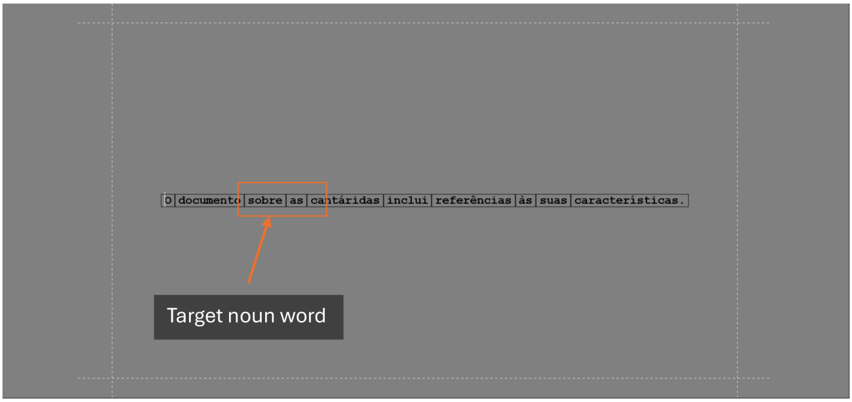


Figure 1. A: Stimuli display with the Tobii Eye Tracker magnetically attached at the bottom of the display. The sensor works at a 120Hz sampling rate. The luminance of the environment was controlled to avoid the reflections at the display. **B**: The standing desk setup has a controller which allows the desk to move up or down and these positions can be saved in one of 5 memory positions.

All participants performed reading tasks with two different sentence contexts (rich vs. neutral) either sitting on a stull or standing in front of the standing desk. The distance from the display to the participant's head and the standing table height were adjusted according to the participant's preferences, however, the right arm of the participants should rest on the standing desk close to the keyboard to avoid disturbances of body movement or participants movements unrelated to the task, characterizing a study limitation.

All the stimuli were created using Tobii Pro Lab software (full version) in which all stimuli were randomized and counterbalanced to avoid learning effects. All the sentences were created with a gray background color, bold black font color and Courrier New typographic font (Figure 2). A margin of 5% of the display resolution (1920x1080 pixels) were implemented to avoid out of depth eye fixations which could miss eye gaze toward the display depth and confuse the eye tracking system. All participants learned all words in all conditions. Likewise, all words occurred in all four conditions: by body position (sitting vs. standing) and by sentence context (rich vs. neutral). To avoid item-sentence cofounds, it was created a counterbalanced list as for each word, sentence variants were sampled without replacement so that, per participant, a different set of sentences instantiated each of the four conditions. Across participants, assignment of the 3 rich context (RC) and 3 neutral context (NC) sentences to the four conditions (RC-sitting; RC-standing; NC-sitting; NC-standing) was rotated such that each sentence variant appeared equally often in each condition. Trial order was also randomized.



O documento sobre as cantáridas inclui referências às suas características.

Figure 2. Example of the design of a sentence. The target noun word would be positioned at the middle position of the sentence. The rectangles around each word are Area of Interest (AOI) drawn automatically on a reading task thus allowing to capture metrics related to phrases, words or characters within a sentence.

The sentences phrases were produced focusing on lexical, phonological and contextual features of the stimuli. A total of

28 nouns were selected from the LexPorBr lexical database, adhering to the following inclusion criteria: i) word category: all items were nouns; ii) word length: each noun contained between 10 and 15 letters; iii) lexical frequency: only nouns with a frequency of less than 0.85 occurrences per million words were retained, to ensure low familiarity and reduce frequency effects; iv) phonological simplicity: all nouns conformed to a simple syllabic structure, specifically the CVCV pattern, which minimized phonotactic complexity and facilitated reading and processing.

For each of the 28 selected nouns it was embedded six unique sentence contexts, yielding a total of 168 sentences. These were divided into two conditions: i) rich context sentences (n=84): for each noun, three sentences were created that provided semantically rich information, such as definitions characteristics functions, or descriptive cues. These sentences were designed to enhance the saliency of the target word's meaning through context; ii) neutral context sentences (n=84): for each noun, three additional sentences were constructed that provided minimal semantic support, offering grammatically correct yet contextually neutral environments. Before all presented sentences, a poll black ball with the number 8 was used as an icon positioned at the vertical middle and horizontal center of the display to standardize and baseline value for the pupil diameter prior to the sentence reading task.

Additionally, all sentences were controlled for length, containing between 9 to 11 words, to ensure consistency in syntactic complexity and processing demands. Initial sentence drafts were generated using a large language model-based AI system (e.g., ChatGPT model o3) tailored to Brazilian Portuguese. The model was prompted to generate both richly informative and neutral contexts for each noun. Subsequently, all AI-generated sentences were manually reviewed and revised by native Brazilian Portuguese speakers with linguistic training, ensuring naturalness, grammatically accuracy, and semantic appropriateness in both sentence types.

The participants performed two sentences context reading tasks (RC vs. NC), with 3 trials per task in two body positions (sitting vs. standing) for all 28 nouns. Figure 3 presents the body position of participants while performing the experiment. The conditions are explained below.

As for the body position, the order of word blocks was randomized and would be shown on the screen if it was a standing or sitting reading block. So, the experimenters would remove or place the stull in the designated position. Markings of the floor were created to ensure the right positioning of the stull.

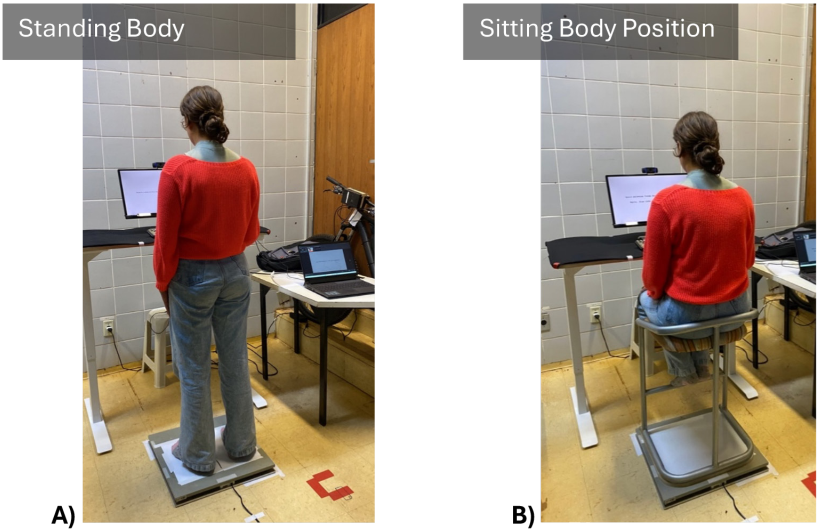


Figure 3. A: Participant performing the reading task while standing. **B:** Participant performing the reading task while sitting. The right arm of the participant is resting on the table while the left arm was resting and should not move throughout the experimental procedures.

Participants were instructed to, whenever they saw phrases appear in the center of the screen, read them very carefully, sit in front of the screen in the indicated position, and press any key to continue, noting that they would be asked questions about the phrases at the end of the experiment. No feedback was given during learning.

Procedures

Upon arrival at the experimental room, participants provided written informed consent and received an information sheet. Body mass and height were noted. Visual acuity was assessed using a Snellen chart; only participants with acuity between 20/20 and 20/25 were permitted to continue. Participants were then asked to remove their shoes before the experiment began. Prior to the experimental procedure, the standing desk table height was adjusted and saved for later use: participants alternated between sitting and standing as they would during the task to set the table to a comfortable height according to their preferences. Eye-tracker calibration was then performed. Participants with data loss less than 5% were allowed to continue; those with higher values repeated the calibration until they met the threshold. The experiment was self-paced: participants silently read sentences and advanced at their own pace until an on-screen message prompted them either to take a short break or to change body position (from sitting to standing or vice versa). After completing all 168 sentences, a message appeared thanking the participant for their participation in the experiment.

Data analysis

The pupil diameter was recorded for the entire sentence reading task. For each word inside a sentence, an area of interest was drawn (the black rectangle around each word, Figure 2). However, for the purpose of this study, the pupil diameter time series was generated only for the target noun word AOI of each condition for each of the 28 nouns. The TEPR was considered as the sentence reading, specifically, the moment the participant read the target noun word entirely.

To create a pupil outcome comparable within participants, it was applied a trial-wise baseline correction. For each participant × trial, we computed the mean baseline pupil diameter from the average pupil diameter; when a trial baseline was missing, we used participant's overall baseline computed from all their baseline rows. The dependent variable was the baseline-corrected pupil diameter.

For the analyses, we used only non-baseline rows that corresponded to word AOIs and had valid body position, context, and non-missing pupil diameter baseline corrected values. To limit undue influence of extremes (i.e., outliers) while preserving within-person scaling, the pupil diameter baseline corrected value was z-scored within participant and observations outside ±3 SD (standard deviation) were removed. Both word length and word index were standardized (mean 0, SD 1).

Statistical analysis

For statistical analyses, it was modeled trial-level baseline-corrected pupil diameter ($pupil\_diameter_{bc}$) using a linear mixed-effects model. All calculations were implemented in RStudio with R language.

The fixed-effects model was defined as:

$$\boldsymbol{pupil\_diameter_{bc}} = body_{position} * text_{context} + word_{length_c} + word_{index_c} * (1 + context_c \,||\, participant)$$

With:

$\boldsymbol{pupil\_diameter_{bc}}$ = baseline-corrected pupil diameter for a target word, computed as the trial/participant's current average pupil minus its baseline (millimeters). With the reference of higher values means larger dilation relative to baseline.

$\boldsymbol{body_{position}}$ = participant body position during reading. A factor with two levels (sitting; standing).

$\boldsymbol{text_{context}}$ = linguistic context type of the sentence containing the target word. A factor with two levels (neutral; rich).

$\boldsymbol{word_{length_c}}$ = standardized word length of the target word (z-score). Base length is the number of characters in AOI when available.

$\boldsymbol{word_{index_c}}$ = standardized ordinal position (z-score) of the target word within its sentence/phrase, where larger values mean later positions.

$\boldsymbol{1 + context_c \,||\, participant}$ = participant-level random effects with a random intercept (each participant has their own overall level), and an uncorrelated random slope for $\boldsymbol{context_c}$, allowing the $\boldsymbol{text_{context}}$ effect to vary across participants.

Fixed-effect inference relied on Type-III ANOVA with Satterthwaite degrees of freedom. For interpretation, we estimated marginal means (EMM) for all body position × text context cells and ran Tukey-adjusted pairwise contrasts (standing vs. sitting within each context; rich vs. neutral within each body position), reporting EMMs with 95% of confidence intervals and adjusted p-values. Model-level effect sizes were summarized with Nakagawa's R^2 (marginal and conditional).

In summary, baseline-corrected mean pupil diameter was analyzed with a linear mixed-effects model fit (Satterthwaite degrees of freedom), predicting pupil diameter baseline-corrected from body position (sitting, standing), text context (neutral, rich), and their interaction, controlling for standardized word length and word index cofounds, with by-participant random intercepts and a random slope.

Results

The linear mixed-effects model fit showed a main effect of body position, with pupil diameter higher in standing when compared to sitting (larger pupils/higher TEPR), F(1,1347.44)=37.45, p<.001. The body position with text context interaction was also significant, F(1,1349.32)=8.69, p=.003, whereas the main effect of text context was not significant, F(1,15.21)=0.03, p=.876. Estimated marginal means (Kenward–Roger) were the smallest TEPR in sitting-rich (EMMs = −0.0659, SE = 0.0276) and the largest in standing–rich (EMMs = −0.0099, SE = 0.0276), with neutral conditions in between (sitting–neutral = −0.0464; standing–neutral = −0.0271). Planned contrasts indicated a larger body position effect under rich context (standing − sitting = +0.0560, p<.0001, ≈ 0.49 residual-SD units) than under neutral (+0.0194, p=.027, ≈ 0.17 SD), yielding a difference of +0.0366 (≈ 0.32 SD). Within-body position context comparisons showed rich < neutral when sitting (estimate = 0.0195 for neutral − rich, p=.0475) and a nonsignificant trend for rich > neutral when standing (−0.0172, p=.075). Covariates were not significant in this model (p≥.19).

Model fit indices suggested modest fixed-effect signal amid substantial individual variability (marginal R^2=.017); conditional R^2=.492).

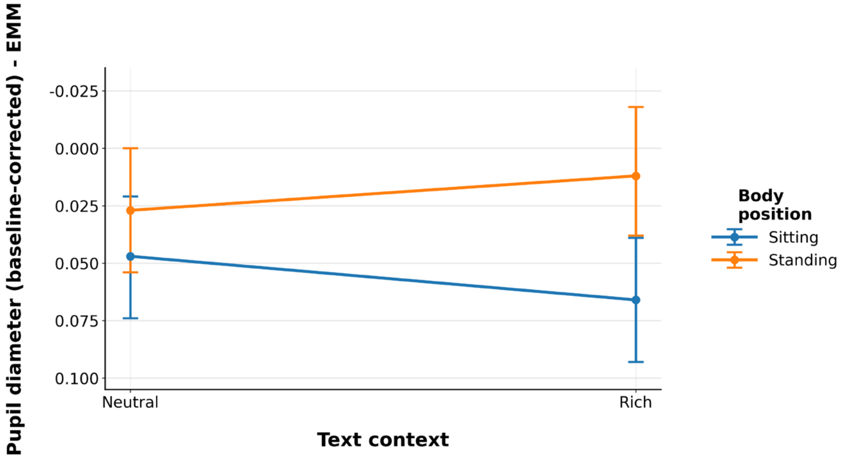


Figure 4. Mean and standard deviation of pupil diameter in the neutral and rich environment and in the sitting and standing condition. Pupil diameter was higher in standing when compared to sitting; the body position with text context interaction was also significant, with the largest pupil diameter in standing–rich and the smallest sitting-rich.

Discussion

The present study investigated whether body position (sitting vs. standing) can influence the acquisition of new words presented in sentences varying in semantic richness (neutral vs. rich contexts), using pupil diameter (TEPR) as a physiological index of cognitive effort. The results showed that standing, compared to sitting, led to greater pupil dilation across conditions, indicating increased cognitive effort. Moreover, an interaction between body position and context revealed that rich semantic context amplified TEPR only in the standing condition, whereas in sitting, rich context reduced pupil dilation. These results suggested that body position might modulates how linguistic context affects cognitive load during word learning.

The first hypothesis posited that standing, due to its demands on postural control, would increase cognitive workload compared to sitting. This was supported by our data (Figure 4) as standing significantly elevated pupil dilation relative to sitting, across both rich and neutral linguistic contexts. These findings align with previous work showing that maintaining balance during standing requires continuous sensorimotor coordination and attentional resources, particularly under more challenging postural conditions (Kahya *et al.*, 2018; Rosker *et al.*, 2024; Strauch *et al.*, 2022). Furthermore, the steady-state pupil dilation observed in standing conditions was consistent with prior research identifying pupillometry as a reliable marker of increased postural cognitive demands (Kahya *et al.*, 2022; Rosker *et al.*, 2024). These results confirmed that even in a static standing posture, greater cognitive effort is needed relative to sitting, supporting the embodied cognition perspective that bodily states shape the allocation of cognitive resources (Kang, Lee, & Jin, 2021).

The second hypothesis suggested that semantically rich contexts would reduce cognitive effort during word acquisition, as they provide stronger cues for integration. This hypothesis was partially supported. In the sitting condition, rich context reduced TEPR, consistent with previous findings showing that semantic richness facilitates processing and reduces mental load (Cain *et al.*, 2004; Geller *et al.*, 2019; Rojas *et al.*, 2024). However, in the standing condition, the rich context increased pupil dilation (Figure 4). This unexpected result could suggest that under higher cognitive load induced by postural control, additional semantic cues may require greater integration effort.

