

# The gaze-gait connection: Assessing Alzheimer's severity through gaze behaviors

A. D'Ermo<sup>1</sup>, A. Rodio<sup>1</sup>, A.M. Abbatecola<sup>1,2</sup>, C. Carissimo<sup>3</sup>, S. Poce<sup>3</sup>, G. Cerro<sup>3</sup>, C. Provenzale<sup>4</sup>, T. Di Libero<sup>1</sup>

<sup>1</sup>Department of Human Sciences, Society and Health, Xlab, University of Cassino and Southern Lazio, Cassino, Italy

{annalisa.dermo, a.rodio, angelamaria.abbatecola, tommaso.dilibero}@unicas.it

<sup>2</sup>Department of Life Science, Health and Health Professions, Link Campus University of Rome, School of Medicine Rome, Rome, Italy, a.abbatecola@unilink.it

<sup>3</sup>Department of Medicine and Health Sciences "Vincenzo Tiberio", University of Molise, Campobasso, Italy

{chiara.carissimo, gianni.cerro}@unimol.it, s.poce@studenti.unimol.it

<sup>4</sup>Department of Electrical and Information Engineering, University of Cassino and Southern Lazio, Cassino, Italy  
cecilia.provenzale@unicas.it

**Abstract**—This study explores the use of eye-tracking (ET) technology as an aid tool in the diagnosis of Alzheimer's disease (AD). A group of participants, consisting of subjects diagnosed with AD and healthy controls, performed walking tasks enriched with auditory and visual stimuli while wearing ET glasses. The main objective was to assess whether visual behavior data could be a useful parameter in the diagnosis of the condition. To this end, the presence of differences between the two groups was preliminarily analyzed in order to define a solid starting point for possible diagnostic use. The analysis focused on two main parameters: elevation and azimuth of gaze. Results showed that the elevation parameter was particularly effective in detecting alterations in visual attention associated with AD, while azimuth proved to be less discriminating. Tasks based on visual stimuli provided more significant data than acoustic ones, probably due to the simplicity of the proposed auditory rhythm (60 bpm). In addition, a correspondence was observed between scores obtained on the Mini-Mental State Examination (MMSE) and the Short Physical Performance Battery (SPPB), suggesting a potential integrated approach for classifying disease severity. Overall, the results highlight the potential of eye-tracking as an objective tool to support cognitive and motor assessment in AD diagnostic protocols.

**Index Terms**—Alzheimer's disease, Ocular Movement Measurement, Wearable Devices

## I. INTRODUCTION

Alzheimer's disease (AD) is a progressive neurodegenerative disorder that severely affects cognitive and functional abilities, posing a growing social and economic burden [1]. Despite extensive research, no definitive pharmacological cure exists, making early diagnosis crucial for optimizing non-pharmacological therapies [2]–[4]. Current diagnostic methods, such as cerebrospinal fluid analysis and PET imaging, are effective but expensive, invasive, and not widely accessible. Consequently, cognitive and functional assessment scales are commonly used to monitor AD progression. The Mini-Mental State Examination (MMSE) is widely applied to assess

This work is partially supported by the Project "A wearable system for motion and glucose joint monitoring for neurodegenerative disease status evaluation in elder people", CUP MASTER D53D23015960001, CUP H53D23007310001 funded by EU in NextGenerationEU plan through the Italian "Bando Prin 2022 PNRR - D. D. n. 1409 del 14-9-2022" by MUR.

cognitive impairment and dementia severity [5]. For physical assessment, no AD-specific tests exist, but the Short Physical Performance Battery (SPPB) [6] is a validated tool to evaluate physical condition and fall risk in older adults [7]. Advances in understanding physiopathological mechanisms, including neuroplasticity [8], emphasize the need for objective, accessible, and non-invasive diagnostic tools to monitor cognitive changes over time [9]. Traditional assessment scales often lack the sensitivity to detect mild impairments early, highlighting the necessity for specific tests that accurately profile individuals [10], [11]. Innovative technologies, such as eye-tracking (ET), offer precise and quantifiable insights into cognitive decline [12]. Eye movements serve as sensitive indicators of cognitive changes, providing a non-invasive and cost-effective alternative for AD detection [13], [14]. ET technology allows for the non-invasive recording of eye movements by tracking the position and motion of the pupil and corneal reflection, typically using infrared light. Modern ET systems provide high-resolution data on gaze direction, fixation durations, saccades, and pupil dynamics in real time.

