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The impact of age-related cognitive changes and cognitive decline in speech understanding in noise: a clinical observational study in older adults with normal hearing and mild hearing loss

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ABSTRACT

Introduction and aim: The world population is aging, leading to several challenges. Cognitive decline and Age-Related Hearing Loss (ARHL) occur to many people as they get older, affecting independence, well-being, and quality of life. ARHL can be caused by deficits in either peripheral hearing or Central Auditory Processing (CAP). Difficulties in CAP could interfere with a listener's ability to understand speech, especially in noisy conditions. However, speech comprehension may depend not only on the status of the auditory system, but also on cognitive functioning. This information can be particularly relevant in aging, which is characterized by a decline in cognitive abilities and a reduction in available mental resources. Potential sources of decline in cognitive functioning are explained by cognitive aging theories through the so-called "fundamental cognitive mechanisms", which include processing speed, inhibitory control, and working memory. The aim of the present study is to shed a light on the relationship between central auditory processes (through a speech understanding in noise test) and cognitive functioning in older adults with mild to moderate cognitive decline and healthy matched controls. The hypothesis is that poorer performance in specific cognitive tasks could be associated with difficulties in understanding sentences in noise, particularly among those experiencing cognitive decline.

Materials and methods: A total of 38 older adults with normal hearing and mild hearing loss (mean age 76.95 years old [SD: 5.33], n=25 female) was sorted into two groups: mild to moderate cognitive decline group (n=21) and a control group (n=17). Both the experimental and control group underwent a complete neuropsychological and audiological evaluation. Cognitive functioning was assessed using Mini-Mental State Examination (MMSE), the Brief Neuropsychological Assessment-2 (ENB-2) and the Reaction Times (RT) test from the Vienna Test System; also, cognitive reserve was measured with the Cognitive Reserve Index Questionnaire (CRIq). The audiological assessment included Pure Tone Audiometry (PTA) and the Italian Matrix Sentence Test (IMST).

Results: Auditory performance at the IMST showed significant negative correlations with ENB-2 total score (r = -0.488; p = .002), Digit Span (r = -0.378; p = .019), Interference Memory – 30" (r = -0.549; $p < .001$), and Phonemic Fluency test (r = -0.576; $p < .001$). Positive correlations were found between IMST performance and TMT-A (r = 0.373; p = .021), RT/S1 (r = 0.610; $p < .001$), and RT/S3 (r = 0.540; $p < .001$). Multiple regression analysis with stepwise selection was carried out to investigate the relative contribution of selected cognitive variables in predicting IMST performance. The regression model found that performance on the IMST was predicted by RT/S3 (β = 0.519; $p < .001$), Interference Memory – 30" (β = -0.350; p = .003), and Digit Span (β = -0.240; p = .030). The results showed that this model has a significant explanatory power $R^2 = .619$, $F_{(3,34)} = 21$, $p < .001$, accounting for approximately 62% of the variance in IMST performance.

Conclusions: To the best of our knowledge, this is the first clinical Italian study to analyze this association in older adults by assessing CAP through IMST. In line with previous evidence, this study supports the hypothesis of an interaction between CAP and cognitive functioning. Processing speed, working memory, and short-term memory span were found to be particularly involved in the processing of auditory stimuli, predicting performance on the IMST. This information can be particularly relevant for patients experiencing cognitive decline, as deficits in these functions can impact more their ability to process auditory information. A larger sample study, controlled for the type of cognitive decline, and further research are needed to corroborate these findings and to better investigate the shared mechanisms between auditory and cognitive functioning.

CHAPTER 1 – A BACKGROUND ON AGING

1.1 World Population Aging

According to the World Health Organization (2022), by 2030 one in six people in the world will be aged 60 years or over. By 2050, the world's population of those aged 60 years and older will double, reaching 2.1 billion. Moreover, the number of people aged 80 years or older is growing even faster (United Nations [UN], 2023, p. 18) and it is expected to triple from 2020 to 2050, reaching 426 million (World Health Organization [WHO], 2022). These data suggest the magnitude of a global long-term trend namely *World population aging* that is an unavoidable result of demographic transition (decrease in birth and death rates) and represents one of the most important issues of our times.

Aging, at a biological level, is defined as a complex involuntary process characterized by a gradual, lifelong accumulation of molecular and cellular damage, leading to a progressive decline in physiological function and an increased vulnerability to environmental challenges, disease, and eventually death (Kirkwood, 2008; World Health Organization [WHO], 2015). So, aging entails several irreversible changes, and it represent a risk factor for many health disorders that become more frequent in older people (WHO, 2015). We can therefore expect an increase in the prevalence of age-related diseases in line with an increase in the aging of the global population. In this regard an analysis on the 2010 estimated data of the Global Burden of Disease (GBD) found that disorders affecting individuals aged ≥ 60 years account for 23.1% of the total disease burden (Prince et al., 2015). The same study found that the primary drivers of disease burden in older individuals were cardiovascular and circulatory disease, cancer, chronic respiratory conditions, musculoskeletal disorders, and neurological and mental diseases. A more recent investigation used data from GBD 2019 to estimate trends in older people aged ≥ 70 (GBD 2019 Ageing Collaborators, 2022). Analysis identified functional disorders (i.e. Alzheimer's disease and other dementias, and stroke), chronic pain conditions, sensory organ disease (hearing and vision loss), and oral disorders as the main factors related to disability globally in this population segment. It was also found that worldwide the leading five causes of death in people aged ≥ 70 years in 2019 were ischemic heart disease, stroke, chronic obstructive pulmonary disease, Alzheimer's disease and other dementias, and lower respiratory infections (GBD 2019 Ageing Collaborators, 2022). Furthermore, most of the health problems of older age are the result of a chronic disease (WHO, 2015), that is a long-term condition that progresses slowly and requires a prolonged period of care and treatment, without leading to a recovery state (Denton & Spencer, 2010). When people age, the likelihood of experiencing multiple chronic diseases at the same time increases (multimorbidity) (WHO, 2015). In their systematic review, Marengoni et al. (2011) found that more than a half of the older population is affected by multimorbidity, and prevalence increases in very aged people. In this review, the main consequences of multimorbidity were functional impairment, lower quality of life (depression, psychological distress) and increased health care utilization and costs.