While rich semantic context typically facilitates word learning (Cain *et al.*, 2004; Geller *et al.*, 2019), our findings suggest that in standing posture, these benefits may require increased cognitive control demands. This aligns with findings by Brock (2024), who observed that standing under added mental load amplifies pupil response, indicating elevated cognitive effort when multiple resource-intensive tasks are combined. This interpretation echoes prior models of resource allocation, in which effortful tasks (e.g., balancing and semantic integration) compete for shared attentional resources (Just & Carpenter, 1993; Bonnet & Baudry, 2016; Perfetti, 2007).

Despite its contributions, this study has several limitations. First, the sample size was limited, and replication with a larger and more diverse sample is necessary to confirm these findings. Second, only two body positions (sitting and standing) were examined. Including more demanding or dynamic conditions (e.g., balancing on foam, walking) would help clarify the relationship between postural load and language processing. Third, although pupil dilation is a validated index of cognitive effort, it is influenced by factors like luminance, arousal, and fatigue. While controls were implemented, future studies may consider additional physiological or behavioral measures (e.g., EEG, reaction time) for converging evidence. Finally, the semantic richness manipulation was sentence-level; word-level or discourse-level manipulations may yield different patterns.

These findings open several directions for future research. Most notably, they support an embodied view of language learning, wherein bodily states such as body position influences cognitive effort during word acquisition. The interaction between standing and semantic richness suggests a non-linear relationship: body position may not merely add load but could also alter the way linguistic cues are processed. Future studies could explore whether such effects extend to longer learning sessions, real-world educational environments, or dynamic movements. Additionally, investigating the neural mechanisms (e.g., with EEG or fMRI) could clarify how motor and cognitive systems co-regulate effort during language tasks. Ultimately, this research contributes to a growing literature on embodied cognition by highlighting how even subtle motor factors like body position can shape the efficiency of linguistic learning.

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Analysis of Maxwell’s centroids in scholars aged 7 to 14 years with and without dyslexia

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Abstract

The aim of this study was to investigate the general characteristics and magnitude of the Maxwell’s centroids in students aged 7 to 14 years, with and without dyslexia. Fifteen students diagnosed with dyslexia and 11 typically developing peers participated in the study. Each participant sat facing a device positioned on a table and viewed a white screen through a central aperture of a viewing tube. The tube contained blue and green optical filters that were manually alternated by the experimenter using a lever. As the filters changed, participants identified a dark spot on the screen and subsequently reproduced the perceived image on a tablet, from which data were stored for analysis. Ocular dominance was assessed using the fenestrated card test. A custom LabView program (National Instruments, Inc.) was used to record the contour of the reproduced images and calculate the corresponding radius, area, circumference, and x-y coordinates were calculated. Using these coordinates, an asymmetry coefficient between dominant and non-dominant eyes was computed with a custom MATLAB routine (MathWorks, Inc.). Overall, the characteristics of Maxwell's centroids were similar between groups, although the magnitude of centroids parameters was consistently greater among students with dyslexia.

Introduction

Dyslexia is widely characterized as a marked difficulty in reading, decoding, and spelling words, regardless of an individual's educational background, cognitive ability, or motivation (Adlof & Hogan, 2018; Ferrer *et al.*, 2010; Peterson & Pennington, 2015). Importantly, the reading challenges experienced by individuals with dyslexia are not attributed to learning disabilities (Tunmer & Greaney, 2010), but rather to slow and effortful reading (Shaywitz *et al.*, 2021). As a result, even when enrolled in mainstream educational settings, individuals with dyslexia typically struggle to develop fluent and accurate reading, writing, and spelling skills (Fletcher, 2009).

Because vision plays a central role in the act of reading, the visual system has been examined as a potential contributor to the manifestations of dyslexia (Barela *et al.*, 2025; Bucci *et al.*, 2012; Razuk *et al.*, 2018; Seassau *et al.*, 2014). Among the many components of this complex system, particular attention has been directed to a region of blue cones known as the area of Maxwell's centroids (Le Floch & Ropars, 2017).

Maxwell's centroids are perceived as a dark circular spot comprised of three concentric zones: a central point, a lighter intermediate ring, and an outer halo (Miles, 1953). Their shape, however, is not uniform across individuals and may vary according to the relative distribution of red and blue cones in the fovea. For example, some centroids display larger or smaller intermediate rings, others are characterized only by the halo, and some lack the central point altogether (Isobe, 1955). Such morphological variations are linked to differences in the structure of the foveal wall and the foveola.

Le Floch and Ropars (2017) explored these centroids in adults with and without dyslexia. In adults without dyslexia, the authors observed clear asymmetries between the right and left eyes. Typically, the dominant eye exhibited a more circular centroid, whereas the non-dominant eye showed a more irregular and elliptical shape. This pattern was interpreted as an expression of neural selection processes, through which the central nervous system preferentially relies on input from the dominant eye. In striking contrast, adults with dyslexia demonstrated symmetrical centroids, with highly similar configurations in both eyes (Le Floch & Ropars, 2017). According to the authors, symmetrical centroids provides to the central nervous system nearly equivalent visual signals from both eyes, which may hinder the extraction of fine visual details. They proposed that this absence of asymmetry could interfere with the establishment of a dominant eye, thereby complicating the processing of visual information in individuals with dyslexia.

Given these findings in adults, an important question emerges: does the same symmetry in centroids occur in children and adolescents? Investigating this possibility may deepen our understanding of how neural connections develop within the central nervous system and how these developmental processes relate to dyslexia. Furthermore, if such symmetry is present early in life, it may hold promise as a potential indicator for the early detection of dyslexia, well before children reach the age at which reading skills are typically acquired. This idea is consistent with evidence that visual acuity develops progressively after birth, reaching a functional peak around four years of age as foveolar cones mature (Green, 1970; Yuodelis & Hendrickson, 1986).

Based upon this background, the present study aimed to investigate Maxwell's centroids in school-aged children (7 to 14 years) with and without dyslexia. More specifically, the study sought to compare the characteristics of Maxwell's centroids between the dominant and non-dominant eyes within each group and to examine potential relationships involving asymmetry between the two eyes.

Methods

Participants

Twenty-nine students aged 7 to 14 years participated in this study. Of these, 17 participants were diagnosed with dyslexia ("dyslexia group") and 12 participants had not reported learning disabilities ("control group"). Participants with dyslexia were required to have a formal diagnosis of dyslexia established by a multidisciplinary team (i.e., speech therapist, psychologist, ophthalmologists or neurologists, among others). To be included in the control group, participants could not present any report suggestive of learning disabilities. Participants with dyslexia were recruited from centers dedicated to the treatment of phonological difficulties, whereas control participants were recruited through contact with the local community.

The study was conducted in accordance with the guidelines of the local Ethics Committee (CAAE: 19418419.7.0000.5465). All procedures were performed with the appropriate understanding and written informed consent of the participants' legal guardians.

Procedures

Participants completed a single experimental session. Each participant sat facing a device and placed one eye at a viewing tube mounted on a table (Figure 1). Through the central aperture of this tube, they viewed a white screen positioned 3 m ahead. Inside the tube, a structure housed two optical filters, a blue filter (OD 6 Fluorescent Filter, Edmund Optics) and a green filter (Hard Coated OD 4.0, 25 nm Bandpass Filter, Edmund Optics), that were manually alternated by the experimenter using a lever. Moving the lever upward or downward allowed the participant to view the screen through either the blue or the green filter, respectively.

The filters used in this study were the same type used in the protocol described by Le Floch and Ropars (2017), which we replicated. This procedure corresponds to the foveascopy technique, and the images produced are referred to as "Maxwell's centroids". The blue fluorescent filter transmitted light centered at 450 nm (bandwidth 20 nm), whereas the green band-pass filter transmitted light centered at 534 nm (bandwidth 25 nm).

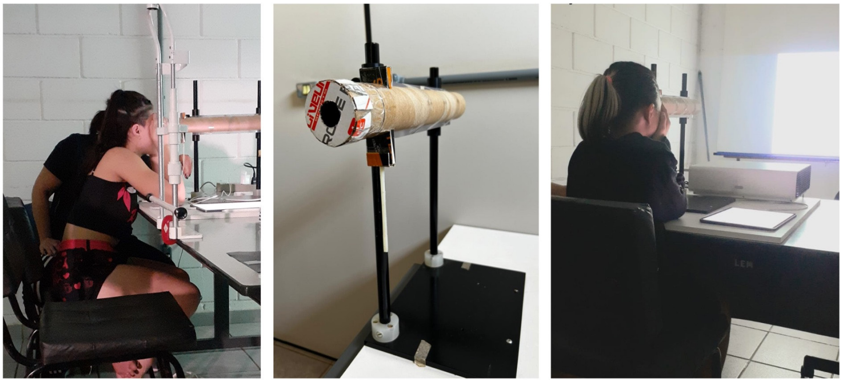

Figure 1. Ilustrative pictures of a participant's position facing the device (left), the device used in the experiment (center), and an overall view showing the screen placed ahead and the tablet positioned next to the participant (right).

Participants were instructed to identify a dark spot that appeared on the screen while the experimenter alternated the filters every 5 s. After perceiving the image, they reproduced what they saw on a tablet (iPad Pro 12.5", 5th generation, Apple Inc.) using a digital pencil (Apple Pencil, 2nd generation, Apple Inc.). The procedure was then repeated for the other eye. All reproduced images were recorded and stored directly on the tablet.

After completing the reproduction task, each participant performed the hole-in-the-card test to determine ocular dominance. For this test, participants held a 20 × 25 cm card with a 6 mm central hole (Barbeito, 1981) at arm's length, keeping both eyes open. They aligned the hole with a fixation point located 6 m ahead and were instructed not to move the card. The experimenter then alternately occluded each eye and the dominant eye was identified as the eye that maintained alignment with the fixation point through the hole in the card (Seijas *et al.*, 2007).

Data analysis

The images stored on the tablet were transferred to a computer while preserving their pixel dimensions. A custom program developed in LabVIEW (National Instruments, Inc.) was used to manually trace the contour of each participant's reproduced image for each eye using a mouse. Before outlining, a calibration procedure was performed to convert pixel measurements to centimeters based on three reference points whose distances were measured and digitized. During the contour tracing, the horizontal (x) and vertical (y) coordinates of the cursor were recorded at a sampling rate of 20 points per second.

The recorded coordinates were plotted as scatter data, and a circular fit was applied using the least-squares method. This procedure yielded the radius (r) of the best-fit circle for each outlined image. The area (A) and circumference (C) were then calculated as: $A = \pi r^2$ and $C = 2\pi r$. The resulting measurements were saved in ASCII files separately for each eye and each participant in the dyslexia and control groups. Following, a custom MATLAB routine (MathWorks, Inc.) was used to estimate the ellipse parameters of each reproduced image (Gal, 2003), for both dominant and non-dominant eyes. This procedure followed the methodology described by Le Floch and Ropars (2017).

Asymmetry of the Maxwell's centroids was quantified as the ratio between the minor (AB) and major (CD) axes of the ellipse. Specifically, asymmetry values were calculated as AC/BD for images corresponding to each participant's dominant ($\varepsilon_D = AC/BD$) and non-dominant ($\varepsilon_{ND} = AC/BD$) eyes. The asymmetry coefficient was then obtained by subtracting these values ($\Delta\varepsilon = \varepsilon_D - \varepsilon_{ND}$). Positive values of $\Delta\varepsilon$ indicate greater asymmetry in the dominant eye, negative values indicate greater asymmetry in the non-dominant eye, and values near zero indicate minimal or no asymmetry (Le Floch & Ropars, 2017).

After all these procedures, the variables obtained and analyzed in this study included the area, radius, and circumference of the Maxwell's centroid images for each eye, as well as the asymmetry coefficient for participants in both groups.

Statistical analysis

To examine similarities in age, body mass, height, and body mass index (BMI) between participants with and without dyslexia, both univariate (ANOVA) and multivariate (MANOVA) analyses of variance were conducted with group (dyslexia and control) as the independent factor. Age was included as the dependent variable in the ANOVA, whereas body mass, height, and BMI were included as dependent variables in the MANOVA.

Because the area and circumference variables did not meet the assumption of normality, data transformations were applied following Field (2009): a base-10 logarithmic transformation for area and a square-root transformation for circumference. After transformation, both variables satisfied the normality requirement, and ANOVAs were subsequently performed.

To assess potential differences in the characteristics of Maxwell's centroids, ANOVAs were conducted with group and eye (dominant and non-dominant) as factors, with repeated measures on the eye factor. Separate ANOVAs were performed for area, radius, and circumference as the dependent variables. To examine potential asymmetry between the dominant and non-dominant eyes, an additional ANOVA was performed with group as the factor and the asymmetry coefficient as the dependent variable.

All analyses were conducted using the Statistical Package for the Social Sciences (SPSS). The significance level was set at 0.05 for all tests.

Results

From the 29 participants assessed in the study, two from the dyslexic group and one from the control group reported that they did not see the Maxwell's centroids and were excluded from the final analysis. Table 1 presents the general information of the final sample, according to the group. The ANOVA did not reveal any group effect regarding age ($F_{1,24}$=1.42, *p*=0.245), neither MANOVA regarding body mass, height, and body mass index (Wilks'Lambda=0.97, $F_{3,21}$=0.21, *p*=0.889).

Table 1. Means and standard deviations for age, body mass, and height, and number of participants for sex and eye dominance in the dyslexia and control groups.

Characteristic	Dyslexic group (n=15)	Control group (n=11)
Age (years)*	10.7 ± 2.1	11.6 ± 1.6
Body mass (kg)*	47.9 ± 21.4	43.8 ± 17.3
Height (m)*	1.48 ± 0.16	1.48 ± 0.12
Sex (female/male)	10/5	10/1
Eye dominance		
Right	n=8	n=8
Left	n=6	n=3
Non-dominance	n=1	n=0

Figure 2 illustrates images reproduced by four participants from the dyslexia and control groups using their dominant and non-dominant eyes. This figure highlights the variability in what each participant perceived with each eye and subsequently reproduced the Maxwell's centroid spots.

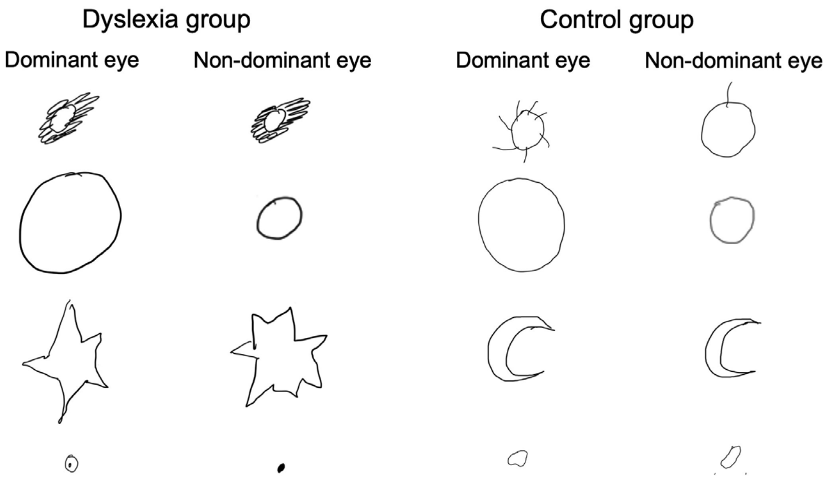

Figure 2. Examples of the Maxwell's centroid images reproduced by four participants in the dyslexic (left) and control (right) groups using their dominant and non-dominant eyes.

Figure 3 shows the boxplots for the interquartile range, median, and mean values of area, radius, and circumference from the images of Maxwell's centroids reproduced by participants in the dyslexia and control groups. The ANOVA for area revealed a group effect ($F_{1,24}$=4.48, p=0.045), but no eye effect ($F_{1,24}$=1.03, p=0.320) and no group and eye interaction ($F_{1,24}$=0.29, p=0.591). The dyslexia group exhibited larger area compared to the control group (Figure 3A).