These metrics provide insights into cognitive domains such as attention, processing speed, visuospatial awareness, and executive function. In AD, changes in oculomotor behavior may reflect cognitive decline and support early diagnosis or monitoring. ET is a non-invasive technology that captures eye movements via infrared-based monitoring of pupil position and corneal reflection. It allows continuous, objective assessment of visual behavior, including fixation patterns, gaze duration, and orientation (azimuth and elevation). These oculomotor parameters are linked to functions often impaired in AD, such as attention control and executive processing [15], [16]. Delivering real-time data, ET is a promising tool for identifying subtle cognitive changes and monitoring disease progression [17]. This approach deepens understanding of how AD affects attention, perception, and decision-making, and can inform targeted therapies. Despite its potential, few studies have assessed ET in dynamic settings [18], [19].

Traditional assessments are often performed in static or controlled environments, which may fail to capture the in-

tricate interactions between cognitive, sensory, and motor systems that occur in everyday activities. By introducing visual and auditory stimuli while participants walk, we aimed to recreate real-world dual-task conditions that require attention, executive function, and motor coordination. This multimodal assessment offers a more nuanced understanding of cognitive-motor interference and provides insights that are not easily detectable through the MMSE or SPPB alone. Particularly, eye-tracking metrics such as fixation duration and gaze shifts may indicate underlying deficits in attention allocation, processing speed, and sensorimotor integration. When these measures are combined with MMSE and SPPB scores, they could enhance our ability to differentiate early pathological signs from normal age-related changes and contribute to the development of more sensitive tools for early diagnosis and functional assessment in AD.

In line with our ongoing research aimed at integrating technological tools into field-based cognitive and functional assessments, we included eye-tracking in this study to explore its potential in dynamically monitoring attentional and oculomotor behavior during real-life tasks. Given its non-invasive nature and ability to provide high-resolution, objective data, we aim to assess whether such tools can enhance the early detection and monitoring of AD-related traits.

Building on these advancements, the present study investigates how different sensory stimuli influence visual behavior during walking in patients at various stages of AD. The use of an eye-tracking-based measurement system allows for the collection of objective data that inform both motor coordination and cognitive engagement during movement. Additionally, a possible correlation is hypothesized between clinical assessment scales and specific oculomotor features extracted from eye-tracking data. This correlation could support the estimation of disease severity through objective metrics and automated decision systems, potentially reducing the burden on healthcare services.

The paper is organized as follows: Section II describes the participants involved, the cognitive and physical assessment tests used, the experimental protocol involving walking tasks with acoustic and visual stimuli, and the eye-tracking monitoring system employed. Section III presents the results obtained, focusing on gaze behavior and fixation patterns, and highlighting differences between healthy participants and individuals with AD. Section IV discusses the significance of the obtained findings, comparing them with existing scientific literature and exploring their implications for neurophysiological understanding and clinical practice. Section V provides the conclusions of the study, emphasizing the relevance of eye-tracking as an objective diagnostic tool for AD, and suggests future directions for research and practical applications.

## II. MATERIALS AND METHODS

### A. Participants

The study involved two distinct groups of participants. The first group consisted of 17 individuals selected from the users of a day care center for AD patients (between mild and

moderate pathology degree) located within the territory of the Azienda Sanitaria Locale (ASL) of Frosinone, in Atina Inferiore (Italy). Specifically, the study population included 3 men and 14 women (Age  $70y \pm 3.2$ ), all of them are diagnosed with dementia of varying degrees. The study involving this population was approved by Registro Sperimentazioni ASL (51.24 CET2 aslfr). The second group comprised 6 healthy subjects (baseline), 3 women and 3 men (Age  $35y \pm 4.6$ ), from the University of Cassino and Southern Lazio. The involvement of the healthy population was approved by the Institutional Review Board of the University of Cassino and Southern Lazio (no. 24777.2022.12.12). The informed consent process and the approval regarding benefits and risks adhered to the principles established by the 1964 Declaration of Helsinki for research involving human subjects. Selected participants had to give their consent to use the eye-tracker. This research started only after obtaining informed consent from patients and their caregivers, following a comprehensive explanation of the study protocol to both parties.

Inclusion criteria for AD patients were:

- a degree of dementia ranging from mild to severe (MMSE  $\leq 24$ );
- the ability to perform motor tasks (SPPB  $\geq 4$ );

Exclusion criteria included:

- use of a walking device;
- use of glasses (to avoid problems related to visual impairment and to avoid the risk of falling).