To be aware of these data represents the starting point to define what individuals and, more broadly, society can do to shape this path in the perspective of healthy aging. The association between chronological age and illness with consequent disability is not constant or unchangeable (Prince et al., 2015). Especially it would be an error not to distinguish aging from disease: getting old does not mean becoming automatically ill and it is not necessarily disabling (De Beni & Borella, 2015). Currently it seems that years of life in good health have remained widely constant, implying that the additional years are in poor health (WHO, 2022). Analyzing the period 2000-2019 it was found that the proportion of time spent in ill-health has slightly increased worldwide (UN, 2023, p. 44). This means that there is still to cover a lot of ground in terms of healthy aging. It's important to integrate a quality dimension to these additional years (quantity), that is to say "how" these extra years of life are spent. The United Nations (UN) General Assembly designated 2021–2030 the UN Decade of Healthy Aging with the aim of fostering longer and healthier lives through a worldwide effort (WHO, 2022). Healthy aging is defined by WHO as "the process of developing and maintaining the functional ability that enables wellbeing in older age" (WHO, 2015). Functional ability is about having the capabilities that enable individuals to achieve what they have reason to value, such as meeting basic needs, learning, growing, and making decisions, being mobile, building and maintaining relationships, and contributing to society (WHO, 2015). Age-related physiological changes (biological aging) as well as the possible presence and severity of disease can influence a person's functional ability, affecting intrinsic capacity. However, these changes are only generically linked to chronological age and there is high variability in the way these modifications are experienced at an individual level (aging as multidimensional and multidirectional process) (De Beni & Borella, 2015). In addition, older people could achieve what they have reason to value (i.e. functional ability) not just through their intrinsic (physical and mental) capacity, but also through their environment (home, communities, and society) as well as the ongoing interaction between these aspects (WHO, 2015). The environment plays a crucial role in determining one's ability to participate in personally meaningful activities across different levels of intrinsic capacity, so exerting an even stronger influence on an individual's functional ability (WHO, 2015). Therefore, different variables must be considered to appreciate the complexity that characterize this population. Focusing only on the physiological dimension may led to underestimate the effects of lifestyle, behavior, and the various psychosocial factors that could mitigate potentially debilitating conditions and enhance the well-being of older people (Young et al., 2009).

As diversity represents the hallmark in the experience of older age, to achieve good public-health policies on aging it must be considered the entire spectrum of differences without paying attention on one extreme which outlines the "typical" older person. Also, in the framework of public health, the focus should be on individual functioning, avoiding disease-centered approaches (Beard et al., 2016). Indeed, studies have found that when assessing quality of life in older adults, functional ability contributed to overall wellness together with good social relations (e.g., family, friends), independence, active engagement in social activities and psychological well-being (e.g., emotional stability, resilience, coping strategies) (Brett et al., 2019; Gabriel & Bowling, 2004; Netuveli & Blane, 2008). In this way quality of life extends beyond the simplistic concept of health, as older adults emphasize other factors as crucial for well-being. Better alignment between health systems and the needs of older adults is essential for implementing interventions and creating supportive environments that can enable individuals with a given level of capacity to achieve what they value (Beard et al., 2016).

1.2 Understanding cognitive impairment and age-related hearing loss

As outlined in the previous paragraph, neurocognitive disorders and hearing loss are among the main contributors of disease burden in older adults worldwide (GBD 2019 Ageing Collaborators, 2022; Prince et al., 2015). Additionally, even though the frequency of many pathologies increases with advancing age, none is as specifically associated with aging as neurocognitive disorders and age-related hearing loss.

In this section, the main characteristics of these disorders, the epidemiological profile, the resulting implications in the healthcare, economic and social domains as well as the theories attempting to explain the hearing-cognition relationship will be provided.

1.2.1 Neurocognitive disorders

Dementia also known as Major Neurocognitive Disorder, as renamed in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), is characterized by a progressive, significant decline from a previous level of cognitive functioning (impairing one or more cognitive domains). This decline is reported both subjectively and objectively and affects independence in daily living (American Psychiatric Association [APA], 2013). Considering a continuum ranging from normal aging to severe impairment, an intermediate state represented by Mild Cognitive Impairment (MCI or Mild Neurocognitive Disorder) exists (Petersen et al., 1999). The diagnostic criteria for this disease are similar to those of dementia, except for the severity of cognitive and functional impairment. Indeed, DSM-5 describes a modest cognitive decline (1–2 SD below the normative mean on tests) which do not interfere with independence in daily activities, but greater effort or compensatory strategies may be required (APA, 2013). Individuals diagnosed with MCI are more likely to progress to dementia compared to healthy-matched control. Anyway, MCI does not always precede dementia and its diagnosis does not require further decline: impairment may progress or be stable (Petersen et al., 2018; Sachdev et al., 2014).

The number of people with dementia is increasing worldwide in line with the above-mentioned trends and patterns in population aging and growth. Currently, people that are living with dementia are more than 55 million and this number is expected to rise globally in 2050 to approximately 152 million (Alzheimer's Disease International [ADI], 2019; GBD 2019 Dementia Forecasting Collaborators, 2022). It ranks as the seventh most common cause of death and one of the main causes of disability and dependency among older adults (World Health Organization [WHO], 2023). Dementia prevalence rates vary across countries, particularly showing a notable increase in Low- and Middle-Income Countries (LMICs), where around two-thirds of people with dementia reside due to a higher burden of risk factors (Livingston et al., 2020). Furthermore, there seem to be some differences in dementia rates between sexes. The Framingham Heart Study found that women have a higher life-time risk of dementia or Alzheimer's disease compared to men (Chêne et al., 2015). Authors interpreted this result as the combination of women's longer life expectancy and the early selective mortality of men attributable to cardiovascular risk factors. Epidemiological studies have indicated a higher dementia rate in women compared to men after the age of 80, with rate decreasing in both sexes in very old age (Beam et al., 2018). Dementia also has implications for both healthcare and the economy, with substantial global costs estimated to rise from $355 billion in 2021 to over $1.1 trillion in 2050 (Alzheimer's Association, 2021).

Neurocognitive disorders are subtyped based on the nature of the etiological process. Initially a distinction is made between neurodegenerative (e.g., Alzheimer's disease, Lewy body disease, Frontotemporal lobar degeneration, Parkinson disease dementia) and non-neurodegenerative dementias (e.g., Normal pressure hydrocephalus, Depressive pseudodementia) (De Beni & Borella, 2015). While the former condition characterizes most dementias in older adults, the latter can occur across the lifespan, often showing an earlier age of onset and a more rapid progression (Gale et al., 2018).

Alzheimer's Disease (AD) accounts for an estimated 60% to 80% of dementia cases, resulting in the most common cause of cognitive decline (Alzheimer's Association, 2021). It typically begins with a gradual decline in learning and episodic memory, although less common AD subtypes may present with dominant behavioral, visuospatial or language symptoms (Gale et al., 2018). *Vascular dementia*, the second most common cause after AD, results from damage to brain blood vessel or insufficient blood flow, oxygen or nutrient (e.g. stroke, small-vessel ischemic disease). Post-mortem studies have shown evidence of vascular pathology in brains of individuals diagnosed with AD, a condition known as mixed dementia, which lowers the threshold for the clinical diagnosis of AD (Kapasi et al., 2017). The probability of experiencing mixed dementia rises with age, peaking in individuals aged 85 or older (Alzheimer's Association, 2021). Another pathology that often co-occur with a diagnosis of AD is *Dementia with Lewy Bodies* (DLB), indeed roughly 5% of dementia cases exhibit signs of DLB alone (Alzheimer's Association, 2021). DLB is characterized prominently by fluctuations, visual hallucinations, parkinsonian symptoms, and sleep disorders (Kapasi et al., 2017). Among the most common forms of neurocognitive disorders, finally, there is *Frontotemporal Dementia* (FTD). It is an early-onset dementia that particularly affects patients younger than 65 years, accounting for around 10% of all dementia cases in studies with participants under 65 and 2.7% in studies limited to those older 65 (Hogan et al., 2016). FTD is mainly characterized by a behavioral variant, which is associated with personality changes, disinhibition, and executive dysfunction. Another subtype of FTD is primary progressive aphasia, which presents with speech and language deficits (Gale et al., 2018). In this context it is crucial to identify the cognitive areas that are commonly affected in neurocognitive disorders. The Neurocognitive Work Group categorized cognitive functions into six primary domains: attention, executive function, learning and memory, language, perceptual-motor function, and social cognition (Sachdev et al., 2014). Assessing cognitive functions to identify those affected in a specific patient is important for gaining a better comprehension of the etiology and extent of the neurocognitive disorder.