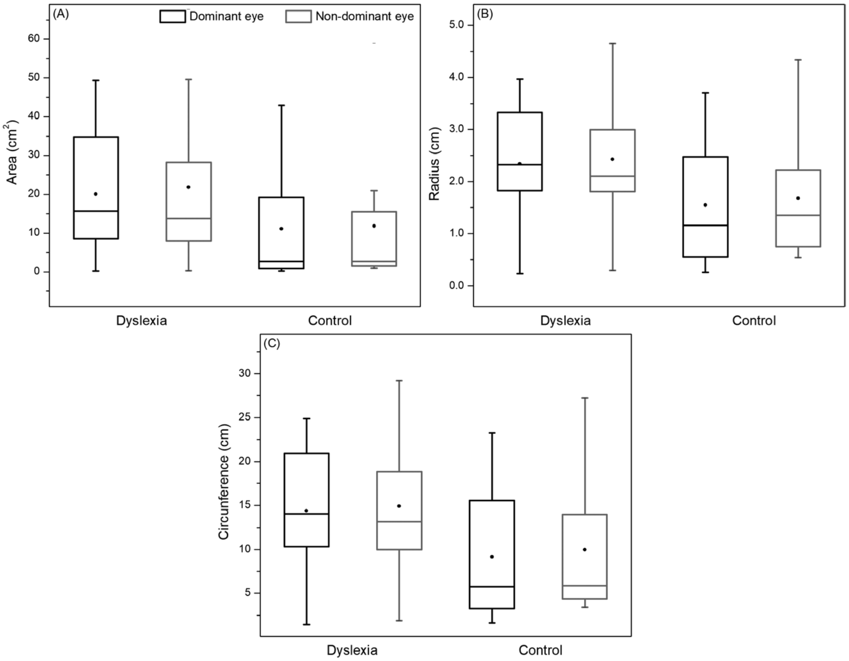

Figure 3. Area (A), radius (B), and circumference (C) values from the Maxwell's centroid images reproduced by participants in the dyslexia and control groups for the dominant (black) and non-dominant (gray) eyes. The boxplots show the median, interquartile range, and the full range (maximum to minimum), and the black dot denotes the mean.

The ANOVA for radius revealed a group effect ($F_{1,24}$=4.28, *p*=0.049), but no eye effect ($F_{1,24}$=0.19, *p*=0.666) and no group and eye interaction ($F_{1,24}$=0.01, *p*=0.916). The dyslexia group presented larger radius compared to the control group (Figure 3B). Finally, the ANOVA for circumference revealed a group effect ($F_{1,24}$=4.71, *p*=0.040), but no eye effect ($F_{1,24}$=0.46, *p*=0.502) and no group and eye interaction ($F_{1,24}$=0.090, *p*=0.764). The dyslexia group presented longer circumference compared to the control group (Figure 3C).

Figure 4 shows the individual asymmetry coefficient values, with each participant's eye dominance also indicated. It is important to note that one participant from the dyslexia group did not present eye dominance. As we had taken into consideration dominant and non-dominant eyes in the data analysis, for this participant specifically, we had considered the right eye as “dominant”. As shown in Figure 4 A and 4B, there was no apparent relationship between the tested eye dominance and the calculated asymmetry.

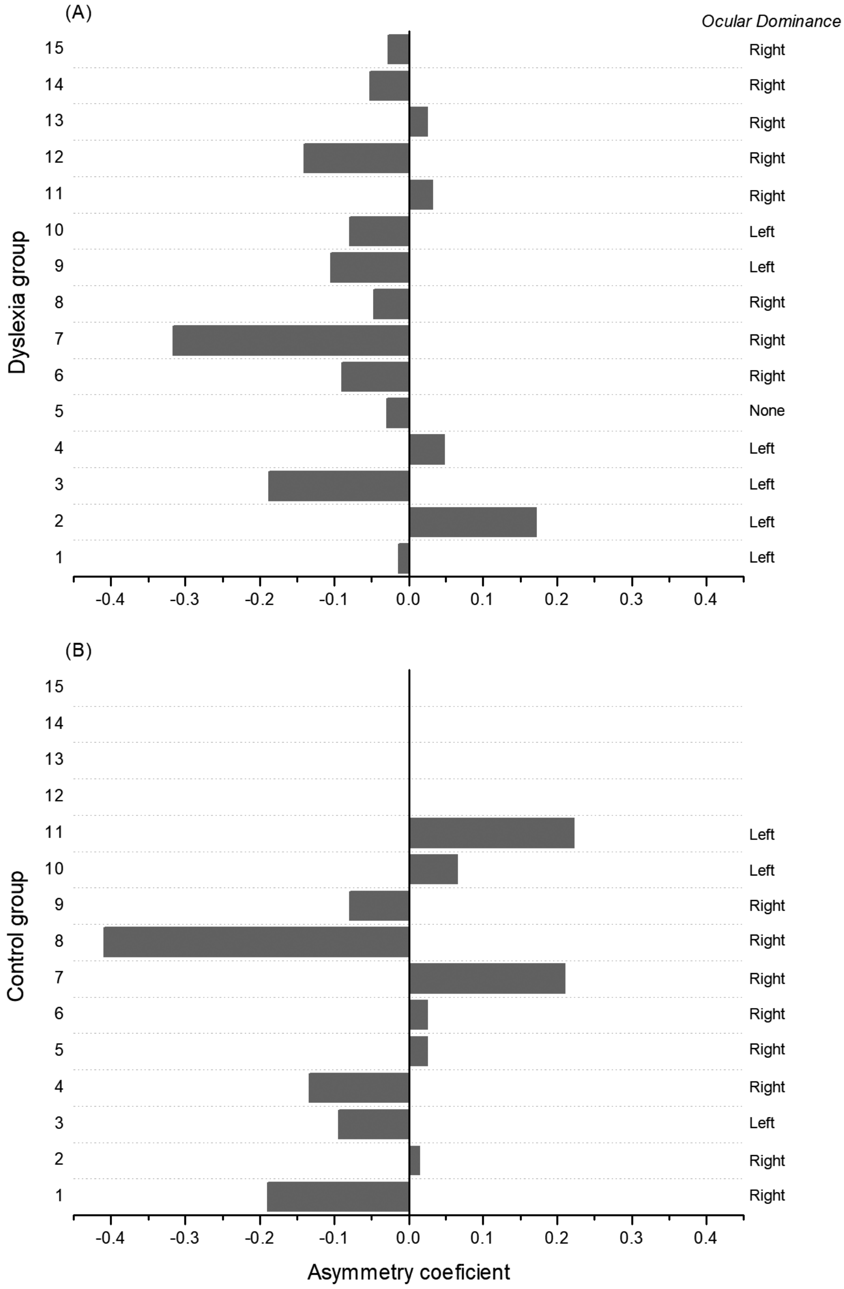

Figure 4. Individual asymmetry coefficient values from the Maxwell's centroid images reproduced by participants in the dyslexia and control groups, with each participant's eye dominance indicated.

Figure 5 shows the boxplots for the interquartile range, median, and mean values of asymmetry coefficient from the images of Maxwell's centroids reproduced by participants in the dyslexia and control groups. The ANOVA revealed no group effect ($F_{1,24}$=1.04, *p*=0.318).

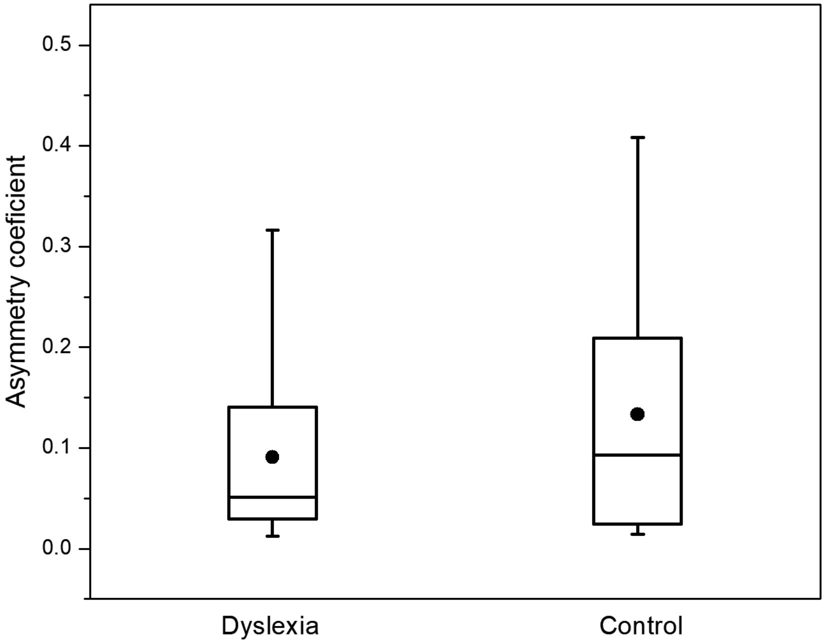

Figure 5. Individual asymmetry coefficient values from the Maxwell's centroid images reproduced by participants in the dyslexia and control groups. The boxplots show the median, interquartile range, and the full range (maximum to minimum), and the black dot denotes the mean.

Discussion

The aim of this study was to investigate the characteristics of Maxwell's centroids in students aged 7 to 14 years, with and without dyslexia, and to examine whether there is a relationship in asymmetry between the dominant and non-dominant eyes in these students. Overall, participants in the dyslexia group exhibited larger area, greater radius, and greater circumference of the reproduced Maxwell's centroid images compared to participants in the control group. On the other hand, the asymmetry coefficient of these centroids between the dominant and non-dominant eyes was similar across both groups.

Unlike the study by Le Floch and Ropars (2017), which reported that adults reproduced images with circular or elliptical shapes, the participants in the present study reproduced images with varied shapes (Figure 2). More specifically, our participants reproduced images resembling a diffuse spot, an expanded shell, a star, a ring, a ring with a central spot, a distorted ring resembling a crescent moon, or a ring with a dark peripheral halo. It is important to note that the shapes observed in our study are similar to those reported by Chen and colleagues (2015). Previous studies have also reported Maxwell's centroids reproduced as a dark ring or an expanded shell (Miles, 1953), or as a diffuse dark spot, a star with a central dark spot, a dark ring without a central spot, or a dark ring with a central dark spot (Isobe & Motokawa, 1955). Thus, the varied shapes reproduced by participants in the present study may be related to individual differences in the distribution of macular pigment within the fovea (Chen *et al.*, 2015).

Le Floch and Ropars (2017) associated the symmetry of Maxwell's centroids with the absence of ocular dominance in individuals with dyslexia. The results of the present study revealed the presence of asymmetry in Maxwell's centroids and ocular dominance in both dyslexia and control groups. Considering that those investigators suggested that the nervous system has difficulty processing visual information from both eyes in individuals with dyslexia (Le Floch & Ropars, 2017), such an explanation does not appear to apply to students between 7 and 14 years old.

In this study, students with dyslexia not only exhibited asymmetry in Maxwell's centroids but also reproduced images that were notably larger than those of the control group. These results lead us to question whether this magnification perceived by children with dyslexia is related to the distribution of red and blue cones in the fovea (Isobe, 1955), to a steeper and narrower foveal pit (Chen *et al.*, 2015), or perhaps whether the increased radius of Maxwell's centroids is associated with the spatial density of macular pigment distribution (Misson *et al.*, 2023). It is likely that individuals with dyslexia present a different macular structure. However, this possibility needs to be investigated in future studies using optical coherence tomography to assess foveolar dimensions and foveal rim geometry, as performed in previous work (Chen *et al.*, 2015), or through examinations that detect macular pigment density and distribution, such as non-mydriatic fundus photography, like that employed by Misson and colleagues (2023).

In summary, the results of this study indicate that students with dyslexia aged 7 to 14 years show Maxwell's centroid characteristics similar to those students without dyslexia, but with larger magnitude. The characteristics of these centroids were similar between the dominant and non-dominant eyes for both groups. Finally, there was no relationship in asymmetry between the dominant and non-dominant eyes for most participants in either group. Thus, the results of the present study differ from those reported by Le Floch and Ropars (2017), likely due to differences in macular pigment density or foveal pit geometry between individuals under 15 years old and adults.

Acknowledgments

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Acuate effects of prismatic lenses on reading speed in children with developmental dyslexia

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Abstract

The aim of this study was to examine the acute effect of active prismatic lenses on reading speed of children with developmental dyslexia. Fifteen dyslexic children (10.6 ± 2.1-year-old; 11 girls and 4 boys) performed a silent reading test. After, children were tested for sensorimotor impairments and prism lenses were defined, for each eye, aiming such impairment. Children performed the silent reading test again wearing the prims lenses. Average total reading for each condition was obtained and compared. Results showed that 11 children reduced total reading time when

wearing the prims and a t test showed overall total reading time reduction (pre - 87.8 ± 103.7; post – 56.3 ± 59.4; $p<0.05$). These results suggest that children with dyslexia can take advantage of using prismatic lenses, minimizing sensorimotor impairment, and most importantly improving reading speed.

Introduction

Developmental dyslexia is a neurodevelopmental disorder, described as a specific disorder of language and written language learning. Developmental dyslexia is a pathological reading disorder with no explanatory cause in children of normal intelligence that resists interventions with an impact on schooling (APA, 2013). Resistance to interventions explains why developmental dyslexia is recognized as a disability, related to a disorder of reading automation.

Despite all the controversy, two main theoretical approaches attempt to explain developmental dyslexia. Traditionally, dyslexia has been explained by the phonological theory suggesting a single cognitive deficit in phonological skills (for a review, Snowling *et al.*, 2020), but without indicating a specific causal link responsible for this deficit. Despite of this, indeed specific phonological interventions improve phonological skills but do not transfer such improvement to the reading performance of children with dyslexia (Pennington, 2006; Torgesen & Wagner, 1992). On the other hand, dyslexia has been explained by changes in sensory-motor related approaches suggesting that such deficits in how sensory cues and motor activity integration disrupt the processes of reading automation. As a result, the temporal (Tallal, 1980), the magnocellular (Stein, 2001) and the cerebellar (Nicolson *et al.*, 2001) theories have been suggested.

There is a large literature showing that dyslexia is not solely related to reading and writing. Children with dyslexia also present several changes in tasks such as walking (Moe-Nilssen *et al.*, 2003), isometric force production and control guided by visual feedback (de Freitas *et al.*, 2014), and postural control (Brookes *et al.*, 2010; Patel *et al.*, 2010). A common feature among these tasks is that sensory cues provide a basis for coherent muscle activation considering environmental and task requirements (Barela *et al.*, 2014). This process is not trivial and instead is considerably challenging given that sensory cues are obtained from several sources and are subject to considerable change owing to all the variations that constantly occur in the environment, to continuously modify the coupling strength between the available sensory stimuli and the motor activation to perform even the simplest of daily activities.

The multisensory reweighting mechanism differs in children with developmental dyslexia, as recently shown (Razuk *et al.*, 2020), but despite difficulties in integrating sensory cues into appropriate muscle activation, can improve their performance improvement when sensory cues are enhanced. This has been already observed when improvement in reading was observed due to larger font size and space between letters (Zorzi *et al.*, 2012). Similarly, we showed that children with dyslexia can take advantage of guided eye movements to improve motor tasks, such as postural control (Barela *et al.*, 2020) and more applied force to resolve sensorimotor conflicting (Razuk *et al.*, 2020) in maintain upright stance.

Recently, we have shown the impact of specific interventions on reading speed in children with dyslexia. Virlet and colleagues observed a positive effect of a 9-month proprioceptive intervention, based upon prism glasses, oral neurostimulation, insoles and breathing instructions (Virlet *et al.*, 2024). Similar results were observed by employing a 2.5-month sensorimotor intervention based upon general motor activities with cognitive engagement in which children with dyslexia showed reading, and attentional and self-steam improvements (Barela *et al.*, 2025). A common and important improvement observed in both studies was improvement in eye movement patterns (Barela *et al.*, 2025; Virlet *et al.*, 2024), showing that any improvement in reading due to intervention in children with dyslexia is also related to eye movement pattern change.