### B. Protocol

After the initial cognitive and functional assessment, subjects were asked to walk a short 4 m distance along a corridor in order to assess eye behavior under dynamic conditions. The distance of 4 m was chosen to reproduce a task already provided by the SPPB protocol, to which the patients were thus accustomed [6]. During this task, subjects wore the eye-tracker. The tasks included two types of stimulation during the walk to observe the participants' response and any changes in visual behavior.

At the Alzheimer Center, the ambient temperature is consistently maintained at  $23^{\circ}\text{C}$  to ensure optimal comfort for the patients. Regarding the test duration, participants in the visual stimulation condition were instructed to walk at a self-selected comfortable pace to minimize the risk of falls. In contrast, during the auditory stimulation condition, the duration was dictated by the tempo of the auditory cues proposed.

Acoustic stimuli were delivered through a metronome set at 60 bpm, providing a consistent acoustic signal corresponding to a standardized stride cadence of one step per second. This specific tempo was chosen to improve rhythmic synchronization, promote uniform walking speed among participants, and ensure the reproducibility of stride performance measures. Visual stimuli were made with colored adhesive strips placed along a 4 m path according to the SPPB [6] protocol. The strips were placed 45 cm apart to indicate stride length, a distance that corresponds to the average stride measurements

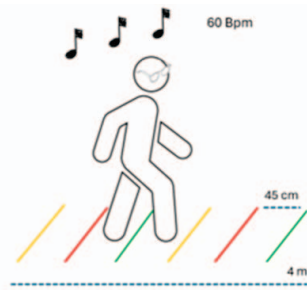


Fig. 1. Description of experimental scenario used during the measurement protocol.

of the elderly, thus facilitating a standardized and reproducible assessment of gait in line with the validated protocol (see Fig. 1).

The integrated use of acoustic and visual stimuli ensures reliable and controlled conditions for gait assessment, minimizing variability and improving the accuracy of performance assessment. The motor tasks required of the subjects differed according to the type of stimulus administered. For Acoustic stimuli, subjects were asked to synchronise their steps with the sound emitted by the smartphone metronome. In contrast, in the case of visual stimuli, the subject was asked to walk while trying not to step on the tape strips placed on the floor. The execution of the tests was enhanced by the collaborative efforts of the center's staff and the medical team, ensuring a synergistic approach. The administration of the motor-cognitive tasks was conducted consistently across the healthy group. During the walking activity, participants were wearing the eye tracker *Neon Pupil lab Eye-Tracker glasses* (2023, Pupil Labs GmbH, Berlin, Germany), allowing the precise recording of eye movements and fixation events during exposure to visual (VS) and acoustic (AS) stimuli. Data collected from the healthy group were used as baseline to better analyse gaze behaviour of the first group, serving as a reference point. To analyse gaze behaviour in relation to the diagnostic scales, the AD population was characterized according to the scores obtained on the screening tests, by setting suitable thresholds by considering the overall ranges for MMSE and SPPB and dividing participants in two groups (MILD and MODERATE) according to a threshold placed at the median point of each scale (15 for MMSE and 6 for SPPB). Consequently, all participants scoring higher than 15 (6, respectively) were classified as having a MILD pathology, while those who scored lower or equal to 15 (6, respectively) were classified as having a MODERATE pathology. Finally, baseline participants were selected regardless of the considered scales. The objective of the study was to ascertain the existence of any specific patterns of eye movement that were associated with the SPPB and MMSE scores, with the results of the Healthy Group serving as a reference point. Secondly, the investigation sought to identify any potential differences based on the nature of the stimulus.

- The following data were extrapolated from the record-

ings made with the eye-tracker, particularly focusing on fixation events:

- **Fixation per second (Fixps):**  $\frac{No. fixations}{TotalDuration}$
- **Duration (s):** fixation events' time extension in seconds;
- **Fixation Elevation [°]:** referring to vertical ocular movement;
- **Fixation Azimuth [°]:** referring to lateral ocular movement.

### C. Monitoring Instrument

The eye-tracker Neon glasses from Pupil Labs are advanced devices designed for eye tracking. These glasses are used in various fields, such as scientific research, psychology, neuroscience, and virtual reality, to monitor and analyze eye movements accurately and in real time [20], [21]. Thanks to its lightweight structure, this device is designed to be comfortable during prolonged use. The glasses are equipped with advanced technology, including two high-speed video cameras for capturing eye movement (with a refresh rate of 200 Hz), a wide-angle camera to record the user's field of view, stereo microphones, and IMU sensors. Deep learning-based algorithms allow an accurate estimation of gaze direction, pupil diameter measurement, and eye state analysis. The device is controlled through the Neon Companion App. The latter allows to calibrate the device before data acquisition and to manage the communication with the *Pupil Cloud*. It processes data in real-time, allowing the visualization of the environment seen by the subject and the analysis of eye movements. In Fig. 2, the setup block diagram used during the experiences was presented.