Considering the personal, social and economic implications of living with dementia, along with the lack of available treatments with disease-modifying properties, immediate action is necessary to mitigate these expected trends (GBD 2019 Dementia Forecasting Collaborators, 2022). To address these issues, disease prevention through interventions targeting lifestyle and modifiable factors is required. Results from the 2020 Lancet report on dementia prevention, intervention, and care suggest that addressing the 12 modifiable risk factors could be prevented or delayed up to 40% of dementia cases (Livingston et al., 2020). They proposed a lifelong model that integrates risk factors across three phases of the lifespan, suggesting that certain factors pose greater risk at different stages of life. This underscores the idea that dementia prevention is relevant and possible at any age. Education level, which begins in childhood and can continue throughout life, is considered an early life factor due to the greatest plasticity of those years. *Low education level* (accounting for 7% of the total risk of dementia) could lead to vulnerability to cognitive decline because of reduced cognitive reserve. Among midlife (45–65 years) factors, there are hearing loss (8%), traumatic brain injury (3%), hypertension (2%), alcohol consumption (1%), and obesity (1%). *Hearing loss* presents the highest risk percentage among the identified factors and continues to increase the risk of dementia even later in life. Studies included in the Lancet report found that with every 10 dB of worsening of hearing loss, there was an increased risk of cognitive decline. The mechanisms underlying this association are not yet clear and will be examined further. *Traumatic brain injuries* can increase the risk of dementia depending on their severity and number, while midlife *hypertension* was associated with reduced brain volumes and white matter hyperintensity. Additionally, persistent hypertension in later life further increases the risk of developing dementia. *Excessive alcohol consumption* (> 21 units/week) was associated with increased dementia risk compared to drinking less than 14 units (more than 14 units was also linked to right sided hippocampal atrophy). A review of longitudinal studies included in the Report found a correlation between *obesity* (BMI ≥ 30) and dementia, but not with being overweight. Lastly, smoking (5%), depression (4%), social isolation (4%), physical inactivity (2%), air pollution (2%) and diabetes (1%) are indicated as later-life risk factors. *Smoking* could be linked to cognitive decline through its association with cardiovascular disorders; moreover, the risk is heightened by neurotoxins present in cigarette smoke. There is still debate about the impact of *depression* on dementia: it could be a risk factor or an early symptom of dementia. Treated versus untreated depression may differ in mitigating dementia; indeed, some antidepressants have been found to reduce amyloid production. *Social isolation* can be a risk factor not only for dementia but also for hypertension, and depression. Lifelong single and widowed individuals were found to have a higher risk of dementia compared to married people. Moderate-to-vigorous *physical activity* was linked to a lower risk of dementia, whereas physically inactive people in the decade leading up to diagnosis showed a higher incidence. Studies reported global cognitive improvements in both healthy adults and individuals diagnosed with MCI engaged in aerobic exercises. *Air pollution*, particularly high levels of nitrogen dioxide and fine particles from traffic and residential wood burning, may accelerate neurodegenerative processes, potentially increasing dementia rates. Ultimately, type 2 *diabetes* increases the risk of future dementia, with the extent influenced by duration and severity; however, it is unclear if any medication can reduce this risk.

In the context of prevention, *cognitive reserve* can be considered a protective mechanism against dementia, explaining differences in vulnerability to age- and disease-related brain changes among older individuals (Stern, 2012). The concept of cognitive reserve, proposed by Stern (2012), suggests that the brain actively tries to handle pathology by utilizing existing cognitive processes or compensatory mechanisms. Consequently, as levels of cognitive reserve change, so does the brain resilience to neuropathological damage. An individual with high cognitive reserve would manage the same level of pathology better than someone with low cognitive reserve (Stern, 2012). In other words, they can sustain a higher burden of neuropathology without showing cognitive impairment. Thus, thanks to this compensatory strategy, older adults with better cognitive reserve are expected to show disease-related clinical symptoms later than those with low cognitive reserve. So, neurodegeneration may be masked by higher cognitive reserve, and cognitive performance would remain fairly good until pathology overwhelms cognitive functioning at advanced stages, resulting in a more rapid rate of decline (Stern, 2012). Differently from brain reserve that is a passive, quantitative form of reserve linked to brain size and number of neurons, cognitive reserve is an active model of reserve. Indeed, evidence indicates that different life experiences, including those acquired in adulthood and later life, can enhance resilience against age- or disease-related changes, thus slowing cognitive decline (Stern, 2013). Protective effects were observed for education, occupational attainment, and leisure activities. For this reason, these dimensions are considered among the indicators of cognitive reserve used in estimating this construct (Nucci et al., 2012).

Dementia prevention involves both public policies and individual actions that contribute to risk mitigation. Interventions are crucial at all stages: preventive actions should begin early in life and continue throughout life (Lancet, 2020). Targeting modifiable risk factors and enhancing cognitive reserve capacity is essential for preventing, delaying, or slowing cognitive decline, resulting in both cost-effective and favorable outcomes.

1.2.2 Age-related hearing loss

Age-Related Hearing Loss (ARHL), or presbycusis, is a progressive decrease in hearing, most marked at higher frequencies, that can occur when people get older as a result of cumulative effects of aging on the auditory system (Bowl & Dawson, 2019). More specifically, Gates & Mills (2005) described presbycusis as characterized by diminished hearing sensitivity and speech comprehension in noisy environments, as well as slowed central processing of acoustic information in the central nervous system, and difficulty localizing sound source.

Hearing impairment of any degree affects approximately 42% of individuals aged 60 years and older, rendering it the most prevalent chronic sensory deficit experienced by older adults (Bowl & Dawson, 2019; World Health Organization [WHO], 2021). The prevalence of hearing loss rises with age, starting at 27% among people aged 60-69, 55% in those aged 70-79 years, and reaching 80% among those aged over 80 years (Lin et al., 2011). This prevalence is expected to increase due to a rapidly aging population. Additionally, men are at higher risk of developing hearing loss compared to women of similar age (Lin et al., 2011).

The impact of ARHL is significant from various perspectives. With the projected increase in life expectancy and the prevalence of hearing issues among individuals aged 65 years or older by 2030, it is estimated that medical expenses for the first year of hearing loss treatment will reach $30 billion by 2030 (Stucky et al., 2010). Furthermore, people typically cover the expenses for treating hearing loss themselves, resulting in considerable financial strain.