Proprioceptive intervention in our previous work (Virlet *et al.*, 2024) is considered a global intervention towards correcting spatial multisensory integration disorders. However, recent preliminary data (Silva *et al.*, 2024) have shown that the use of active prisms might contribute to alleviate reading difficulties in children with dyslexia similarly to the proprioceptive intervention. Our results reassemble some other important preliminary data (Sampaio *et al.*, 2009). Therefore, the goal of this study was to examine the acute effect of active prims on reading speed of children with dyslexia. Our hypothesis is that active prisms will improve reading speed of these children.

Methods

Participants

Fifteen children with dyslexia (10.6 ± 2.1 year-old; 11 girls and 4 boys) participated in this study. Dyslexic children were recruited from local phonological clinicians after they had undergone a complete evaluation and dyslexia screening assessment including neurological, psychological, and phonological capabilities. Non-dyslexic children were recruited from the local community through personal contacts. Children's participation in the present study was conditional upon permission being given by parents, who signed an informed consent form. The local Institutional Ethical Committee reviewed and approved all the procedures employed in the study.

Procedures

Children and parents were invited to visit the laboratory when participants comfortably seated in a regular chair near a table. After a period of adaptation to the laboratory environment, children were asked to read structured texts. In order to read the texts, a chin support was fixated on a table with texts presented in a tablet (iPad 13") placed in front of this structure. Children were asked to place their chin and front head and read the text lines presented in this tablet positioned about 0.5 meter in front of them and at their eye level (Figure 1).

We used six texts taken from children's books for 7- to 10-year-olds, with a controlled random order of presentation. Four lines of text in Portuguese from a children's book were presented on a computer screen in front of each child. The paragraph contained 40 words and 174 characters. The text was 29° wide and 6.4° high, and the average character width was 0.5°. The text was written in black Courier font on a white background. The texts were adapted for children aged 7-9 years. Each child had to read the text silently, and at the end of each reading, the experimenter asked each child a few questions to ensure that they had read and understood the content of the text.

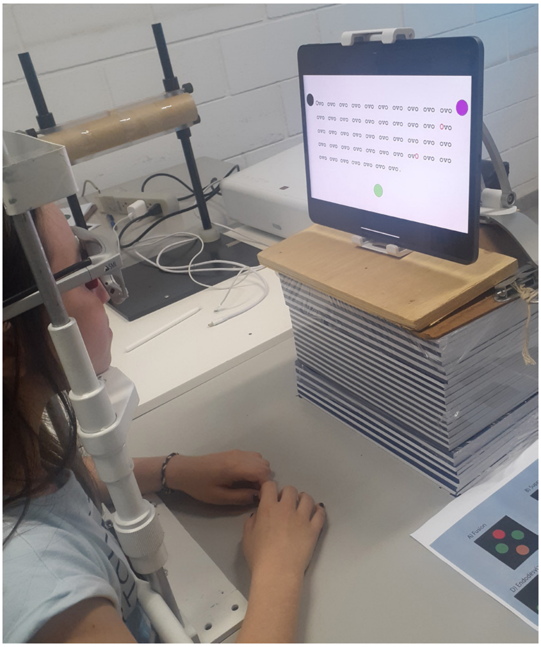

Figure 1. Representative picture showing a child positioned in front of the tablet with the text presented.

After reading the text, children were invited to laid down in a flat surface and their hip rotator muscle tonus was evaluated. Active prisms were employed to obtain hip rotator muscle tonus alignment (Figure 2) aiming to minimize sensorimotor impairments (Virlet *et al.*, 2024). After defining the corrective active prisms, children wore the prisms and read another text, with the same structure that the previous one in the same previous conditions.

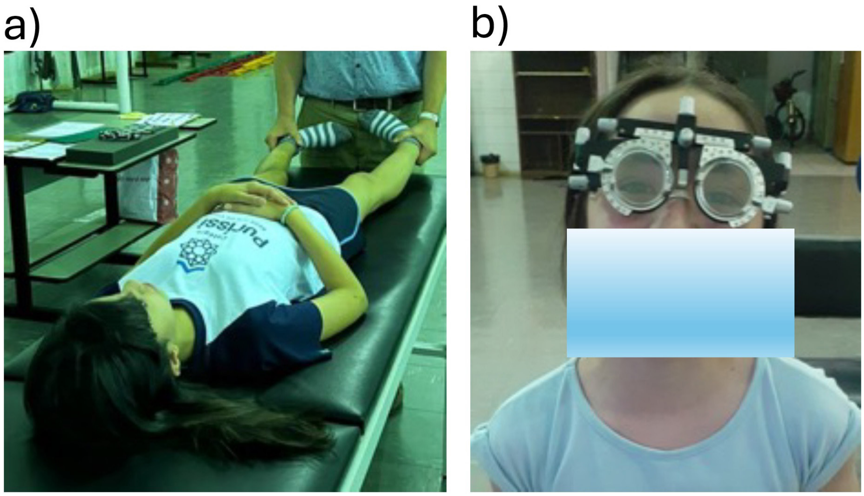

Figure 2. Representative pictures showing a child laying down and being tested regarding the hip rotator muscle tonus (a) and wearing the active prisms (b).

In all cases, total reading time was obtained as the time until the participant started reading the text until the participant had finished reading the text. Finally, total reading time was compared between conditions of without and with prims using a paired t test.

Results

Table 1 depicts the sex, age and total reading time without and with active prisms of all 15 participants. Test t depicted significant difference between reading with and without prism, t(14)=2.50, p=0.02, Cohn's d=0.64, with total reading time reduced from 87.8 to 56.3 seconds.

Table 1. Sex, age and total reading time with no prism and with prism.

Participants	Sex	Age (years)	No Prism (s)	With Prism (s)
1	Female	13.7	17.68	12.63
2	Female	11.6	310.39	147.32
3	Female	7.3	325.51	226.00
4	Male	12.8	24.56	24.23
5	Female	12.0	27.62	24.17
6	Female	9.3	182.17	97.57
7	Female	8.3	129.50	75.61
8	Male	10.4	48.50	40.52
9	Female	10.8	37.00	37.81
10	Male	14.8	29.50	17.10
11	Female	10.3	41.31	44.42
12	Female	11.1	25.50	16.37
13	Male	10.6	30.00	26.67
14	Female	8.7	25.84	25.16
15	Female	7.5	62.51	29.36
Mean		**10.6**	**87.8**	**56.3**
Standard Deviation		**2.18**	**103.72**	**59.49**

Because of the higher variability among children for total reading time, it is important to verify the behavior for each child (Figure 3). In this case, it is possible to identify that 13 children decreased the time when wearing the prism whereas only 2 children slightly increase the time. Moreover, for those who reduced the total reading time, eight children reduced more than 20% the total reading time when wearing the prism compared to with no prism.

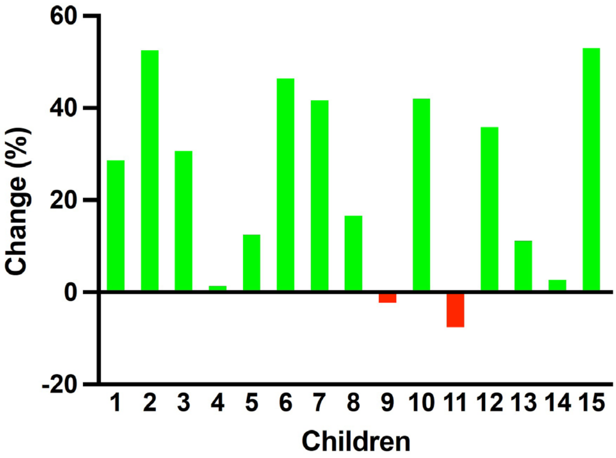

Figure 3. Individual change for each child in the comparison with no prism and with prism. Note: The green color indicates reduction, and the red color indicates increase in the total reading time comparing without and with active prisms.

Discussion

The goal of this study was to examine the acute effect of active prims on reading speed of children with dyslexia, and our hypothesis was that active prisms will improve reading speed of these children. Our results clearly supported this hypothesis as children wearing the active prisms read faster compared to the condition of no active prism. This result is in line with previous results, when reading speed was also improved in children with dyslexia, but advance our knowledge showing that such reading improvement can be observed shortly after wearing the prisms instead of after a few months of intervention.

Right after wearing the active prisms, correcting the unbalance of the hip rotator muscle tonus alignment, children improved reading speed. Besides the statistical group results, most of the children improved reading speed over 20% compared to the condition with no active prisms. Improvement in reading was also recently observed after a 9-month period of intervention aiming to minimize proprioceptive impairments (Virlet *et al.*, 2024). In this study, alignment of the hip rotator was also obtained, but due to active prisms, somatosensory lures acting through the trigeminal nerve, oral stimulation and breathing instructions. Results of this study advances our knowledge showing that solely employing active prisms already is sufficient to improve reading in most of the children with dyslexia who participated in this study.

Proprioceptive dysfunction has been observed in children with dyslexia (Da Cunha & Da Silva, 1986; Quercia *et al.*, 2007) that might be associate with multi-sensory integration disorder of spatial (Quercia *et al.*, 2015) and perceptive components (Quercia *et al.*, 2020) impacting besides reading performance of sensory motor tasks (Barela *et al.*, 2011; de Freitas *et al.*, 2014; Razuk & Barela, 2014). Fortunately, we have showed (Virlet *et al.*, 2024) that appropriate intervention, initially suggested as a global intervention (Quercia *et al.*, 2007), minimizes this multisensory integration disorder and children improve their reading performance. Our results indicate that minimization of this multisensory integration disorder might also be obtained, at least partially, by the active prisms. Moreover, the impact on reading, as results from this study showed, might even occur just after wearing the active prisms. In this study, reading performance was obtained right after adjusting the prism correction, based upon the hip rotator tonus alignment, showing the acute effect of such manipulation, different from results from our previous study when children wore the active prisms, along the other corrections, during 9-month period (Virlet *et al.*, 2024).

Although results from this study are promising, it would be interesting to examine eye movement during reading that unfortunately was not possible in this case. In our previous study, it was observed a clear change in eye movements after the proprioceptive intervention (Virlet *et al.*, 2024) similar to those observed in studies in which reading speed improved in children with dyslexia due to intervention (Barela *et al.*, 2025) or reading conditions (Razuk *et al.*, 2018). Unfortunately, it was not suitable to obtain eye movements with the active prisms during reading, but we could suggest that reading improvement would be related to better eye movement screening the text during reading, but it is an issue that needs further investigation and it is under way.

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Proprioceptive intervention positively affects visual attention of children with dyslexia after 21 months

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Abstract

Abnormal eye patterns and poor visual attention are often exhibited by children with dyslexia while performing reading and fixation tasks. Recently, many intervention programs, such as oculomotor exercises and visual attentional training have been tested to help attenuate or mitigate these difficulties. In the present study, our objective was to investigate the effects of the proprioceptive intervention in dyslexic children performing a fixation task. Our hypothesis was that children with the proprioceptive intervention would present better visual attention than dyslexic children only with a regular orthophonic intervention and equal results to a healthy control group. The proprioceptive intervention (which involves the use of prism glasses, oral neurostimulation, insoles and breathing exercises) was administered for 21.2 months (SD: 14.7), superimposed on a regular orthophonic intervention, for a group of 12 dyslexic children. Two other groups participated in this study: 20 dyslexic children with only the orthophonic intervention and 20 healthy children. All three groups (52 children) performed a basic fixation task (fixate a cross target in the middle of a fully white screen). Our results validated the initial hypothesis. Indeed, they showed that children with the proprioceptive intervention presented blink and saccade number and pupil dilation equivalent to healthy children; and that the dyslexic children only with the orthophonic intervention required higher blink and saccade number and pupil dilation than both other groups. Overall, the proprioceptive intervention had a positive impact on lowering cognitive workload in dyslexic children, thus showing a promising solution to reduce ocular difficulties in dyslexia.

Introduction

Children with developmental dyslexia often present several literacy difficulties, that vary in type and severity, including phonological and reading deficits: fluency, accuracy and comprehension (Richlan, 2020). Problems at the level of phonological representation and literacy skills often persist into adulthood, despite the access to a proper educational environment (Snowling, Hulme & Nation, 2020). It is well established that children with dyslexia exhibit abnormal eye movement patterns, i. e. significant more fixations of longer duration and significant more frequent saccades with smaller amplitude than typical children in fixation, saccadic and simple reading tasks (Bucci *et al.*, 2024; Bucci *et al.*, 2018). In addition, these children also present significant more blinks and greater pupil dilation during reading, which is tied to a heavier cognitive load, concentration and visual attention to perform the same task than healthy children (Ozeri-Rotstain *et al.*, 2020; Tooze, 2022). To help understand and overvome these difficulties, several strategies have been tested, such as visual training or adaptations to reading materials.

Bucci *et al.* (2018) conducted an oculomotor training with four exercises (rapid naming task, Stroop task, motion perception and saccades) for 8 weeks (15 minutes, 5-7 days a week) with infants with dyslexia. They found that infants with dyslexia exhibited a significant decrease in total reading time and fixation duration after such a training. Caldani *et al.* (2020) tested a 10-minute visual attentional training (pursuit, saccade and searching tasks) after a control reading task and before the experimental reading task. The results showed that the 10-minute visual attentional training helped infants with dyslexia to significantly decrease their total reading time, fixation duration and saccade number (in the second reading task in contrast to the first one). In terms of blinking and pupil size, Wang (2019) tested the efficiency of an E-learning environment for dyslexia. Students with dyslexia performed three reading tasks, with a visual and motivational training of 5-10 minutes between each task. Students with dyslexia presented a significant decrease in blink number and increased pupil size after the training in comparison to healthy students, meaning students with dyslexia became more concentrated and engaged in the learning process after the training session.

Another type of intervention that has shown promising results is the proprioceptive intervention, which is primarily aimed at correcting sensorimotor impairments. The proprioceptive intervention involves ocular correction with the use of prism glasses, and other strategies such as postural treatment, oral neurostimulation, use of insoles and breathing exercises (Quercia *et al.*, 2007). Virlet *et al.* (2024) administered this proprioceptive intervention to dyslexic children for 9 months, with a minimum of 25 sessions, each lasting half an hour. In this study, the dyslexic patients attended a medical appointment to adjust the prism and insoles and learn the breathing exercises, and then they only had to perform this exercises 10 minutes each morning, in addition to their regular orthophonic intervention. In Virlet *et al.* (2024), the authors tested the influence of the proprioceptive intervention in addition to the regular orthophonic intervention for reading performance in dyslexic children. The study showed i) equivalent reading performance between healthy children and dyslexic children performing both orthophonic and proprioceptive interventions and ii) significantly better reading performance in both previous groups than in dyslexic children who were not treated with the proprioceptive intervention. This previous study have shown a positive significant effect on the proprioceptive intervention in improving reading skills. However, to the best of our knowledge, no study has investigated the effects of the proprioceptive intervention on eye movements and visual/cognitive load in children with dyslexia.

In the present study, our objective was to test the effects of a proprioceptive intervention on eye movements and visual attention in dyslexic children. We tested three groups: i) children treated with the proprioceptive intervention in addition to a regular orthophonic intervention; ii) children treated only the orthophonic intervention; and iii) typical children, as a control group. The children performed a basic fixation task, in which they had to fixate the gaze on a black target in the middle of a white screen. Our main hypothesis was that children with the proprioceptive and orthophonic interventions would i) present significantly less demand for visual attention (less blinks, decreased pupil dilation) and eye movements closer to normal (less fixations with smaller duration, less saccades with larger amplitude) than the children only with the orthophonic intervention and ii) equivalent results to the control group.

Methods

Participants

G*power was used to calculate the required sample size for detecting a main effect of group between dyslexic and healthy children. Based on the results published by Sacaklidir *et al.* (2025) (who performed a stationary gaze task on firm surface, as in our study), and using a t-test for independent sample, the power analysis determined that approximately 28 participants are needed to achieve 80% power at an alpha level of 0.05.