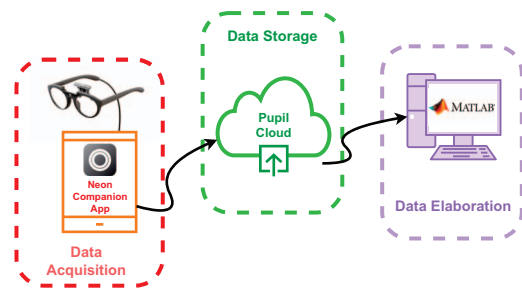


Fig. 2. Block Diagram of Neon Eye-Tracker glasses setup

## III. RESULTS

### A. General Remarks on the obtained results

Table I presents the mean and standard deviations (with a coverage factor (k) equal to 1) of the aforementioned data for trials with acoustic and visual stimuli. For acoustic stimuli the mean number of fixations remains unchanged when considering the total duration of the test. In particular, both baseline and Alzheimer's participants obtain approximately 2 Fixps for MMSE and SPPB, respectively. In the three groups,

the average duration of fixation events also remained almost unchanged. In the visual stimuli test the number of Fixps was different from baseline to Mild and Moderate groups, particularly for baseline, the participants obtained 4 Fixps, while the other two groups performed 2 Fixps. Compared to baseline, the duration of fixation events approximately doubled in the mild and moderate groups.

TABLE I

MEAN ( $\mu$ ) AND STANDARD DEVIATION ( $\sigma$ ) OF FIXATION DATA RECORDED DURING ACOUSTIC (AS) AND VISUAL (VS) STIMULI ADMINISTRATION.

$\mu \pm \sigma$		Baseline	Mild		Moderate	
			MMSE	SPPB	MMSE	SPPB
Fixation per second (Fixps)	AS	2.2 ± 1.1	2.0 ± 0.3	2.3 ± 0.4	2.5 ± 0.5	2.1 ± 0.5
	VS	3.9 ± 0.5	2.6 ± 0.5	2.3 ± 0.6	2.3 ± 0.6	2.5 ± 0.7
Duration (s)	AS	0.50 ± 0.26	0.50 ± 0.09	0.40 ± 0.10	0.40 ± 0.11	0.40 ± 0.12
	VS	0.20 ± 0.03	0.30 ± 0.06	0.40 ± 0.13	0.40 ± 0.14	0.40 ± 0.15

To better describe the ocular orientation, the elevation and azimuth parameters for each fixation were considered.

TABLE II

MEAN ( $\mu$ ) AND STANDARD DEVIATION ( $\sigma$ ) OF ELEVATION AND AZIMUTH DATA RECORDED DURING ACOUSTIC (AS) AND VISUAL (VS) STIMULI ADMINISTRATION

$\mu \pm \sigma$		Baseline	Mild		Moderate	
			MMSE	SPPB	MMSE	SPPB
Elevation (°)	AS	-8.83 ± 1.73	-2.70 ± 2.67	-3.23 ± 3.82	-1.36 ± 4.52	-1.16 ± 1.52
	VS	-18.68 ± 0.28	-1.56 ± 0.59	-1.78 ± 3.54	-3.66 ± 1.67	-4.96 ± 3.12
Azimuth (°)	AS	0.77 ± 1.09	0.65 ± 1.60	1.37 ± 1.92	1.58 ± 1.90	0.62 ± 0.86
	VS	-0.28 ± 0.66	-0.44 ± 0.24	-0.58 ± 1.01	0.66 ± 1.11	1.67 ± 1.35

Table II shows the mean and standard deviation (with a coverage factor (k) equal to 1) results for the elevation and azimuth parameters obtained for both the visual and acoustic stimuli. The elevation describes a clear difference between the reference group (baseline) and the two groups representing the pathological sample, obtaining in both tests an increase of the mean value with respect to the baseline group. The Azimuth, on the other hand, did not show any differences among the three groups studied. Based on these results, it was decided to focus only on the elevation parameter.

### B. Fixation Elevation Related Results

Figs. 3 and 4 show the raw elevation data time series considering acoustic and visual stimulations, respectively. To create each figure, one person for each disease condition has been selected, considering only people whose disease severity was coherently classified into one group (baseline, mild, moderate) by both the considered examination scales (MMSE and SPPB). The data reported in the figures are shown as examples and should not be considered significant for the overall analysis.