Growing evidence also suggests that presbycusis is strongly associated with different negative health outcomes, including increased risk of falls, depression, social isolation, and dementia (WHO, 2021). ARHL is regarded a multifactorial disorder resulting from multiple interactions. While some risk factors associated to genetic predisposition (i.e. age, sex) cannot be controlled, others are modifiable as they are related to health conditions, lifestyle choices, and environmental exposures. Preventable factors that can increase the chance of developing hearing loss in adulthood include exposure to loud noise (both in occupational and recreational settings), ototoxic medications, poor diet, presence of cardiovascular risk factors (e.g. hypertension, diabetes, smoking) (Bowl & Dawson, 2019; WHO, 2021).

WHO (2021) adopted a hearing-impairment grading system which allows for the classification of hearing loss into six categories based on audiometric measures (hearing thresholds in the better hearing ear): mild (20 to < 35 dB), moderate (35 to < 50 dB), moderately severe (50 to < 65 dB), severe (65 to < 80 dB), profound (80 to < 95 dB), or complete (95 dB or greater). The system provides also a description of the functional effects on communication (in quiet and noisy environments) expected to characterize each level of severity for most adults. In the early stages, ARHL affects the detection of high-frequency sounds (6000-8000 Hz), which can interfere with the understanding of normal speech in both quiet and noisy environments (Panza et al., 2015). As hearing loss progresses to the range of 2000-4000 Hz, which is crucial for understanding voiceless consonants (e.g. t, p, f, s), difficulties become clearer, and deficits are observed more frequently in daily conversations (Gates & Mills, 2005). First stages often go unnoticed and untreated, with the impairment typically identified when speech comprehension is significantly affected (Panza et al., 2015).

Aging leads to significant physiological changes in both the peripheral and central auditory systems. Indeed, hearing problems can originate from a dysfunction affecting peripheral processing and/or Central Auditory Processing (CAP), depending on the localization of the impaired auditory components. The peripheral auditory system consists of the external, middle and internal ear (*Figure 1*), whereas the central auditory system encompasses the cochlear nuclei, superior olivary nuclei, lateral lemniscus, inferior colliculus, medial geniculate nuclei, and auditory cortex.

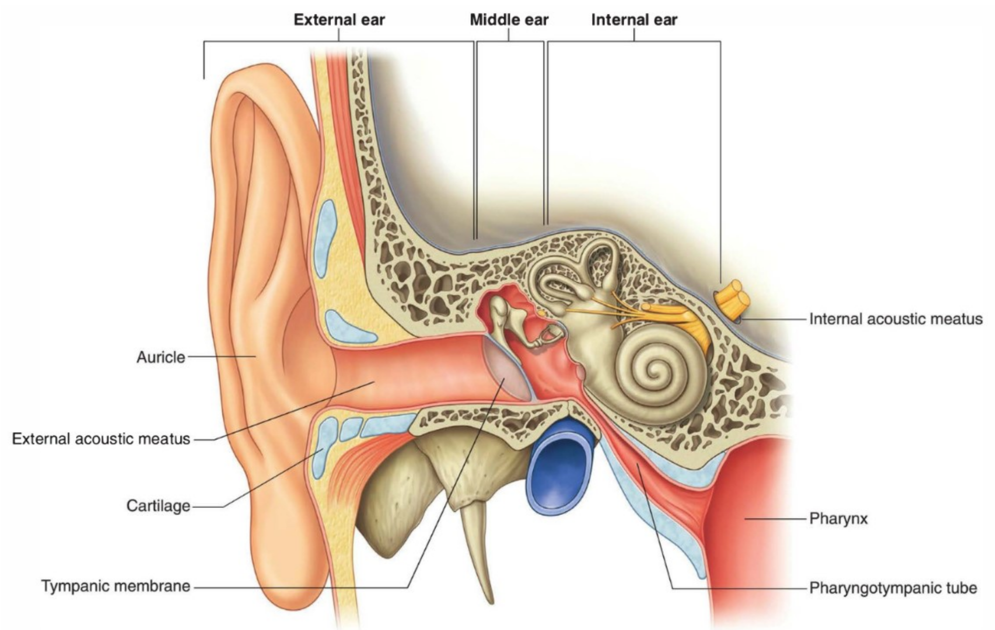

Figure 1: *Anatomy of the human ear, showing the subdivisions into the external ear, middle ear, and internal ear.* From Drake et al., 2014 (p. 953).

In peripheral presbycusis different patterns of degeneration were identified, all of which are related to the inner ear that seems more vulnerable to aging than both the external and middle ear (Jayakody et al., 2018) (*Figure 2*).

According to Schuknecht & Gacek (1993) classification, there are four main categories of peripheral deficit related to specific cochlear pathologies (Roth, 2015):

1) *Sensorial presbycusis*, characterized by loss of cochlea outer hair cells, elicits predominantly high-frequency losses.
2) *Strial or metabolic presbycusis* is the result of atrophy of cochlear lateral wall and stria vascularis which are responsible for metabolic process. It leads to flat loss at lower frequencies and gradual sloping at higher frequencies.
3) *Neural presbycusis* originates from loss of spiral ganglions neurons. When 80-90% of cells have degenerated, hearing impairment results in poor word discrimination.
4) *Cochlear conductive presbycusis* is caused by stiffness in the cochlea's basilar membrane.

Many cases of presbycusis do not fit into this classification, but instead show a combination of pathological changes (referred to as mixed presbycusis). Others exhibit no specific changes in the aforementioned structures (referred to as indeterminate presbycusis) (Schuknecht & Gacek, 1993).

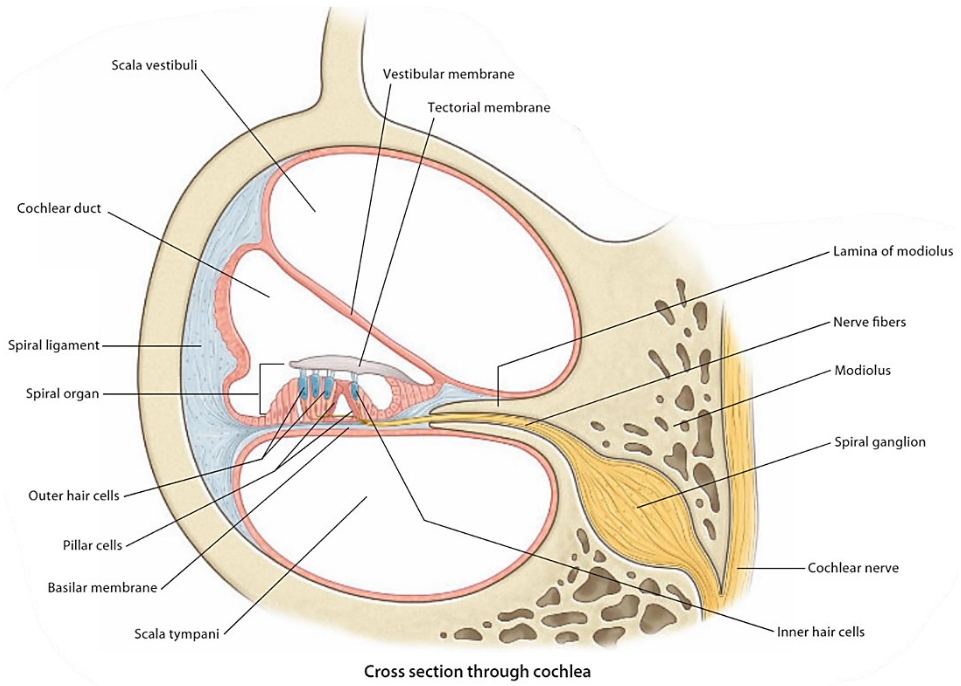

Figure 2: *Cross-section of the cochlea detailing its internal structures, some of which are involved in peripheral presbycusis.* From Drake et al., 2015 (p. 524).