The present study included three groups (n = 52): dyslexic children with proprioceptive and orthophonic intervention (POI group, n = 12, 7 boys, 5 girls, mean age 145.16 months old); dyslexic children only with orthophonic intervention (OI group, n = 20, 7 boys, 13 girls, mean age 132.35 months old); and healthy control children (CO group, n = 20, 15 boys, 5 girls, mean age 142.05 months old).

For the inclusion criteria, all participants had to be native French-speakers, who atentted the French educational system, and were between 9-13 years old. They also had a labile vertical heterophony at the proprioceptive Maddox test, and normal or corrected-to-normal vision (wore glasses, contact lenses). Children with dyslexia were asked to bring their medical diagnose report to confirm their dyslexic condition and, at the day of the study, had to score higher than 2 standard deviations at the C-index of the Alouette-R test. For the non-inclusion criteria, children in the dyslexic groups should not have any neurodevelopmental issues (other than dyslexia), and healthy children should not have any neurodevelopmental issues nor proprioceptive dysfunction. Children in all groups should not have medical issues for standing balance nor psychiatric conditions. Furthermore, all children should have an optic correction (if required) lower than +/- 0.75 dioptries and could not show any pathological score at the Parinaud (P2) test (for close vision).

A written informed consent form was signed by participants and their parents before the experiment, which was approved by the Regional Ethical Committee NoSyDys (n°2020_1460).

Experimental tasks

Apparatus

In order to project the fixation task, three video projectors (Philips NeoPix Easy 2+, resolution of 1280×720 pixels) were used. Together, they projected a single image (3840×768 pixels) onto a white panoramic screen (3m wide and 1m high). An eye-tracking system (Pupil Labs CORE, Berlin, Germany, consisting of two infrared cameras with 192×192 pixels of resolution, acquisition frequency of 240 Hz) was used to collect ocular data.

A main computer running MATLAB (MathWorks Inc., Natick, MA, USA, 2010; version 7.10.0; R2010a) was used with a customized script to present the task, record the trials, collect the data and process all the systems.

Task and instructions

The experiment consisted of a basic fixation task (Figure 1), with two trials of 30 sec of duration. To complete the task, the children had to fixate the gaze on a black target (size: 3° diameter) projected in the middle of a full white screen (composed of three panels measuring 1 m left-right and 60 cm up-down each). Children were standing in a comfortable, relaxed position, with their arms on the side of their bodies. The whole experiment had a total time of approximately 20 minutes.

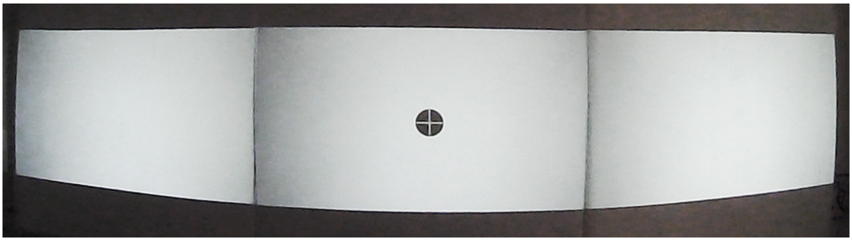

Figure 1. Representation of the basic fixation task.

Procedures

The lights in the room where the experiment took place were turned off. As they arrived, the children were equipped with the eye-tracking glasses. They were positioned at a viewing distance of 2.14 m from the screen, with a visual angle of 70° left-right and 16° up-down. The eye-tracking was calibrated and then the child proceeded to perform both trials in the fixation task, provided that they could rest as long as they needed between the trials.

Dependent variables

Number of blinks and pupil size were used as measures of visual attention, as they often determine areas of interest and suggest more or less efficiency in visual activities (Mahanama *et al.*, 2022). In fact, greater pupil dilation and lower blinking rate indicate a heavier cognitive load while performing certain activities. Thus, blinks were detected by a rapid closing and reopening of the eyelid, when the pupil was obscured and then becomes visible again. In turn, the pupil size was obtained with a cleansing signal method using linear interpolation and Hanning window smoothing after removing blinks and other events. From that, we calculated the mean pupil size and the mean pupil diameter change (MPDC).

For eye movements, the eye-tracker collected the number and duration of fixations. A dispersion threshold was used to detect the fixations, considering the degrees of visual angle with a minimum duration of 100 ms. The fixation duration was obtained considering the difference between the initial timestamps of consecutive fixations with the subtraction of the saccade interval. Saccades were not directly provided by the eye-tracker, so a Python script was employed to detect them. The script is based on the Identification Velocity-Threshold (I-VT) algorithm (Andersson *et al.*, 2017) and it calculates the velocity between each gaze point at each timestamp. The velocity should be higher than 45°/s and the amplitude higher than 0.65° (the size of the center of the target used in the tasks) to be counted as an unwanted saccade.

Statistical analyses

Outliers, that is, extreme values that were two standard deviations outside the quartiles were identified for all the variables prior to the statistical analysis (Tabachnik & Fidell, 2006, pp. 76–77, 92, 100).

Shapiro-Wilk tests revealed that the data for saccade number and amplitude and blinks did not comply with normality assumptions, and were then transformed using natural log. After that, we conducted our statistical analyses using ANOVAs (with the basic fixation task and the three groups of participants as factors for each of the dependent variables). When necessary, Holm-Bonferroni post-hoc tests were used. All analyses were performed at the level of significance at 0.05. All the statistical analyses were conducted with JASP 0.19.3 package.

Results

Outliers

We identified 0.86% outliers for group OI, 1% for group CO, and 1.25% for group POI in the ocular data. These outliers were not considered for statistical analyses.

Visual attention and eye movements

Number of blinks and pupil size

Figure 2 shows number of blinks and pupil size for all three groups (POI, OI and CO). In terms of number of blinks, ANOVA showed a significant effect of group ($F (2, 49) = 7.08$, $p = 0.002$). Post hoc tests showed that OI had significantly higher number of blinks than CO ($p = 0.004$) and POI ($p = 0.01$). ANOVA did not show significant group and visual task interaction ($F (2, 49) = 0.49$, $p = 0.61$; Fig. 2a). For pupil size, ANOVA showed a significant effect of group ($F (2, 22) = 7.54$, $p = 0.003$). Post hoc tests showed that OI had significantly higher pupil size than the CO (p = 0.004) and the POI (p = 0.016). Finally, ANOVA did not show group and visual task interaction (F(2, 22) = 0.41, p = 0.66; Fig. 2b).

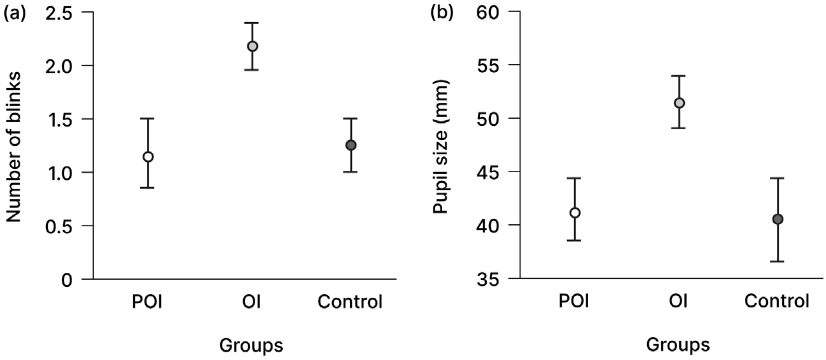

Figure 2. Mean and standard deviation of number of blinks (a) and pupil size (b) for the proprioceptive and orthophonic intervention (POI), orthophonic intervention (OI) and control groups.

Number and amplitude of saccades

Figure 3 depicts number and amplitude of saccades for all three groups (POI, OI and CO). Regarding number of saccades, ANOVA showed a significant main effect of group (F (2, 49) = 3.79, p = 0.029). Post-hoc tests showed that the OI group had significantly higher number of saccades than the CO (p = 0.04). However, ANOVA did not show group and visual task interaction (F (2, 49) = 0.83, p = 0.44; Fig. 3a). For saccade amplitude, ANOVA showed a significant effect of group (F (2, 49) = 5.76, p = 0.006). Post hoc tests showed that OI had significantly larger saccade amplitude than CO (p = 0.009) and POI (p = 0.027). However, ANOVA did not show group and visual task interaction (F (2, 49) = 0.71, p = 0.49; Fig. 3b).

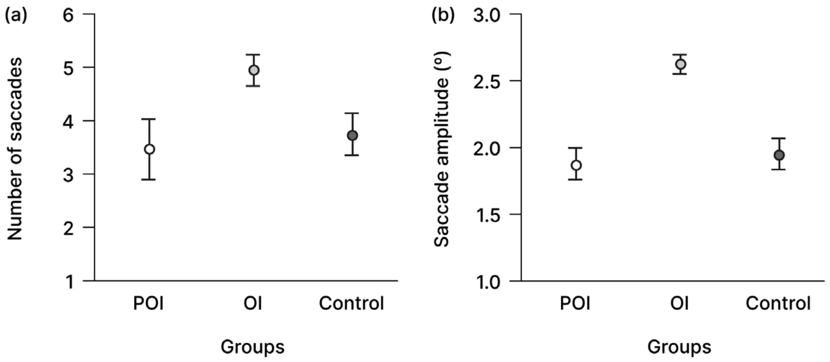

Figure 3. Mean and standard deviation of number (a) and amplitude (b) of saccades for the proprioceptive and orthophonic intervention (POI), orthophonic intervention (OI) and control groups.

Number and duration of fixations

Figure 4 depicts number and duration of fixations for all three groups (POI, OI and CO). For number of fixations, ANOVA did not show a significant effect of group, F (2, 49) = 0.74, p = 0.48, nor group and visual task interaction, F (2, 49) = 0.05, p = 0.95 (Fig. 4a). Also, for fixation duration, ANOVA did not show a significant effect of group, F (2, 49) = 2.13, p = 0.12, nor group and visual task interaction, F (2, 49) = 0.07, p = 0.92 (Fig. 4b).

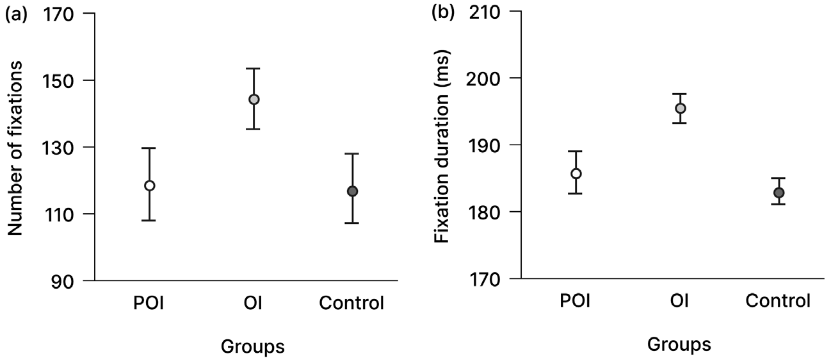

Figure 4. Mean and standard deviation of number (a) and duration (b) of fixations for the proprioceptive and orthophonic intervention (POI), orthophonic intervention (OI) and control groups.

Discussion

In the present study, we aimed to test the effects of the proprioceptive intervention on eye movements and visual attention of children with dyslexia. Our results showed that the POI group presented significantly less blinks, reduced pupil size, decreased number and amplitude of saccades than the OI group, and that these measures were also equivalent to the CO group.

Proprioceptive intervention leads to better visual attention

Our hypothesis was that children in the POI group would i) present significantly less demand for visual attention (less blinks, decreased pupil dilation) than the OI group and ii) equivalent results to the control group. Our results validated that hypothesis. Firstly, the POI group exhibited significantly less blinks (Figure 2a) and significantly reduced pupil size (Figure 2b) than the OI group. Consistent with the literature, our results showed that children in the POI group required less cognitive and visual attention to perform the fixation task than the OI group. In fact, in the literature reports, blink rate is recognized as an indicator of workload (Wang, 2019; Ozeri-Rotstain *et al.*, 2020). Our results with blink rates were in line with Wang's (2019) findings, whom reported decreased blink number in dyslexic children during reading after a visual and motivational training.

Secondly, and also as expected, the POI group showed significantly lower pupil dilation than the OI group (Figure 2b). Pupil diameter usually increases with the cognitive load required to perform certain activities, and is also connected to fatigue, stress and motivation levels (Le Cunff, Dommett and Giampietro, 2023). The novelty in our study was to demonstrate that the proprioceptive intervention can cancel the dyslexic-related impairment in pupil behavior found in a fixation task. Other studies showed that dyslexic students could increase pupil size after a motivational training when performing reading tasks, meaning they became more concentrated (Wang, 2019). Altogether, all these results show that training and/or proprioceptive intervention can favor an improvement in cognitive load.

Overall, our results showed that the POI group performed the fixation task as the CO group and better than the OI group in considering blinks and pupil size. Normally, fewer attentional resources are available in children with dyslexia when they are exposed and process a particular visual stimulus (Kristjánsson and Sigurdardottir, 2023). Hence, our results confirmed the beneficial effects of the proprioceptive intervention in reducing cognitive workload and need for high visual attention in dyslexic children. To the best of our knowledge, these patterns of results with blink and pupil size contrasting groups with/without the proprioceptive intervention and a control group are novel in the literature.

Saccade number closer to normal with the proprioceptive intervention

Our hypothesis was that children in the POI group would i) exhibit eye movements closer to normal (less fixations with smaller duration, less saccades with larger amplitude) than the OI group and ii) equivalent results to the control group. Our results validated our hypothesis only for saccade number. In fact, regarding eye movements, our results indeed showed that the POI group exhibited significantly fewer number of saccades (Figure 3a) and smaller saccade amplitude (Figure 3b) than the OI group and equivalent ones to the CO group. In terms of number of saccades, our results were consistent with Caldani *et al.* (2020) who reported significant difference in saccade number for a reading task after a visual attentional training. Barela *et al.* (2020) also found a significant decrease in saccade number, using both a fixation task and a visually-guided eye movement task.

In terms of saccade amplitude, we are not aware of any published study showing similar result in a fixation task. Virlet *et al.* (2024) reported larger saccade amplitude in dyslexic children after a proprioceptive intervention but their dyslexic and healthy children performed a reading task and not a fixation one. The contrast between our results and Virlet *et al.*'s (2024) might be explained by the fact that reading and non-reading tasks depend on different brain regions and mechanisms (such as the dorsal visual pathway, which plays a crucial role in visual attention and eye movements) (Kristjánsson and Sigurdardottir, 2023). Variations in the magnocellular input may cause differences in attentional processing during reading and other types of visual stimuli. The novelty in our study was to find that the proprioceptive intervention also had some positive effects in eye movements in tasks other than reading: i.e. fixation task.

Limitations, opening and conclusion

A first limitation in the present study concerns the sample size. Our results would have been more generalizable if we had included a larger sample, with participants more evenly distributed between groups (with and without proprioceptive intervention). In addition, it could be interesting to include a more diverse sample, with different age ranges, levels of literacy, languages and/or cultural contexts (Coenen *et al.*, 2024). A second limitation is that we transformed some of our data using natural log to comply with normality assumptions. Better it is at the statistical level if a future research can validate our results again without any data transformation.

For recall, our main results show that the POI group exhibited less cognitive workload, visual attention and saccade number than the OI group and equivalent results to the CO group in performing a basic fixation task. These findings indicate that, after a proprioceptive intervention of 21 months, the dyslexic children were able to significantly improve their eye movements (saccade number) and visual attention (blinks and pupil size). We should mention that, by itself, the proprioceptive intervention is not demanding and/or constraining as it only requires the patient to attend one medical appointment to adjust prism glasses and insoles and receive instructions on how to perform the breathing exercises. Then, the dyslexic patient only has to perform breathing excercices 10 minutes a day each morning and attend their classical orthophonic intervention appointments (once a week, in general). Our findings thus show beneficial effects of the proprioceptive intervention to approach dyslexia visual impairments.