On the other hand, Figs. 5 and 6 show a comparison of the mean fixation elevation for each group, taking into account the

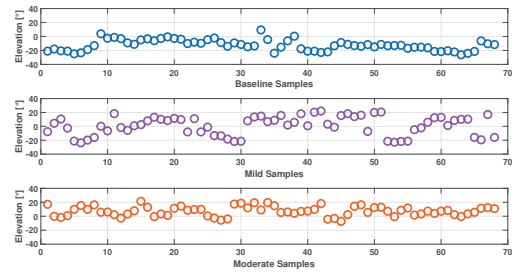


Fig. 3. Examples of Fixation Elevation data under Acoustic Stimulation for people affected by different Alzheimer's disease status

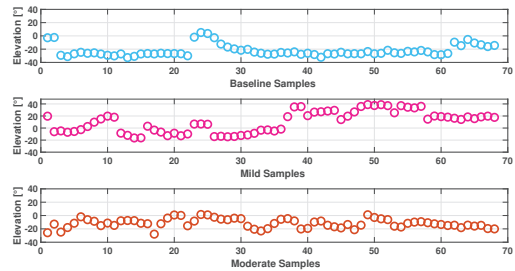


Fig. 4. Examples of Fixation Elevation data under Visual Stimulation for people affected by different Alzheimer's disease status

two examination scales. It can be seen that there is an overlap between the MMSE and SPPB curves for both the acoustic and the visual stimuli, indicating a good level of agreement between MMSE and SPPB performed grouping.

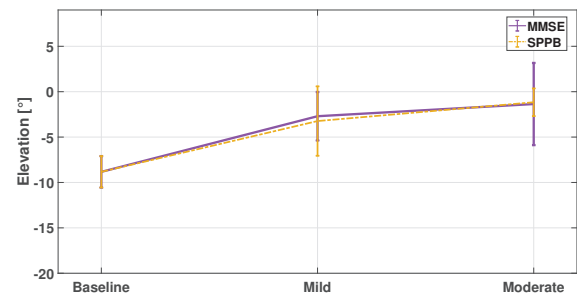


Fig. 5. Comparison of Fixation Elevation data considering all people involved in the experimental campaign: inter-group compatibility evaluation - acoustic stimulation

Conversely, interesting insights can be carried out by considering the comparison of the obtained elevation values for each disease condition (baseline, mild, moderate). In particular, considering the acoustic stimulus (Fig. 5) the measurement intervals calculated for each group are compatible with each other, emphasizing that the acoustic exercise did not produce any differentiation among the three investigated groups.

On the contrary, in the case of the visual stimulus (Fig. 6), the two pathological groups (mild, moderate) are not compatible with the measurement interval obtained in the

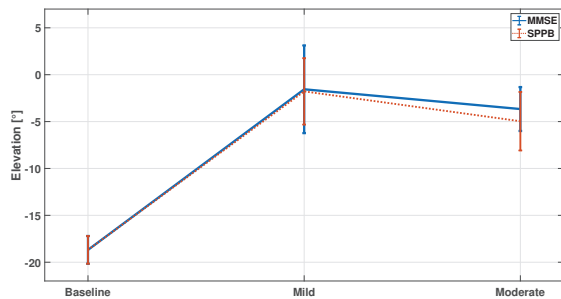


Fig. 6. Comparison of Fixation Elevation data considering all people involved in the experimental campaign: inter-group compatibility evaluation - visual stimulation

baseline case. The exercise with the visual stimulus showed the difference in test performance among the three groups. In particular, it was observed that in the baseline group, the participants kept their gaze low in the direction of the stripes that identified the path, whereas in the pathological groups, the gaze was higher on average, with greater variability in terms of standard deviation.