However, this categorization of presbycusis focuses on peripheral components of auditory system, without taking into account that some changes on hearing ability may have a central origin. Hearing impairment is traditionally evaluated using Pure-Tone Audiometry (PTA), which measure the softest level of sound (in dB) that can be detected across various frequencies in a quiet room (pure-tone thresholds). However, even if PTA is widely considered the gold standard method for assessing the peripheral system, relying solely on PTA during the assessment of hearing impairment is not recommended (Musiek et al., 2017). Changes in audiometry do not give information on how sounds are processed by the central auditory system (responsible for temporal and frequency discrimination as well as binaural processing), thus providing only limited insight into an individual's everyday functioning (WHO, 2021). Sometimes it happens that people, despite having a normal hearing threshold according to PTA, report difficulties in speech understanding, particularly in noise and in complex listening environments (Musiek, 2017). If an individual can understand speech well in quiet conditions but struggles significantly with speech understanding in background noise or in other challenging listening situations (e.g. competing speech), central presbycusis is likely playing a role (Gates & Mills, 2005). Indeed, ARHL can also affect neurons along the central auditory pathway, especially in the region of inferior colliculus that is considered an important relay point indispensable for sound integration and processing of complex sound features (Jayakody et al., 2018; Nixon, 2019). Identifying the specific site of ARHL and discerning whether the peripheral, central, or both components are primarily affected poses a significant clinical challenge. Indeed, age-related changes in the cochlea, particularly in the basal turn of the Corti organ, can also contribute to difficulties in speech recognition (Roth, 2015). CAP dysfunction is therefore suspected especially when individuals have difficulty in understanding speech in noise despite having normal peripheral hearing (Nixon, 2019). However, central ARHL has a heterogeneous clinical presentation, making it challenging to differentiate from peripheral deficits. An extensive review of approximately 165 articles concluded that there is not enough evidence to establish the existence of "pure" CAP dysfunction (Humes et al., 2012). In this regard, central presbycusis is considered more as a consequence of peripheral problems. However, some studies support the existence of a central ARHL regardless of peripheral presbycusis (Bao et al., 2020). Panza et al. (2019) highlighted two possible hypotheses that could better explain the pathophysiology of central ARHL. In particular, according to the *direct hypothesis*, pure central changes (central effects of biological aging) can be observed without the simultaneous presence of peripheral deficits. This hypothesis found support in animal studies which shown evidence of age-related structural changes within central auditory areas (e.g. inferior colliculus) independently of peripheral deficits. The *indirect hypothesis* conceptualizes a central effect of peripheral dysfunction. It supposes that the presence of peripheral hearing impairment can lead to central auditory changes from the cochlear nucleus through the auditory cortex (bottom-up theory). The authors thus affirmed that the CAP dysfunction is the result of a complex interplay of factors involving age- or disease-related auditory and brain changes. In this regard, a review by Sardone et al. (2019) listed several fMRI studies that found changes in central auditory pathways through the involvement of a compensatory network to support linguistic processing in patients with peripheral presbycusis. Additionally, defective neurotransmission as well as decreased grey matter volume in the auditory cortex and in the global brain were found in individuals with peripheral ARHL. The literature supports the existence of a third hypotheses, the *cognitive hypothesis*, which assumes that age-related cognitive decline can result in poorer processing of auditory information (Nixon, 2019). Despite central presbycusis not being fully understood yet, both peripheral and central dysfunction should be evaluated. Achieving a better comprehension of these difficulties could lead to significant improvements in current rehabilitation practices by tailoring interventions based on the type of impairment. In fact, clinical interventions targeting peripheral presbycusis (i.e., hearing aids) often fail to provide adequate benefits for many older patients, likely due to deficits in central components that make difficult understanding conversations in noisy settings (Parham et al., 2013; Roth, 2015). Individuals with CAP dysfunction were found to perform better with a single hearing aid in the better ear, rather than using binaural aids (Parham et al., 2013). Another study found that during speech recognition in noise 71% of older patients showed better performance using unilateral amplification than bilateral (Henkin et al., 2007). Therefore, bilateral amplification may not always be the best solution for older adults.

1.2.3 How is ARHL associated with cognitive impairment and dementia?

The hypothesis of a possible interaction between hearing and cognitive impairment was reported around 60 years ago. The strength of this association has been consolidated in the last decade thanks to the accumulation of evidence and to several research that were carried out.

Different longitudinal studies found an association between peripheral ARHL and cognitive decline and dementia in older adults (Deal et al., 2017; Jayakody et al., 2018; Lin et al., 2013). In particular, findings from the Health ABC study revealed that participants with peripheral hearing impairment had a 30-40% faster rate of cognitive impairment and a 24% higher incident of cognitive decline over a 6-years period compared with those with normal hearing (Lin et al., 2013). Similarly, Deal et al. (2017), in their 9-years longitudinal study with older adults aged 70-79 with moderate/severe peripheral hearing impairment, found a 55% increase in the risk of incident dementia compared to participants with normal hearing. As mentioned above, also the Lancet Commission found hearing loss as a risk factor for developing dementia with the highest impact among other risk factors, accounting for 8% of the total risk (Livingston et al., 2020). A meta-analysis of 33 studies investigated the impact of hearing intervention on cognition (Taljaard et al., 2016). It revealed a significant association between the degree of cognitive impairment and the severity of hearing impairment in both treated and untreated participants, but individual with treated hearing impairment showed improved cognition compared to untreated ones. Additionally, better peripheral hearing correlated with a better performance across different cognitive domains, among which attention/processing speed, short-term/working memory and long-term memory revealing larger effect sizes.

Fewer studies have specifically analyzed the association between central ARHL and cognitive decline and dementia, even though a relationship is becoming evident. Moreover, determining the specific contribution of CAP dysfunction to cognitive decline could be challenging due to peripheral deficits that complicate the interpretation of results. Several studies found that central ARHL was implicated in MCI, dementia and AD. Two based-population studies demonstrated an association between central ARHL and AD, suggesting that CAP deficits may have predictive value for a later diagnosis of AD (Gates et al., 2002, 2011). Over an average of 8 years of follow-up, the presence of central hearing impairment was associated with a tenfold increased risk of developing probable AD (Gates et al., 2002). These findings were confirmed in a second longitudinal report, which found that people with severe central auditory dysfunction had an adjusted hazard ratio for incident AD of 9.9 over a 3-year follow-up (Gates et al., 2011). Yuan et al. (2018), in a pooled analysis of 11 studies, found that the relative risk for cognitive impairment in older individuals with moderate and severe CAP dysfunction was 2.42 and 3.21 respectively, compared to individuals with normal hearing. Therefore, central hearing deficits in cognitively intact older adults may be an early manifestation of probable AD and dementia, preceding the onset of diagnosis by many years (Panza et al., 2015).