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

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Abstract

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

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

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 breaking 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.

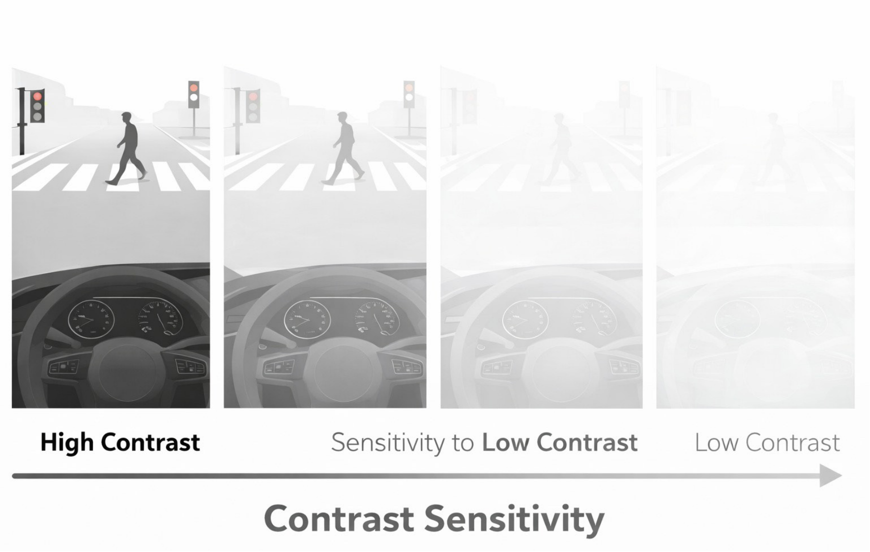

Figure 1. Example of contrast sensitivity during car driving.

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.

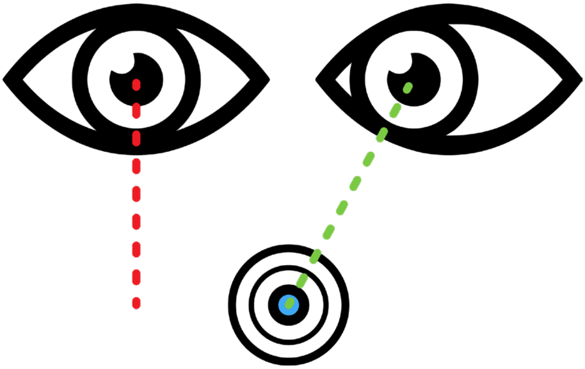

Figure 2. An example of convergence insufficiency, a condition marked by the inability of the eyes to move in unison, manifests as a disruption in the synchronization of ocular movements, thereby impeding the efficient scanning of visual targets.

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

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).

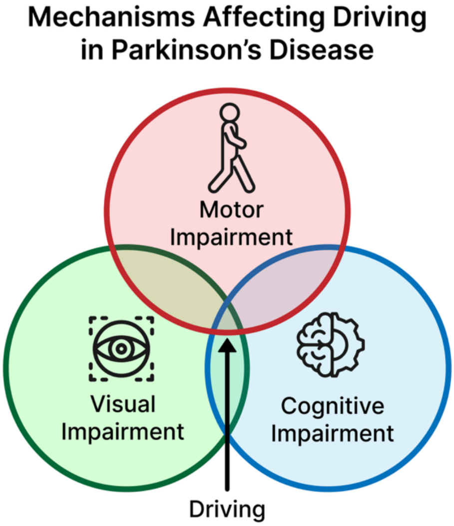

Figure 3. General mechanism that affects driving in individuals with Parkinson's disease.

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.

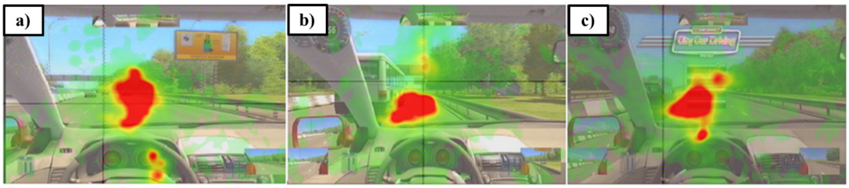

Figure 4. Heat maps representing the relative density of visual fixation for: a) younger drivers; b) older healthy drivers; and c) PD drivers. Cooler colors (green) indicate less visual activity, while hotter colors (red) indicate areas where more time was spent gazing. *Source: Gotardi et al. (2022);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

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). n 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

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.

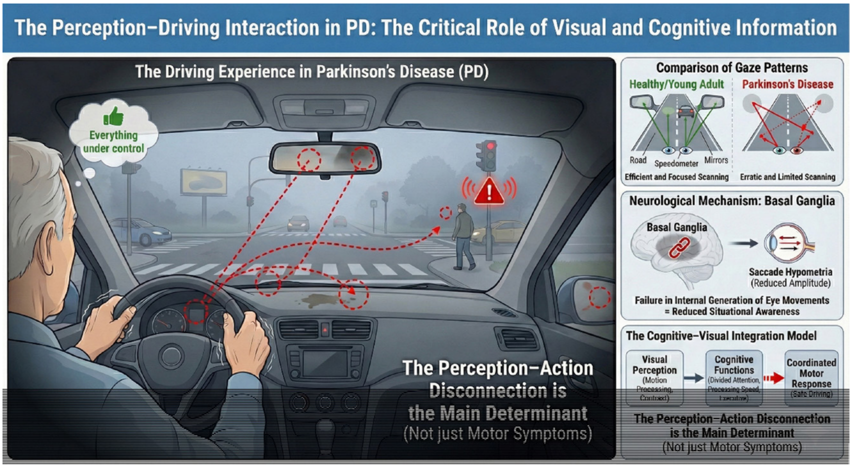

Figure 5. The perception–driving interaction in Parkinson's Disease. The central panel illustrates the driving experience and perceptual deficits. Side panels detail: (A) Comparison of gaze patterns between healthy adults and PD drivers; (B) Basal ganglia involvement in saccadic control; and (C) The 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 rompts 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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Characterization of eye movements and their impact on postural control in Parkinson's disease

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Abstract

More than 75% of individuals with Parkinson's disease (PD) exhibit impaired eye movement functions. The most frequently impacted eye movements are saccades and smooth pursuit. These oculomotor impairments have been directly associated

with postural instability in PD, reflecting a broader association between visual perception deficits and balance. This establishes a direct mechanistic link in which impaired vision exacerbates motor deficits, thereby significantly elevating the risk of falls. Despite the substantial scientific rationale supporting a relationship between eye movement impairments and reduced postural control in pwPD, a comprehensive synthesis of the current evidence on specific oculomotor deficits and their impact on postural control in PD is still lacking. Therefore, this chapter characterizes eye movements and their subsequent impact on postural control in individuals with PD. It begins by outlining the neuroanatomical regions most impacted by the disease and the manner in which these pathologies manifest as visual impairment. Specifically, this chapter discussed three primary oculomotor deficits: saccadic dysfunction, smooth pursuit eye movement, and convergence insufficiency. Subsequently, an exploration of postural control mechanisms and their degradation in PD issues, with particular emphasis on the role of dopaminergic neurodegeneration. The chapter further explored postural impairments, including deficits in static, dynamic, and anticipatory postural adjustments, as well as reactive postural responses. Finally, the critical interplay between visual input and postural control was analyzed, including the complex impact of medication. Crucially, it argues that although visual impairments often exacerbate postural instability, the visual system remains a highly plastic and effective target for rehabilitation to enhance postural control in PD.

Introduction

Parkinson's disease (PD), the second most common neurodegenerative disease, is characterized by motor impairments such as tremor, rigidity, bradykinesia, and postural instability (Magrinelli *et al.*, 2016; Yang *et al.*, 2016). In addition to these motor features, non-motor symptoms such as visual and cognitive impairments have also been reported in this population (Weil *et al.*, 2016; Ekker *et al.*, 2017). Indeed, vision is among the main contributors to quality of life (Leissner *et al.*, 2014). As PD progresses, 78% of individuals with PD (pwPD) report at least one visual symptom, such as difficulty reading, sometimes with double vision, and misjudging objects and distances (Archibald *et al.*, 2011; Urwyler *et al.*, 2014).

Anatomically, the basal ganglia regulate the oculomotor control through the substantia nigra - superior colliculus pathway. This pathway includes the pars compacta and pars reticulata. The GABAergic neurons in the pars reticulata typically inhibit neuronal activity in the superior colliculus and thalamus (DiChiara *et al.*, 1979; Yoshida & Omata, 1979; Chevalier *et al.*, 1981). These neurons act as a gate, allowing collicular burst neurons to signal the brainstem and generate saccadic eye movements (Sparks & Hartwich-Young, 1989; Moschovakis *et al.*, 1996). In the classical model, this gating process is orchestrated by two parallel circuits: the direct and indirect pathways (Calabresi *et al.*, 2014) (Figure 1).

The striatum integrates inputs from cortical regions - including the frontal, supplementary, and parietal eye fields - and modulates basal ganglia output based on dopaminergic signaling. In the direct pathway, D1-receptor neurons provide direct inhibition to the basal ganglia output nuclei, which are the internal globus pallidus (GPi) and the substantia nigra pars reticulata (SNr). Conversely, the indirect pathway involves D2-receptor neurons that modulate the GPi/SNr via external globus pallidus and subthalamic nucleus (DeLong & Wichmann, 2007). The SNr then inhibits the superior colliculus. In PD, dopaminergic depletion disrupts this balance, resulting in a shift toward indirect pathway dominance. The resulting SNr hyperactivity leads to excessive superior colliculus inhibition, likely driving the oculomotor deficits characteristic of the disease (Terao *et al.*, 2013).

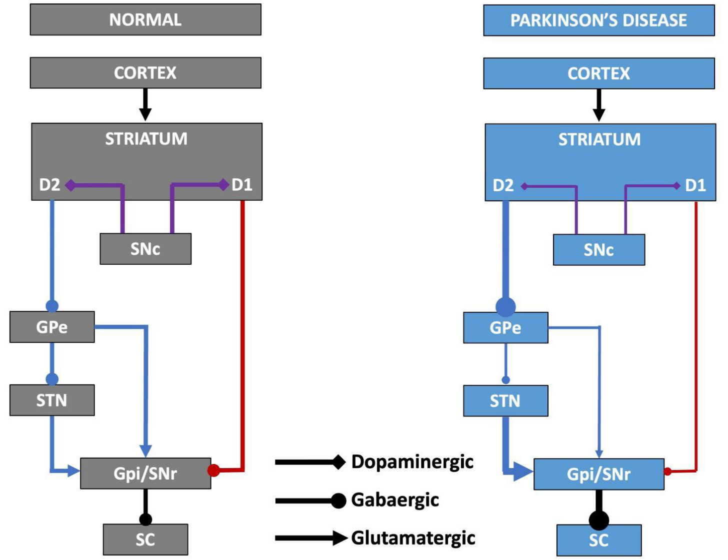

Figure 1. Basal ganglia circuitry in neurologically healthy individuals (gray) and individuals with PD (blue). Cortical inputs converge on the striatum, where the substantia nigra pars compacta dopamine (violet connectors) targets the D1 (direct pathway—red connectors) and D2 (indirect pathway—blue connectors) receptors. The direct pathway has been shown to inhibit the internal globus pallidus/ substantia nigra reticulata, while the indirect pathway modulates it via the external globus and subthalamic nucleus. In PD, dopaminergic depletion triggers a functional imbalance, characterized by reduced inhibition through the direct pathway and increased excitation via the indirect pathway. This imbalance results in excessive substantia nigra reticulata inhibition onto the superior colliculus. SNc: substantia nigra pars compacta; GPe: external globus pallidus, STN: subthalamic nucleus; GPi: internal globus pallidus; SNr: substantia nigra reticulata; SC: superior colliculus.

Functionally, deficits in eye movements have been reported in more than 75% of pwPD (Armstrong, 2015; Frei, 2021). The most frequently impacted oculomotor functions are saccades (rapid eye movements utilized to transition between targets) and smooth pursuit eye movement (SPEM) (movements that maintain a static object's fixation on the retina) (Armstrong, 2015; Frei, 2021). Saccade abnormalities include hypometria and delayed initiation, while SPEM is often slow and saccadic (Armstrong, 2015; Frei, 2021). These oculomotor impairments indicate an underlying dysfunction with the oculomotor frontal-subcortical circuits, which are closely linked to visuospatial processing, working memory, and execution (Ghazi-Saidi, 2020).

These oculomotor impairments have been directly associated with postural instability in PD (Uc *et al.*, 2009; Hamedani *et al.*, 2019), reflecting a broader association between visual perception deficits and balance control (Lee *et al.*, 2025). As pwPD increasingly rely on visual information to compensate for their impaired postural sway control (Rinalduzzi *et al.*, 1995), poor oculomotor coordination has the potential to exacerbate their instability. Specifically, deficits in saccades and SPEM disrupt the stable processing of visual information necessary for balance (Armstrong, 2011; Frei, 2021). This creates a direct mechanistic link where impaired vision compounds motor deficits, significantly elevating the risk of falls (Lord *et al.*, 1994, 1999).

Despite the substantial scientific rationale supporting a relationship between eye movement impairments and reduced postural control in pwPD, a comprehensive synthesis of the current evidence on specific oculomotor deficits and their impact on postural control in PD is still lacking. Therefore, this chapter aims to characterize the main eye movement impairments in pwPD, and to present their relationship with postural control. Therefore, the chapter is divided into three parts. First, a detailed description of the primary eye movement–related visual symptoms observed in pwPD is provided. Secondly, the definition of postural control is provided, along with an exposition of the deficits associated with PD. Finally, the discussion will address the influence of eye movement impairments on overall postural control in pwPD.

Vision and Parkinson's Disease

Visual dysfunction is a highly prevalent non-motor symptom in PD that directly compromises the visual guidance required for maintaining balance. These deficits manifest in a range of symptoms, including oculomotor impairments (eye movement control) and sensory and perceptual losses. This section will detail these common visual deficits in pwPD (Figure 2).

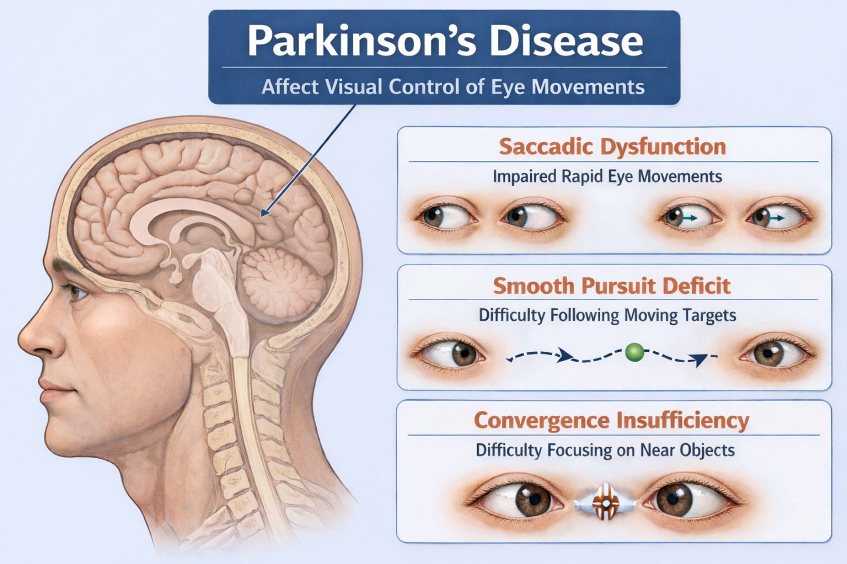

Figure 2. Changes in the brain's basal ganglia can interfere with visual control of the eye movements: saccadic, smooth pursuit, and convergence insufficiency. Adapted from an image generated by OpenAI (2026).