#### IV. DISCUSSION

Research in neurophysiology highlights the role of physical activity in promoting neuroplasticity, even in elderly individuals and those with AD [22]. Similarly, external stimuli such as acoustic and visual inputs can enhance cognitive and motor functions by activating neural pathways involved in learning and adaptation [23]. These mechanisms are consistent with the concept of neuroplasticity, whereby the brain reorganizes itself in response to experience and environmental cues [8], [24], [25]. Cognitive stimulation may also contribute to strengthening attention, sensory integration, and motor coordination [26]. In this context, the present exploratory study aimed to examine gaze behavior in a walking task involving visual and acoustic stimuli. While walking is a standard component in the diagnostic evaluation of neurodegenerative conditions [27], the integration of external stimuli remains underexplored [28]. The use of eye-tracker provides a non-invasive means to collect objective data during motor-cognitive tasks. Some studies have highlighted the influence of age on cognitive and oculomotor measures, particularly in terms of visual attention and gaze behavior [29], [30], a factor that must be considered as a possible confounding variable in our study. The healthy control group was included primarily to obtain an initial characterization of the eye-tracking measures, and not for direct statistical comparison with pathological participants. The fixation features analyzed revealed some observable trends. Fixation durations tended to be longer during acoustic stimuli tasks compared to visual ones (except for the moderate group), particularly in participants with lower MMSE scores. This might reflect slower gait and increased visual focus during task execution in individuals with AD. In contrast, healthy controls exhibited shorter fixations, likely due to faster walking speeds. The elevation parameter appeared more informative

than azimuth, especially in visual tasks, where increasing AD severity seemed associated with impaired downward gaze control. However, these trends were not tested statistically, and as such, they should be interpreted as preliminary observations rather than confirmed findings. In line with the pilot nature of this research, no formal correlation analysis was performed between clinical scores and ET data. Although we noted a pattern of alignment between MMSE and SPPB scores across participants, we recognize that any suggestion of correlation requires statistical validation. For this reason, we have avoided drawing definitive conclusions from these associations. A future study with a larger sample and appropriate statistical power will be necessary to assess these relationships quantitatively. These preliminary findings support the idea that eye-tracking can provide meaningful data on motor-cognitive integration in AD. Nonetheless, further research is needed to confirm its diagnostic value.

#### V. CONCLUSIONS

This pilot study suggests that eye-tracking may help identify visual-motor differences between healthy individuals and those with AD during walking tasks that involve external stimuli. Among the parameters analyzed, gaze elevation appeared to be the most sensitive to group differences, particularly in the visual stimulus condition. Conversely, azimuth did not show consistent trends across groups. Although we observed some alignment between MMSE and SPPB scores, no correlation analysis was conducted; thus, we refrain from drawing inferential conclusions in this regard. These results should be considered preliminary and hypothesis-generating rather than confirmatory. Importantly, this work lays the groundwork for future developments in protocol design. The integration of ET technology with standardized clinical tests could improve the objectivity of field-based assessments, which often rely on subjective clinical judgment. The addition of complementary technologies—such as wearable motion sensors—may further enhance the reliability of motor evaluations in clinical settings. Future studies with larger and more diverse samples will be essential to validate these initial findings and to implement a statistically grounded analysis of the relationship between gaze metrics and clinical scores.

#### REFERENCES

- [1] X. Li, X. Feng, X. Sun, N. Hou, F. Han, and Y. Liu, "Global, regional, and national burden of alzheimer's disease and other dementias, 1990–2019," *Frontiers in Aging Neuroscience*, vol. 14, p. 937486, 2022.
- [2] T. Di Libero, E. Langiano, C. Carissimo, M. Ferrara, P. Diotaiuti, and A. Rodio, "Technological support for people with parkinson's disease: a narrative review," *JOURNAL OF GERONTOLOGY AND GERIATRICS*, vol. 71, pp. 87–101, 2023.
- [3] T.-W. Lin, S.-F. Tsai, and Y.-M. Kuo, "Physical exercise enhances neuroplasticity and delays alzheimer's disease," *Brain Plasticity*, vol. 4, no. 1, p. 95–110, Dec. 2018. [Online]. Available: <http://dx.doi.org/10.3233/bpl-180073>
- [4] A. D'Ermo, T. Di Libero, E. Langiano, B. Tosti, S. Corrado, P. Diotaiuti, L. Fattorini, and A. Rodio, "Exergames in neurocognitive disease management in elderly: a narrative review of therapeutic benefits and applications," *Journal of Gerontology and Geriatrics*, p. 1–11, Nov. 2024. [Online]. Available: <http://dx.doi.org/10.36150/2499-6564-n753>