Therefore, current evidence shows an association between hearing loss and cognitive decline, but the direction of this association has not yet been confirmed. Several factors may be involved in the pathways linking ARHL and cognition. To gain a better understanding of the underlying mechanisms for this association, a brief overview of the possible hypothesis explaining the direction of this association will be provided (Nixon et al., 2019; Panza et al., 2019; Slade et al., 2020; Wayne & Johnsrude, 2015).

The cognitive load on perception hypothesis

This hypothesis posits that cognitive decline causes sensory deficits by increasing cognitive load on perception (Wayne & Johnsrude, 2015). So, it is based on the concept of "resource allocation". Supporting evidence for this hypothesis is limited because few studies have shown cognitive impairment preceding ARHL (Nixon et al., 2019). One study demonstrated that cognitive decline increased hearing thresholds on PTA, but it relied only on a screening tool to assess cognitive functioning.

The sensory-deprivation hypothesis

According to this hypothesis, reduced sensory input caused by ARHL leads to cognitive decline, likely due to the reallocation of cognitive resources, which produces permanent neural alterations that impact cognitive performance in favor of auditory perception (Slade et al., 2020). Atrophy in areas of the auditory system, along with subsequent compensatory cortical reorganization, could be a potential mechanism underlying this hypothesis. Evidence of cortical reorganization due to sensory deprivation found increased reliance on frontal and posterior parietal networks and decreased activation in auditory areas during speech perception in older adults (Wayne

& Johnsrude, 2015). However, according to this hypothesis, hearing loss should precede the onset of cognitive decline through a causal link. But there are some people with cognitive impairment and normal hearing, indicating that ARHL does not always precede cognitive decline (Nixon et al., 2019). So, this hypothesis cannot fully explain this relationship. It has also been suggested that cognitive function could be indirectly affected by inadequate sensory input through social isolation and depression, which may mediate this association (Slade et al., 2020).

The information-degradation hypothesis

Like the sensory-deprivation hypothesis, the information-degradation hypothesis suggests that degraded perceptual input leads to cognitive decline by placing increased demands on limited processing resources (Nixon et al., 2019; Wayne & Johnsrude, 2015). Nonetheless, these two hypotheses differ in the impact of hearing on cognition. While the sensory-deprivation hypothesis emphasizes permanent changes in cognitive functioning, the information-degradation hypothesis suggests that the effect of perception on cognition is short-term and possibly reversible. From this last perspective, cognitive performance in older adults is compromised because mental resources are diverted from other cognitive tasks to compensate for impoverished auditory input. Therefore, greater cognitive resources such as attention, executive functions, and working memory are required in conditions of effortful listening (due either to normal aging or pathology) and fewer resources remain available for other cognitive processes essential for ongoing speech communication (Wayne & Johnsrude, 2015). For example, memory retention of words and sentences heard in degraded conditions tends to be weaker compared to those heard clearly, probably because high processing demand during perception interferes with encoding (Wingfield et al., 2005). Therefore, poorer auditory input and reduced processing resources are suggested explanations for older individuals' impaired memory. Overall, this hypothesis explains cognitive decline as the manifestation of fatigue from everyday effortful listening.

The common cause hypothesis

According to this fourth theory, decline in hearing (as well as other sense modalities) and cognitive functioning may result from a common causal mechanism, such as widespread age-related neural degeneration (Baltes & Lindenberger, 1997; Nixon et al., 2019). Concurrent age-related changes across multiple perceptual and cognitive domains may suggest a shared neurodegenerative etiology within the central nervous system (Wayne & Johnsrude, 2015). This age-related degeneration is characterized by reductions in volume and length of dendritic spine densities in multiple cortical regions, particularly pre-frontal regions. Therefore, a general slowing of processing could be the central deficit associated with aging that affects sensory function and cognition. Yet, it remains unclear the extent to which processing speed accounts for the association between hearing loss and cognition. This hypothesis is supported by evidence showing stronger correlation between sensorial and cognitive decline in older age (Baltes & Lindenberger, 1997). These authors, studying a sample of individuals aged 70 to 103 years, found that age-related differences in cognitive performance (e.g., reasoning, processing speed, memory, verbal fluency) were associated with measures of sensory functioning (visual and auditory acuity). They found that vision and hearing accounted for 52% of the variance in cognitive functioning. In addition, data from structural equation modeling support the presence of a common factor that influences age-related declines in both sensory and cognitive functions. However, a single account cannot explain all the data, suggesting that multiple mechanisms are likely involved (Wayne & Johnsrude, 2015).

Wayne & Johnsrude (2015) proposed a new framework to explain the relationship between hearing loss and cognitive decline, incorporating the information-degradation and common-cause hypotheses. They suggested a common cause approach, where deficits in one part of the system produce cascading effects in other parts (*Figure 3*). The first point involves age-related brain changes that lead to decline in sensory abilities (1) (e.g. ARHL) and increased demand on cognitive resources (2). Sensory deficits, resulting from both neurodegenerative processes and age-related pathology in the inner ear (3), produce greater perceptual difficulties (4), which recruit more mental resources (5). This increased demand on an already strained cognitive system (2) may lead to functional cognitive impairment (6). Additionally, reduced cognitive resources may exacerbate perceptual deficits (5) (e.g. deficits in attention or processing speed could interact with deficits caused by sensory decline). Finally, perceptual difficulties can affect communication, leading to negative psychosocial outcomes such as isolation and depression (7). These aspects may accelerate and worsen cognitive decline (8).

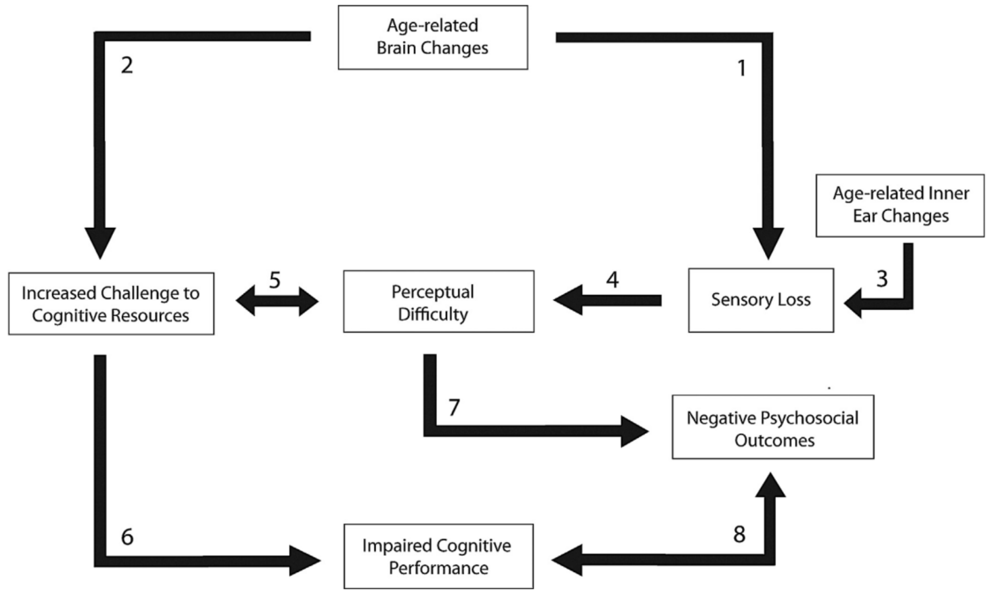

Figure 3: *The new framework proposed by Wayne & Johnsrude (2015) for conceptualizing the relationship between hearing loss and cognitive decline.* From Wayne & Johnsrude, 2015.