Oculomotor (eye movement) abnormalities

Saccadic

Saccadic movements, defined as the ballistic eye movements that rapidly redirect the high acuity fovea of the retina toward new visual targets, have been employed as a diagnostic tool in PD. Comparing the saccadic direction, the vertical eye movements are more challenging than the horizontal eye movements, resulting in a delayed gaze response (Waldthaler *et al.*, 2019). Clinically, these movements helped differentiate PD from atypical Parkinsonian syndromes (Termsarasab *et al.*, 2015), where up to 75% of pwPD will exhibit abnormal saccadic and SPEM (Shibasaki *et al.*, 1979). Specifically, pwPD exhibited reduced saccade amplitude, prolonged latencies, and longer time to achieve a specific target (Mosimann *et al.*, 2005; Terao *et al.*, 2013). The impairment of antisaccade latencies has been related to an indirect marker of impaired anticipatory postural adjustments (Ewenczyk *et al.*, 2017). As the disease progressed, both saccade amplitude and latency got worse (Terao *et al.*, 2011). Furthermore, compared with neurologically healthy controls, pwPD presented more directional antisaccade errors (Briand *et al.*, 1999), along with a notable decrease in visually guided saccades, particularly in the upward hypometric direction (Waldthaler *et al.*, 2019). This reduction in control forces pwPD to execute multiple correction saccades to reach a visual target (Kimmig *et al.*, 2002).

Anatomically, saccadic impairments involve the brainstem and the basal ganglia levels (Ewenczyk *et al.*, 2017) that mediate saccade amplitude and latency (Terao *et al.*, 2013), while the cerebellum is involved in saccade accuracy (Beh *et al.*, 2017). Functionally, saccadic eye movements facilitate the accurate shifting of gaze, a process that is critical for visual perception and motor control (Stoffregen *et al.*, 2006). In PD, the loss of dopaminergic neurons disrupts this circuitry. The resulting depletion of dopamine causes a shift in the basal ganglia's output: increased activity in the indirect pathway (via the subthalamic nucleus) combined with reduced activity in the direct pathway leads to excessive inhibition of SNr/GPi (DeLong & Wichmann, 2007). This over-inhibition is the primary driver of abnormal saccadic performance in PD.

The role of levodopa in the management of this visual impairment remains unclear and controversial. While certain studies have documented prolonged prosaccade latencies (Michell *et al.*, 2006; Hood *et al.*, 2007), other investigations have failed to show any significant effect from dopaminergic medication (Nakamura *et al.*, 1991). Conversely, several studies have demonstrated that medication can enhance saccadic parameters by decreasing error rates in voluntary saccadic tasks and enhancing prosaccade accuracy and amplitude (Gibson *et al.*, 1987; Rascol *et al.*, 1989; Hood *et al.*, 2007).

Smooth Pursuit Eye Movements

SPEM, which enable an individual to maintain a moving object's fixation on the fovea, represent a prevalent and early oculomotor deficit in PD (Armstrong, 2015). These deficits are highly prevalent, affecting up to 67% of pwPD compared to only 20% of neurologically healthy individuals (Shibasaki *et al.*, 1979). This impairment frequently complicates the maintenance of repetitive actions for individuals with PD, resulting in a diminution of magnitude of the eye response and an overall decline as the stimulus is repeated (Armstrong, 2015).

Anatomically, the basal ganglia have been demonstrated to play a role in efficient and automatic SPEM performance (Fukushima *et al.*, 2017). Specifically, the SNr modulates both saccades and SPEM (Basso *et al.*, 2005). These deficits manifest as impaired movement speed, latency, and accuracy (Frei, 2021). Quantitatively, pwPD demonstrated reduced SPEM gain (eye velocity relative to target velocity) (Frei, 2021), suggesting a form of ocular bradykinesia - or slowness of eye movement (Shibasaki *et al.*, 1979). Furthermore, the initiation of SPEM is often accompanied by a prolonged latency period (Rottach *et al.*, 1996; Ladda *et al.*, 2008; Helmchen *et al.*, 2012), and the correlation between eye movements and target movement (accuracy) is less precise in pwPD (Bareš *et al.*, 2003). As stated previously, SPEM are imperative for stabilizing the visual scene. The resultant oculomotor bradykinesia—which is characterized by reduced gain and accuracy—directly compromises visual input. This, in turn, exacerbates postural instability and increases the risk of falls. Furthermore, as the PD progresses, SPEM velocity generally tends to decrease (Rascol *et al.*, 1989; Lekwuwa *et al.*, 1999).

It is noteworthy that the direction of SPEM in PD is of particular interest, as abnormalities are more pronounced in the vertical direction (up and down) than in the horizontal direction. Abnormalities in the vertical up direction were found in 54% of cases, while 50% exhibited abnormalities in the vertical down direction, compared to 37% in the horizontal direction (Corin *et al.*, 1972). Moreover, deficits in the SPEM are amplified during higher-level tasks, such as tracking a remembered target or relying on visual cues for target selection (Fukushima *et al.*, 2015). With regard to drug treatment, the role of levodopa in SPEM remains inconclusive. Some studies have demonstrated improvement in SPEM with dopaminergic medication (Corin *et al.*, 1972; Bareš *et al.*, 2003; Marino *et al.*, 2010), while others have reported no significant difference (Rascol *et al.*, 1989; Ladda *et al.*, 2008).

Convergence Insufficiency

Convergence insufficiency (CI) and its associated abnormalities are common and well-documented features in PD (Ekker *et al.*, 2017; Pretegiani & Optican, 2017; Savitt & Aouchiche, 2020; Sun *et al.*, 2023). Vergence —defined as the simultaneous movement of the two eyes in opposite directions—is deficient in PD, thereby compromising depth perception and spatial navigation (Sun *et al.*, 2023). Vergence abnormality may result in strabismus and blurred or double vision (diplopia) (Savitt & Aouchiche, 2020; Sun *et al.*, 2023). Vergence abnormalities in pwPD include increased latency (which is longer in vergence of eye movement), decreased velocity, and decreased gain (amplitude/accuracy) (Sun *et al.*, 2023). PwPD appears to affect disparity-driven vergence significantly differently when compared to neurologically healthy individuals (Sun *et al.*, 2023). However, reported that blur-driven vergence is comparable between neurologically healthy individuals and pwPD (Sun *et al.*, 2023). Furthermore, as a compensatory strategy, pwPD tends to utilize saccadic movements to compensate for deficits in disparity-driven vergence (Sun *et al.*, 2023). The decreasing vergence velocity gain in PD has been found to correlate with the propensity for generating these compensatory saccadic eye movements (Sun *et al.*, 2023), which may affect postural control.

Postural Control and Parkinson's disease

Postural control is a complex sensorimotor process that integrates visual, vestibular, and proprioceptive information to maintain balance and body stability (Rinalduzzi *et al.*, 2015; Feller *et al.*, 2019). In PD, this control system is significantly impaired due to neurodegenerative changes that primarily affect the basal ganglia, which are fundamental structures for the automatic regulation of posture and movement (Rinalduzzi *et al.*, 2015; Takakusaki *et al.*, 2022). The degeneration of dopaminergic neurons in the substantia nigra pars compacta alters striatal neuronal activity and its downstream targets within the thalamo-cortical circuitry of the basal ganglia, leading to the hallmark motor symptoms of the disease (Takakusaki *et al.*, 2022; Bath & Wang, 2024). In addition, the basal ganglia have shown to have downstream GABAergic projections to the thalamus and brainstem, including the pedunculopontine nucleus. These projections have been found to send cholinergic outputs to several motor control centers (Bath & Wang, 2024).

Deficits in postural control in PD manifest across multiple dimensions, including static, dynamic, anticipatory, and reactive control (Rinalduzzi *et al.*, 2015; Bath & Wang, 2024). During static postural control (quiet standing), pwPD exhibit significant variations in postural sway, characterized by augmented displacement in the anterior–posterior and medio-lateral directions when compared with neurologically healthy individuals (Bath & Wang, 2024). These sway metrics have been associated with disease progression and with scores on the MDS-UPDRS (Bath & Wang, 2024). Additional alterations in static postural alignment frequently observed in PD, such as truncal rigidity, stooped posture, and increased co-activation of trunk and lower limb muscles, further contribute to dysfunctional postural responses (Bath & Wang, 2024).

A particularly affected domain in PD involves anticipatory postural adjustments (APAs), which consist of stereotyped and highly regulated muscle activations that shift the center of pressure (CoP) toward the swing leg while stabilizing the body's center of mass over the stance leg in preparation for stepping or turning (Bath & Wang, 2024; Hou *et al.*, 2024; Seuthe *et al.*, 2024). Force plate and inertial sensor assessments of APAs during gait initiation frequently indicate that pwPD present variable and hypometric APAs with dysfunctional timing (Faria *et al.*, 2023; Bath & Wang, 2024; Hou *et al.*, 2024; Seuthe *et al.*, 2024). This dysfunction is directly linked to the phenomenon of freezing of gait (FOG). PD individuals who experienced FOG demonstrated poorer postural control compared with those who do not experience FOG and with neurologically healthy controls (Hou *et al.*, 2024; Onuma *et al.*, 2024). Evidence further suggests that delayed and reduced-magnitude APAs are particularly evident in individuals with FOG, indicating that the APA ratio may serve as a potential biomarker of postural adjustment capacity (Onuma *et al.*, 2024).

Reactive postural responses are also significantly impaired in PD, as evidenced by weakened and delayed automatic responses to postural perturbations, fragmented muscle activation patterns, and disrupted sequencing of muscle recruitment (Rinalduzzi *et al.*, 2015). When exposed to perturbations, pwPD demonstrate increased amplitude of the medium-latency response, which correlates with disease severity, as well as an earlier onset of the long-latency response (Rinalduzzi *et al.*, 2015). The standard sequence of recruitment, from distal to proximal, is inverted, with the activation of the hip muscles preceding that of the ankle muscles. This reversal has been shown to increase limb rigidity and prevent appropriate corrective movements (Rinalduzzi *et al.*, 2015). Consequently, this altered muscle activation sequence leads to less effective postural responses, exacerbating postural instability and fall risk (Rinalduzzi *et al.*, 2015).

Sensory integration, which is crucial for postural control, is also profoundly altered in PD. PwPD display greater reliance on visual information and are often unable to maintain balance when visual cues are absent, unreliable, or in conflict with vestibular and proprioceptive inputs (Vaugoyeau *et al.*, 2007; Rinalduzzi *et al.*, 2015; Feller *et al.*, 2019). Proprioceptive deficits are particularly evident, with studies showing that PD is associated with impaired proprioception, which may represent a key factor contributing to postural instability (Vaugoyeau *et al.*, 2007; Bekkers *et al.*, 2014). The reliance on vision observed in pwPD may be understood as an adaptive strategy that partially compensates for impaired proprioception (Vaugoyeau *et al.*, 2007). Specifically, investigations into proprioceptive integration have revealed that pwPD exhibit altered kinesthesia of the upper limbs, head, and trunk. These alterations are characterized by a higher threshold for the minimal detectable range of motion and a reduced ability to perceive movement direction (Rinalduzzi *et al.*, 2015).

Axial rigidity is another significant contributor to postural deficits in PD, interfering particularly with automatic activities typically performed without conscious effort (Rinalduzzi *et al.*, 2015). Within the axial regions, the neck assumes a pivotal role in maintaining balance, mobility, and coordination. A considerable number of falls are attributed to sudden changes in postural orientation, such as turning, and are associated with an inflexible control of axial postural tone (Rinalduzzi *et al.*, 2015). Alterations in ankle muscle strength and rigidity, in conjunction with distorted perceptions of stability limits, further contribute to impaired postural control (Rinalduzzi *et al.*, 2015). Axial rigidity has also been demonstrated to impede the capacity for expeditious adaptation of postural responses to fluctuating environmental conditions, culminating in inflexible postural behavior that is characteristic of numerous pwPD (Rinalduzzi *et al.*, 2015).

The neural mechanisms underlying postural control deficits in PD involve multiple cortical and subcortical networks (Bath & Wang, 2024). The loss of dopaminergic neurons in the substantia nigra pars compacta alters striatal activity and its downstream targets, affecting thalamo-cortical circuits that are essential for automatic motor control (Bath & Wang, 2024). Furthermore, the disruption of downstream GABAergic connections from the basal ganglia to the thalamus and brainstem, including projections to the pedunculopontine nucleus, are disrupted, leading to dysfunction of brainstem locomotor centers (Bath & Wang, 2024). Functional neuroimaging studies show that pwPD with postural instability exhibit heightened activation in the prefrontal and parietal regions of the brain during anticipatory postural tasks. This finding suggests the presence of compensatory mechanisms and altered connectivity between the frontoparietal and ventral attention networks (Bath & Wang, 2024).

Levodopa remains the gold standard strategy for managing motor symptoms. However, its effects on postural strategies during quiet stance remain to be elucidated. A comparison of the ON and OFF medication states reveals that sway dispersion is higher and more pronounced in the more severe PD group compared to the mild group (Baston *et al.*, 2016). As indicated by the research of Bronte-Stewart (2002) and Bonnet *et al.* (2017), an elevated incidence of body sways has been documented in patients with PD during periods of static standing subsequent to levodopa administration. A body's increased propensity for oscillation has been demonstrated to be a significant predictor of an elevated risk of falling (Revilla *et al.*, 2013). However, an increase in cortical activity has been observed from 60 minutes to 120 minutes after medication intake, which appears to restore the thalamocortical pathway by enhancing basal ganglia function, thereby optimizing postural control (Araújo-Silva *et al.*, 2022). Furthermore, the effects of visual tasks, such as a single gaze shift, on mediolateral postural coordination vary by medication state. During the ON state, patients with Parkinson's disease (PD) rotate their trunk and head less than controls while rotating their eyes more. In contrast, in the OFF state, they tend to track targets by moving their entire body, while controls primarily turn their head (Anastasopoulos *et al*., 2011; Bonnet *et al*., 2015).

These medication-dependent shifts in postural control suggest that the integration of visual cues and motor output is not merely a mechanical issue, but also a disease's underlying pathophysiology. Indeed, the relationship between postural control and the visual system in PD is well established through multiple neural and functional mechanisms, which will be addressed in the following section (Vaugoyeau *et al*., 2007; Rinalduzzi *et al*., 2015; Feller *et al*., 2019). The increased reliance on visual information to compensate for vestibular and proprioceptive deficits, combined with the oculomotor impairments characteristic of PD, creates a multifaceted scenario in which vision concurrently facilitates and restricts effective postural control. This bidirectional interaction between vision and postural regulation is critical for understanding the mechanisms of postural instability and for developing more effective therapeutic strategies in PD. Visual deficits, including hypometric saccades, impaired smooth pursuit, and convergence insufficiency, may impede patients' capacity to utilize visual information as a compensatory strategy, potentially exacerbating postural instability and augmenting the risk of falls.

Interaction between eye movements and postural control in PD

A contemporary overview of the relationship between vision and postural control was provided by means of a comprehensive search of the PubMed/NCBI database. The search was constrained to original, full-length studies published between 2000 and 2025. The inclusion criteria for studies were the publication of English-language articles that assessed balance-related outcomes. The exclusion criteria encompassed review articles, conference proceedings, abstracts, letters, case series, pilot studies, and studies involving participants without a confirmed PD diagnosis. The search strategy combined three primary thematic clusters: Parkinson, postural control (e.g., body sway, CoP, falls), and visual/oculomotor function (e.g., saccades, vestibulo-ocular reflex, eye tracking).

A comprehensive review of the extant literature yielded a multifaceted interplay between sensory systems. Specifically, the role of eye movements in postural control among pwPD has been widely examined using paradigms that manipulate visual input (i.e., visual information) and assess postural control dynamics (Figure 3, Table 1). Overall, the findings indicate a dual role of vision in postural tasks: under certain conditions, visual information contributes to the reduction of postural instability; in other conditions, deficits in sensory integration caused by PD limit its effectiveness.