- [5] K. Juva, R. Sulkava, T. Erkinjuntti, R. Ylikoski, J. Valvanne, and R. Tilvis, "Staging the severity of dementia: comparison of clinical (cdr, dsm-iii-r), functional (adl, iadl) and cognitive (mmse) scales," *Acta Neurologica Scandinavica*, vol. 90, no. 4, p. 293–298, Jan. 2009. [Online]. Available: <http://dx.doi.org/10.1111/j.1600-0404.1994.tb02724.x>
- [6] S. A. Welch, R. E. Ward, M. K. Beauchamp, S. G. Leveille, T. Trivison, and J. F. Bean, "The short physical performance battery (sppb): a quick and useful tool for fall risk stratification among older primary care patients," *Journal of the American Medical Directors Association*, vol. 22, no. 8, pp. 1646–1651, 2021.
- [7] N. Deshpande, J. E. Metter, F. Lauretani, S. Bandinelli, and L. Ferrucci, "Interpreting fear of falling in the elderly: What do we need to consider?" *Journal of Geriatric Physical Therapy*, vol. 32, no. 3, p. 91–96, 2009. [Online]. Available: <http://dx.doi.org/10.1519/00139143-200932030-00002>
- [8] T. Machan and K. Krupps, "The neuroplastic adaptation trident model: a suggested novel framework for acl rehabilitation," *International Journal of Sports Physical Therapy*, vol. 16, no. 3, p. 896, 2021.
- [9] C. Bourelly, D. Capriglione, C. Carissimo, F. Milano, and L. Tari, "Measurement and applications: The role of communication technologies in developing distributed measurement systems and measurement applications," *IEEE Instrumentation & Measurement Magazine*, vol. 26, no. 4, p. 19–26, Jun. 2023. [Online]. Available: <http://dx.doi.org/10.1109/mim.2023.10146568>
- [10] T. Di Libero, A. D'Ermo, B. Tosti, S. Corrado, P. Diotaiuti, and A. Rodio, "The 100-days: Physical exercise and challenges to assess, maintain and improve physical fitness during lockdown," *Sports*, vol. 12, no. 12, p. 337, Dec. 2024. [Online]. Available: <http://dx.doi.org/10.3390/sports12120337>
- [11] T. Di Libero, L. Falese, A. D'Ermo, B. Tosti, S. Corrado, A. Iannaccone, P. Diotaiuti, and A. Rodio, "Physiological profile assessment and self-measurement of healthy students through remote protocol during covid-19 lockdown," *Journal of Functional Morphology and Kinesiology*, vol. 9, no. 3, p. 170, 2024.
- [12] B. Can and N. Sanlier, "Alzheimer, parkinson, dementia, and phytochemicals: insight review," *Critical Reviews in Food Science and Nutrition*, pp. 1–23, 2023.
- [13] F. Yu, U. G. Bronas, S. Konety, N. W. Nelson, M. Dysken, C. Jack, J. F. Wyman, D. Vock, and G. Smith, "Effects of aerobic exercise on cognition and hippocampal volume in alzheimer's disease: study protocol of a randomized controlled trial (the fit-ad trial)," *Trials*, vol. 15, no. 1, Oct. 2014. [Online]. Available: <http://dx.doi.org/10.1186/1745-6215-15-394>
- [14] L. F. ten Brinke, N. Bolandzadeh, L. S. Nagamatsu, C. L. Hsu, J. C. Davis, K. Miran-Khan, and T. Liu-Ambrose, "Aerobic exercise increases hippocampal volume in older women with probable mild cognitive impairment: a 6-month randomised controlled trial," *British Journal of Sports Medicine*, vol. 49, no. 4, p. 248–254, Apr. 2014. [Online]. Available: <http://dx.doi.org/10.1136/bjsports-2013-093184>
- [15] R. Davis and A. Sikorskii, "Eye tracking analysis of visual cues during wayfinding in early stage alzheimer's disease," *Dementia and Geriatric Cognitive Disorders*, vol. 49, no. 1, p. 91–97, 2020. [Online]. Available: <http://dx.doi.org/10.1159/000506859>
- [16] Z. Liu, Z. Yang, Y. Gu, H. Liu, and P. Wang, "The effectiveness of eye tracking in the diagnosis of cognitive disorders: A systematic review and meta-analysis," *PLOS ONE*, vol. 16, no. 7, p. e0254059, Jul. 2021. [Online]. Available: <http://dx.doi.org/10.1371/journal.pone.0254059>
- [17] F. Zuo, P. Jing, J. Sun, J. Duan, Y. Ji, and Y. Liu, "Deep learning-based eye-tracking analysis for diagnosis of alzheimer's disease using 3d comprehensive visual stimuli," *IEEE Journal of Biomedical and Health Informatics*, vol. 28, no. 5, p. 2781–2793, May 2024. [Online]. Available: <http://dx.doi.org/10.1109/jbhi.2024.3365172>