These authors emphasized that the majority of studies conducted up to now on the relationship between hearing and cognitive impairment evaluated hearing loss only on a peripheral level, with audiometric hearing threshold (PTA). Employing tests that assess central hearing abilities and collecting information about the nature of hearing loss could enhance our understanding of this association (Wayne & Johnsrude, 2015).

1.3 Fundamental cognitive mechanisms in aging

Cognitive aging is known to be a multidimensional and multidirectional process, in which different cognitive abilities follow distinct trajectories over time (De Beni & Borella, 2015). Indeed, not all cognitive functions are affected by aging in the same way: some abilities are more sensitive to aging, while others remain relatively stable over time and may even show improvements (De Beni & Borella, 2015). Additionally, as age advances, there is a notable increase in the correlations between different cognitive domains, corresponding with generalized decline in cognitive performance. These correlations are either absent or less pronounced in younger individuals. This observation led many researchers to propose the “dedifferentiation hypothesis”, suggesting that the cognitive structure of older adults is less differentiated compared to that of younger adults

(De Beni & Borella, 2015). Thus, it seems that in older individuals, cognitive abilities may be explained by a single general factor.

For this reason, the current literature on cognitive aging employs a global approach to better explain age-related cognitive changes. This integrated model analyzes how a limited number of general factors can be responsible for cognitive changes, considering aging as the result of modifications in the mental resources available for processing information (Salthouse, 1991). The concept of mental resources implies activating mechanisms that allow for processing a limited amount of information. In this sense, cognitive resources can be defined as "the quantity of mental processing power or mental energy that a given individual has available to use when performing a cognitive task" (Park, 2000). With aging, even in the absence of pathologies, these resources decrease in effectiveness, explaining the decline in performance. These general resources are usually associated with three fundamental cognitive mechanisms that seem to exert increasing influence throughout aging (De Beni & Borella, 2015):

- Processing speed (Salthouse, 1996).
- Attentional abilities and inhibitory control (Hasher & Zacks, 1988).
- Working memory capacity (Craik & Byrd, 1982).

The following sections will provide an overview on these primary mechanisms that influence the functioning of the cognitive system and explain its decline with aging.

1.3.1 Processing speed

Processing speed is a measure of how quickly an individual can process information (Park, 2000). It can be assessed through speed tasks that require individuals to respond as rapidly as possible or to provide the maximum number of responses within a specified time limit. Among the tasks that can be used for assessing processing speed there are perceptual speed tasks (e.g. rapidly comparing series of symbols or letters) and simple or complex reaction time tasks (e.g. quickly pressing a button when the target stimulus appears) (De Beni & Borella, 2015).

Cerella & Hale (1994) described response time as a U-shaped function. Specifically, during childhood, the time required for processing information is longer, but it increases in speed with development. In youth and early adulthood, a plateau phase begins where processing speed continues to increase (i.e., less time is required for processing information), followed by a gradual decline in processing speed in later adulthood and old age. Currently there is enough evidence supporting a decline on performance in processing speed across the lifespan (Park, 2000). The results of studies conducted in this field consistently and clearly demonstrate that older adults exhibit a reduction in processing speed compared to younger individuals. For this reason, this finding emerges as one of the most robust explanations for age-related changes (De Beni & Borella, 2015). At a neurobiological level, several changes that occur with aging could explain this generalized slowing in information processing. For instance, these changes may include a reduction in brain volume and weight (e.g., neuronal atrophy), modifications in dendritic arborization structure and myelination of nerve fibers, as well as a decrease in the density and efficacy of dopaminergic receptors (for a review see De Beni & Borella, 2015).

Along the lines of the general slowing hypothesis, Salthouse (1996) introduced the processing-speed theory. A key aspect of this theory is that the effects of age-related decline in processing speed are hypothesized to be global and to impair older adults' abilities to successfully complete cognitive tasks, even those that may not appear to have a clear speed component. To explain this, Salthouse (1996) proposed two mechanisms through which cognitive functioning is influenced by processing speed:

- The *limited time mechanism* suggests that "the time to perform later operations is greatly restricted when a large proportion of the available time is occupied by the execution of early operations" (Salthouse, 1996). This mechanism is particularly relevant when the execution of a task is under time pressure or when there are concurrent demands on processing.
- The *simultaneity mechanism* suggests that "the products of early processing may be lost by the time that later processing is completed (…) relevant information may no longer be available when it is needed" (Salthouse, 1996). This mechanism could be particularly relevant to age-related decline in working memory capacity.

According to this perspective, older adults would be slower and exhibit lower performance even in tasks that do not directly involve speed (e.g., working memory tasks). Indeed, their slowness, present already in the early stages of information processing, would also disrupt subsequent phases where the product of previous processing is no longer available or activated (De Beni & Borella, 2015; Park, 2000).

Evidence supporting the notion of a common general slowing factor contributing to age-related decline in cognitive performance comes from studies demonstrating processing speed as a reliable mediator of the relationship between age and other measures of cognitive functioning. In their meta-analysis, Verhaeghen & Salthouse (1997) found that processing speed can account for 79% of the variance in reasoning tasks, 72% in spatial ability tasks and, 70% in episodic memory measures. This evidence suggested that a significant portion of the age-related variance in many cognitive functions can be attributed to a general slowing in processing speed. Support for this argument also arose from empirical findings indicating a considerable reduction in age-related differences across various cognitive measures when controlling for variations in processing speed (De Beni & Borella, 2015). Therefore, there is evidence confirming the important role that processing speed plays during aging.

1.3.2 Attentional abilities and inhibitory control

It is known that older adults are slower and struggle more with top-down processes (i.e., processes that are controlled and demand more cognitive effort and attentional resources) (De Beni & Borella, 2015). Thus, the higher the demand for control and/or speed in a task, the more older adults are expected to be burdened. In the case of attentional tasks, it has been hypothesized that the greater difficulty encountered by older adults pertains to a specific aspect of control, namely inhibitory capacity (Hasher & Zacks, 1988; Persad et al., 2002). Therefore, the poor performance of older adults in attentional-demanding tasks could be attributed to a frailty in inhibitory control mechanisms.