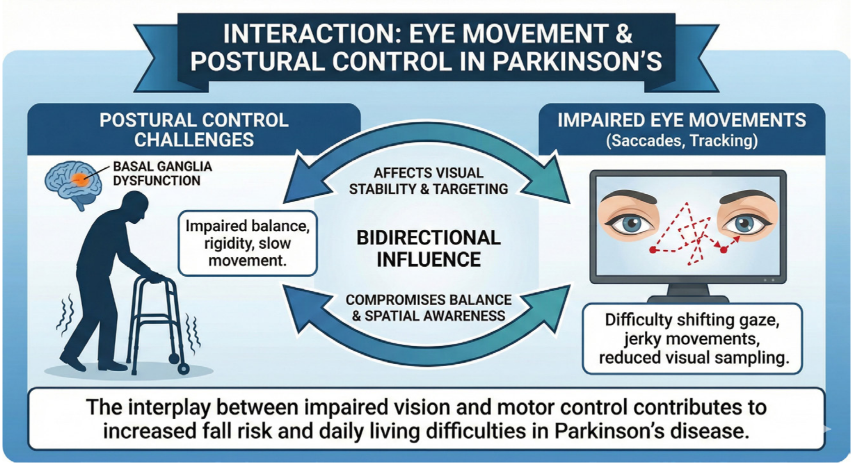

Figure 3. The bidirectional influence of basal ganglia dysfunction on motor and visual systems. This image has been adapted from a model generated by Google's AI model in 2023..

Table 1. Objective and main findings of the studies that investigated the eye movements during postural control tasks in people with PD.

Study	Groups (n)	Objective	Main findings
Smiley-Oyen *et al.* (2002)	PD = 8 CG = 8 YG = 8	To determine the capacity of PD to adapt the postural control when faced with conflicting proprioceptive inputs	- No group x vision interaction effect
Blaszczyk and Orawiec (2011)	PD = 55 CG = 55	To determine the diagnostic utility of the SR in identifying postural instability	- PD - Higher AP and ML sway ratios - EC - Increased SR
Vaugoyeau *et al.* (2011)	PD = 11 CG = 10	To establish the relationship between proprioceptive impairments and postural deficits	- PD - Fewer ability to respond to platform perturbations - PD - With EO the ability to respond to oscillations improved compared to EC
Rabin *et al.* (2013)	PD = 13 CG = 13	To test the efficacy of haptic and proprioception feedback in improving balance control	- PD swayed more than CG in the ML - Visual feedback (eyes open) decreased the ML and AP mean sway amplitude in PD group
Rocchi *et al.* (2014)	PD = 70 CG = 15	To characterize motor subtypes of PD	- EC - CG increased velocity of the sway more than PD in the ML and AP directions
Lahr *et al.* (2015)	PD-D = 9 PD-ND = 9	To assess the interaction between disease lateralization and visual reliance on postural control	- PD-D and PD-ND - Higher total CoP velocity with EC compared to EO - PD-D - Higher total CoP velocity than PD-ND with EC - PD-D and PD-ND - Higher CoP area with EC compared to EO

Study	Groups (n)	Objective	Main findings
Ozinga *et al.* (2015)	PD = 17 CG = 17	To validate the efficacy of tablet-based kinematic data in characterize postural stability	- Double leg stance with EO on a foam surface, and double leg stance with EC on a firm and foam showed great discrimination between PD and CG
Bekkers *et al.* (2018)	PD+FoG = 19 PD-FoG = 14 CG = 28	To compare the impact of dual-tasking on postural control between PD+FoG and PD-FoG	- No group x vision interaction effects during single task - EC - Higher postural DT cost to PD+FoG compared to PD-FoG
Bzdúšková *et al.* (2018)	PD = 13 CG = 13 YG = 13	To clarify the effects of age and PD on postural recovery following muscle vibration	- Larger backward CoP displacement and trunk tilts with EC com to EO (regardless of age and PD) - PD - Shifted their CoP and trunk tilts during vibration with EO - PD - Increased peak-to-peak amplitude in CoP displacement with vibration with EC - PD - Increased peak-to-peak amplitude in upper trunk level with vibration with EC and EO
Cruz *et al.* (2018)	PD = 14 CG = 14	To compare postural control performance and visual information on postural control	- PD - Larger body sway amplitude with stationary room - PD - Less coherence of body sway and visual manipulation compared to CG -PD and CG had similar visual-body sway coupling structure

Study	Groups (n)	Objective	Main findings
Mirahmadi *et al.* (2018)	PD = 17 CG = 17	To evaluate postural stability in early-stage PD with both linear and nonlinear approaches	- PD - Higher path length AP and ML - PD - Higher velocity AP and ML - PD - Higher RMS AP and ML direction - EC - Higher path length AP and ML - EC - Higher velocity AP and ML - No group x vision interaction
Bonnet *et al.* (2020)	PD = 20 CG = 20	To determine PD-related impairment in visual and postural movements during quiet upright stance	- PD - Stronger and weaker correlations between eye and CoP - PD - Used lower and greater attentional resources
Cruz *et al.* (2020)	PD = 21 CG = 21	To evaluate how knowledge and intention influence both postural performance and the visuomotor coupling between visual input and body sway	- PD - Higher MSA to CG with visual manipulation (optic flow manipulated in a moving room)
Delafontaine *et al.* (2020)	PD = 15 CG = 15	To evaluate the impact of visual availability and cognitive load on postural stability	- PD - Longer CoP pathway with EC - PD - Greater ellipse area with EC - PD - Larger RMS AP and ML amplitude with EC
Bonnet *et al.* (2021)	PD = 20 CG = 20	To determine the extent to which PD disrupts the synergistic coupling between the visual and posture systems	- PD - Eye movements and postural movements (lower back, upper back, and head) are correlated in a precise search task

Study	Groups (n)	Objective	Main findings
Cruz *et al.* (2021)	PD = 21 CG = 21	To examine how the complexity and predictability of visual information constrain postural oscillations during an upright stance	- PD - Larger sway magnitude with complex condition compared to CG - PD - Lagged behind the moving room with simple condition compared to CG
Kahya *et al.* (2021)	PD = 33 CG = 35	To assess pupillary response as a marker of cognitive effort under varying postural demands and visual conditions	- PD - Higher pupillary response with increased postural demand compared to CG (single balance eyes occluded, dual task EO and dual task eyes occluded)
Patel *et al.* (2021)	PD = 10 CG = 17 YG = 25	To determine the extent to which DBS and visual availability modify postural adjustments during quiet standing and balance perturbation	- PD - Increased synchronicity (coupled movement) with EC compared to EO (PD vs. CG; PD vs. YC)
Piras *et al.* (2022)	PD = 11 CG = 10	To characterize the postural response to radial expanding optic flow stimuli during standing	- PD - Lower microsaccade amplitude (t-test baseline and fovea stimuli) - PD - Slower microsaccade peak velocity (t-test baseline and fovea stimuli) - PD - Higher ML oscillation (t-test full and fovea stimuli) - PD - Higher sway area (t-test full, fovea, and periphery stimuli)

Study	Groups (n)	Objective	Main findings
Barbieri *et al.* (2024)	PD = 10 CG = 11	To investigate the effects of saccadic eye movements on body sway in PD in two bases of support positions (side-by-side and tandem stances)	- PD and CG - Lower AP displacement and RMS during horizontal saccadic movement compared to the fixation condition - PD - Higher sway area during vertical compared to horizontal saccadic eye movements
Kechabia *et al.* (2025)	PD = 19 CG = 20	To investigate the impact of PD on the coordination between gaze shift, postural sway and mental workload while performing visual tasks in the standing position	- PD - Higher velocity in gaze shift - PD - Higher velocity of postural sway - PD - Higher SD amplitude of gaze shift and postural sway

Note: AP: anterior-posterior; **CG:** control group of older healthy individuals; **CoP**: center of pressure; **D**: dominant; **DBS**: deep brain stimulation; **DT**: dual-task; **EC**: eyes closed; **EO**: eyes open; **+FoG**: presence of freezing of gait; **-FoG**: absence of freezing of gait; **ML**: medial-lateral; **MSA**: mean sway amplitude; **ND**: non-dominant; **PD**: Parkinson's disease group; **RMS**: root mean square; **SD**: standard deviation; **SR**: sway ratio; **YC**: young control group

Eye movements during postural control

Evidence suggests that eye movements play a pivotal role in postural regulation among pwPD. Gaze behavior is inherently associated with body sway, with eye movements exhibiting a strong correlation with postural adjustments of the head, trunk, and lower back during visual search (Bonnet *et al.*, 2021). However, PD is distinguished by particular oculomotor impairments that have the potential to compromise this coordination. Previous studies show that pwPD exhibit diminished microsaccade amplitude and velocity. This decline corresponds with an augmentation in postural instability across a range of visual conditions (Piras *et al.*, 2022). This assertion is further substantiated by the observation of heightened variability and velocity in both gaze shifts and body sway (Kechabia *et al.*, 2025), which points to an unstable visuomotor connection. Additionally, an enhanced synchronicity between ocular and postural movements during eyes-closed conditions has been documented (Patel *et al.*, 2021), suggesting a possible maladaptive strategy characterized by over-coupling rather than flexible sensory integration. These findings suggest that altered oculomotor control is not merely indicative of PD-related instability; rather, it is a contributing factor to the observed instability. This underscores the promise of interventions that focus on eye movement training, microsaccade control, and gaze stability as a means of indirectly enhancing balance.

While oculomotor deficits provide a potential explanation for the observed instability, another critical factor that must be considered is the manner in which the central nervous system integrates visual cues. The extant literature suggests that patients with PD exhibit significant impairments in the central processing and integration of visual information necessary for effective postural control. Reduced vision efficiency has been identified as a critical concern. Research findings indicate that pwPD maintain greater sway and CoP velocity compared to neurologically healthy controls, irrespective of whether their eyes were open or closed (Blaszczyk & Orawiec, 2011; Mirahmadi *et al.*, 2018), suggesting a potential reduction in visual integration efficiency. Additionally, older healthy subjects demonstrated a more significant increase in sway velocity during eyes-closed conditions compared to pwPD (Rocchi *et al.*, 2014), suggesting that pwPD may not fully employ visual feedback to adjust their postural responses. This processing deficit becomes especially apparent under dynamic visual perturbations. When exposed to moving rooms or optic flow manipulations, patients with pwPD exhibit increased body sway, diminished coherence between sway and visual stimuli, and delayed responses to visual perturbations compared to neurologically healthy controls (Cruz *et al.*, 2018, 2020, 2021). These results underscore a compromised visuomotor coupling, thereby impeding the effective utilization of visual cues for balance stabilization.

Oculomotor deficits may further contribute to these impairments. Reduced microsaccade amplitude and slower peak velocity are associated with increased sway magnitude across different visual field conditions (Piras *et al.*, 2022). Additionally, pwPD exhibit abnormal visuospatial responses during proprioceptive and vibratory perturbations, manifesting larger CoP displacements and trunk tilts under both eyes open and eyes closed conditions (Bzdúšková *et al.*, 2018). Furthermore, altered correlations between eye and postural movements indicate that pwPD stabilize posture through both increased and decreased attentional resources to achieve stabilization (Bonnet *et al.*, 2020). Consequently, these findings align with the hypothesis that, while vision provides critical input, individuals with pwPD frequently demonstrate deficiencies in integrating visual and proprioceptive information, resulting in less efficient adaptive postural control.

Positive effects of visual input on postural control

Visual input functions as a compensatory mechanism that mitigates balance impairments in pwPD. Literature has demonstrated that visual feedback significantly reduces sway amplitude in both the anterior-posterior and medial-lateral directions. This effect has been observed to effectively narrow the balance difference between pwPD and neurologically healthy controls (Rabin *et al.*, 2013). Beyond static visual feedback, specific oculomotor patterns have been shown to significantly modulate postural instability. Barbieri *et al.* (2024) found that horizontal saccades reduced anterior-posterior displacement and root mean squared values compared to fixation, while also producing a smaller sway area than vertical saccades. This stabilization may stem from a shift in postural regulation toward subcortical structures (Stoffregen *et al.*, 1999) - specifically the brainstem and cerebellum - while other lower structures manage oculomotor control. Consequently, pwPD are also able to maintain postural stability comparable to neurologically healthy controls in a quiet stance task. The execution of horizontal saccadic eye movements may serve as a compensatory mechanism, circumventing basal ganglia dysfunction to enhance both gaze shifting and postural control. This stabilizing influence has been observed in dynamic tasks as well, where visual input has been shown to enhance the ability of people with PD to respond to platform oscillations. This suggests that visual input may serve as a partial compensatory mechanism for proprioceptive deficits (Vaugoyeau *et al.*, 2011).

The stabilizing role of vision is reinforced by studies using closed-eye conditions, which reveal a marked deterioration in postural control. In the event of vision obstruction, pwPD demonstrate elevated CoP velocity and augmented sway area, a phenomenon that is particularly pronounced in individuals with dyskinesia (Lahr *et al.*, 2015; Delafontaine *et al.*, 2020). Notably, the presence of vision has been shown to reduce sway magnitude and to facilitate eye–posture coupling. A robust correlation has been demonstrated between eye movements and postural adjustments across the head, upper back, and lower back during visual search, underscoring a functional visuomotor linkage (Bonnet *et al.*, 2021). Furthermore, visual information appears to engage attentional resources, thereby contributing to the stabilization of posture. In individuals diagnosed with pwPD, elevated postural demands—particularly during dual-task scenarios—have been demonstrated to be associated with a substantially heightened pupillary response (Kahya *et al.*, 2021). This finding suggests that the visual system's demand for cognitive processing may function as a conscious or unconscious strategy to actively support compromised balance (Kahya *et al.*, 2021). Taken together, these findings underscore that vision can serve as an effective compensatory mechanism to mitigate balance impairments in PD, particularly under challenging conditions.

Clinical implications and future directions

The dual role of eye movement in pwPD underscores the necessity for customized rehabilitation strategies that incorporate visual optimization to enhance postural stability. Visual feedback can be leveraged to enhance training through a variety of methods, including augmented reality, optic flow manipulations, and gaze-control exercises aimed at improving visuomotor coupling. Given that postural control in PD is increasingly dependent on a stable visual frame, rehabilitating oculomotor impairments does not merely improve vision in isolation; it directly enhances balance control. However, clinicians must consider that excessive reliance on visual cues may be detrimental in complex or dynamic environments, where multisensory integration is required. Consequently, training programs that integrate oculomotor training within balanced tasks, particularly in dual-tasking contexts, appear to be the most efficacious. These interventions are designed to emulate the multisensory demands of daily life, thereby ensuring that enhanced ocular motor function translates into a more robust and stable postural system in PD.

Emerging technologies, including wearable eye-trackers, virtual reality systems, and multisensory training platforms, hold considerable potential for enhancing both research and rehabilitation methodologies. These tools may facilitate the elucidation of the causal role of eye movements in stabilizing posture and identify individualized training approaches that fortify visuomotor coupling. Future intervention should aim to not only exploit the compensatory benefits of visual input but also address the sensory integration deficits that limit its stabilizing potential in PD.

Final remarks

This chapter synthesizes the complex dual relationship between oculomotor and postural controls in pwPD. Evidence establishes an anatomical and functional link rooted in basal ganglia circuits in both eye-movement control (saccades, smooth pursuit eye movements, and convergence insufficiency) and axial posture. This relationship is characterized by a critical duality: visual input frequently functions as a compensatory mechanism, helping to attenuate postural instability. However, it can also result in impairment in the processing and integration of visual information, particularly during dynamic visual perturbations. It has been demonstrated that compromised visuomotor coupling results in less efficient adaptive postural control. This is evidenced by greater body sway and delayed response times. Consequently, interventions must be meticulously designed to enhance visuomotor coupling and optimize sensory integration efficiency. This can be achieved by integrating eye movement training with dynamic balance tasks. However, a significant lacuna in the extant literature pertains to the necessity of establishing unambiguous correlations between particular oculomotor deficits and pivotal postural control metrics. This is imperative for the efficacious management of postural instability and the mitigation of fall risk in pwPD.

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