- [18] F. Schöberl, C. Pradhan, S. Irving, K. Buerger, G. Xiong, G. Kugler, S. Kohlbecher, J. Engmann, P. Werner, M. Brendel, E. Schneider, R. Perneczky, K. Jahn, C. la Fougère, P. Bartenstein, T. Brandt, M. Dieterich, and A. Zwergal, "Real-space navigation testing differentiates between amyloid-positive and -negative amci," *Neurology*, vol. 94, no. 8, Feb. 2020. [Online]. Available: <http://dx.doi.org/10.1212/wnl.0000000000008758>
- [19] C. Hao, X. Zhang, J. An, W. Bao, F. Yang, J. Chen, S. Hou, Z. Wang, S. Du, Y. Zhao, Q. Wang, G. Min, and Y. Li, "An effective screening model for subjective cognitive decline in community-dwelling older adults based on gait analysis and eye tracking," *Frontiers in Aging Neuroscience*, vol. 16, Sep. 2024. [Online]. Available: <http://dx.doi.org/10.3389/fnagi.2024.1444375>
- [20] Y. Xu, C. Zhang, B. Pan, Q. Yuan, and X. Zhang, "A portable and efficient dementia screening tool using eye tracking machine learning and virtual reality," *npj Digital Medicine*, vol. 7, no. 1, Aug. 2024. [Online]. Available: <http://dx.doi.org/10.1038/s41746-024-01206-5>
- [21] S.-i. Tokushige, H. Matsumoto, S.-i. Matsuda, S. Inomata-Terada, N. Kotsuki, M. Hamada, S. Tsuji, Y. Ugawa, and Y. Terao, "Early detection of cognitive decline in alzheimer's disease using eye tracking," *Frontiers in Aging Neuroscience*, vol. 15, Mar. 2023. [Online]. Available: <http://dx.doi.org/10.3389/fnagi.2023.1123456>
- [22] T.-W. Lin, S.-F. Tsai, and Y.-M. Kuo, "Physical exercise enhances neuroplasticity and delays alzheimer's disease," *Brain plasticity*, vol. 4, no. 1, pp. 95–110, 2018.
- [23] R.-x. Jia, J.-h. Liang, Y. Xu, and Y.-q. Wang, "Effects of physical activity and exercise on the cognitive function of patients with alzheimer disease: a meta-analysis," *BMC geriatrics*, vol. 19, pp. 1–14, 2019.
- [24] T. Di Libero, C. Carissimo, G. Cerro, A. Abbatecola, A. Marino, G. Miele, L. Ferrigno, and A. Rodio, "Motor abilities analysis using a standardized tapping test enhanced by a detailed processing stage: gender and age comparison," in *2023 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*. IEEE, 2023, pp. 1–6.
- [25] C. Carissimo, L. Ferrigno, G. Golluccio, A. Marino, and G. Cerro, "Parkinson's disease aided diagnosis: online symptoms detection by a low-cost wearable inertial measurement unit," in *2022 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*. IEEE, Jun. 2022, p. 1–6. [Online]. Available: <http://dx.doi.org/10.1109/memea54994.2022.9856546>
- [26] P. Wiegel, A. Kurz, and C. Leukel, "Evidence that distinct human primary motor cortex circuits control discrete and rhythmic movements," *The Journal of Physiology*, vol. 598, no. 6, pp. 1235–1251, 2020.
- [27] M. Bonanno, A. M. De Nunzio, A. Quartarone, A. Militi, F. Petralito, and R. S. Calabrò, "Gait analysis in neurorehabilitation: From research to clinical practice," *Bioengineering*, vol. 10, no. 7, p. 785, Jun. 2023. [Online]. Available: <http://dx.doi.org/10.3390/bioengineering10070785>
- [28] E. Tonti, M. Budini, and E. M. Vingolo, "Visuo-acoustic stimulation's role in synaptic plasticity: A review of the literature," *International Journal of Molecular Sciences*, vol. 22, no. 19, p. 10783, Oct. 2021. [Online]. Available: <http://dx.doi.org/10.3390/ijms221910783>
- [29] S. Dowiasch, S. Marx, W. Einhäuser, and F. Bremmer, "Effects of aging on eye movements in the real world," *Frontiers in Human Neuroscience*, vol. 9, Feb. 2015. [Online]. Available: <http://dx.doi.org/10.3389/fnhum.2015.00046>
- [30] C. Owsley, "Aging and vision," *Vision Research*, vol. 51, no. 13, p. 1610–1622, Jul. 2011. [Online]. Available: <http://dx.doi.org/10.1016/j.visres.2010.10.020>