Inhibitory processes have generally been defined as attentional mechanisms that suppress irrelevant stimuli (both endogenous and exogenous), helping to prevent interference with the efficient processing of target information (Hasher & Zacks, 1988). According to Hasher & Zacks (1988), who consider inhibition processes "fundamental regulatory mechanisms", much of the age-related decline in cognition could be attributed to older adults' difficulties in staying focused on primary information, as they tend to direct their attention to both relevant and irrelevant information (Park, 2000). In their view, inefficient inhibitory processes allow off-goal-path information to enter Working

Memory (WM), potentially resulting in lowered performance due to interference effects and response competition.

Hasher et al. (1999) proposed three interrelated functions of inhibitory processes:

- The *access* function prevents dominant (automatic) but goal-irrelevant information from accessing WM (encoding phase).
- The *deletion* function controls what is active in WM by suppressing the activation of any accidentally irrelevant activated information or no-longer-relevant information because goals may have shifted (N.B., irrelevant information can also become active due to an inefficient access function).
- The *restrain* function serves to prevent dominant but inappropriate responses from gaining control over thoughts and/or actions, allowing other, less probable responses to be considered.

Therefore, this theory posits that cognitive performance in older adults is impaired due to difficulties in selecting appropriate task-related representations and inhibiting irrelevant perceptual and memory representations, as well as irrelevant responses (De Beni & Borella, 2015). According to this model, the role of inhibition is primarily related to the control exerted over the temporary contents of WM, a cognitive system that is crucial for successful performance in different cognitive domains (Persad et al., 2002). These aspects have two main implications. The first is linked to the limited capacity of WM: inefficient inhibitory mechanisms allow irrelevant information to enter WM, saturating its limited capacity (Hasher & Zacks, 1988). This results in an overload of processing capacity due to the presence of excessive information which further depletes limited cognitive resources. The second implication concerns the secondary effects of impaired inhibitory control on tasks that rely on WM: any mechanism that affects WM efficiency will likely impact performance across a variety of tasks (Persad et al., 2002).

Evidence supporting this theory found that the deletion function of inhibition plays an important role in the proper functioning of WM in older adults (De Beni & Borella, 2015). For example, the directed forgetting paradigm, in which participants are presented with a list of words and instructed to remember or forget a word, have been used to study these aspects. It was found that older adults recalled fewer of the remember words and made more intrusions from the forget list (Persad et al., 2002). In addition, they retrieved a greater number of forget words when they were asked to recall them. These studies demonstrated that aging is characterized by difficulties in inhibiting information that has been previously activated (De Beni & Borella, 2015). Research focusing on the role of inhibitory mechanisms in daily life has highlighted that the presence of intrusive, irrelevant thoughts is common among older adults even in everyday situations (Borella et al., 2007). Despite these findings, consensus regarding the hypothesis of the centrality of inhibition in age-related decline is a subject of controversy, as some studies question the universality of this effect (Persad et al., 2002). Some authors argued the need to consider other factors like processing speed before interpreting the results in terms of inhibition (Verhaeghen & De Meersman, 1998). These authors in their meta-analysis revealed that age-related differences between young and older adults in certain inhibition tasks (i.e., negative priming) disappear when processing speed is taken into account.

1.3.3 Working Memory

Different models of WM have been proposed over these years, each with its own structural and functional definitions based on the theoretical approach adopted. A commonly accepted definition of WM described it as a multicomponent system that provides temporary storage and manipulation of information necessary for performing complex cognitive tasks (Baddeley, 1992; Baddeley & Hitch, 1974). Therefore, its primary function is to keep useful task-related representations active in memory, especially when distraction or irrelevant information are present. It is also accepted that WM has a limited capacity, allowing only a small amount of information to be active at any given time. All WM tasks, regardless of the type of material used (verbal, numerical, or visuospatial), require attention-demanding process on the presented material (active processing phase) and retaining information for subsequent recall (maintenance and recall phase) (De Beni & Borella, 2015). So, subjects are asked to store and process information simultaneously. For this reason, the management of attentional resources is a central feature of this system.

Studies on cognitive aging have empirically tested the hypothesis that changes in WM account for age-related cognitive changes. Generally, these studies shown that increasing age is moderately to strongly associated with lower performance on WM tasks, with correlations ranging from -0.39 to -0.52 (e.g., Salthouse & Babcock, 1991). A significant theoretical framework to explain age-related cognitive changes as the result of changes in working memory began with the proposal of Craik & Byrd (1982). According to these authors, older adults have a smaller pool of available attentional resources, which are indispensable for information processing. This results in less mental energy to carry out deep and elaborate processing, such as those required in working memory tasks. In fact, age-related deficits in attentional-executive WM control have been cited as a mechanism to explain declines in different tasks with age. To understand whether WM difficulties in older adults occur as a deficit in information maintenance rather than central-level processing (i.e., central executive component in Baddeley's model), studies compared young and older adults in short-term memory and WM tasks (e.g., Bopp e Verhaeghen, 2005). It was found that WM span tasks, which require active manipulation and thus more cognitive resources, were more sensitive to age compared to simple storage span tasks, which measure short-term memory. Therefore, tasks that demand higher processing are expected to exhibit greater age-related differences. Indeed, unlike simple span, WM tasks predicted performance in complex cognitive tasks such as test comprehension and reasoning (e.g., Brave & West, 2008). As previously mentioned, according to some authors the poorer performance of older adults on WM tasks may also be due to inefficient inhibitory processes (Hasher & Zacks, 1988). Inefficient inhibitory mechanisms can divert focus from relevant task's goals by allowing non-pertinent information to enter, thereby lowering cognitive performance and consuming limited storage capacity.

In conclusion, most studies on cognitive aging typically associate a reduction in resources and, thus, performance with one of the mechanisms described above (i.e., Processing speed, Inhibitory control, or Working memory). However, De Beni & Borella (2015) suggest that these primary factors should not be considered independent of one another. Indeed, processing speed is involved in performing inhibition tasks, just as inhibition contributes to explaining the decline in WM in older adults. Given the complexity of our cognitive system, an age-related decline in cognitive resources can be better explained and understood by considering the dynamic interaction between these fundamental mechanisms.

1.4 Age-related changes in speech understanding

The objective of this paragraph is to provide an updated overview of how speech understanding changes with aging and how age-related changes in cognition can directly affect an older person's ability to perceive and understand speech, particularly in challenging conditions (e.g., background noise). In this work, "speech understanding" refers to how a listener receives, processes, and recognizes spoken messages. This differs from "discourse comprehension", which involves interpreting meaning and providing relevant response to the content.

Older adults often complain about the difficulty of understanding spoken language, especially in challenging everyday situations where there is a noisy background or multiple speakers at once. Indeed, understanding speech requires a complex array of factors to be successful. The first report that tried to highlight the complex interplay of age-related changes in auditory and cognitive abilities affecting speech comprehension in older adults was published 35 years ago (Working Group on Speech Understanding and Aging, 1988). These authors have already explained that the effects of age on speech comprehension cannot be merely attributed to age-related differences in auditory sensitivity. Indeed, understanding speech obviously relies on proper cochlear function and an intact auditory pathway. However, this is not sufficient. Our knowledge of how speech understanding works can only be completed by considering the sensory (peripheral and central systems) and cognitive components within an integrated system (Nixon et al., 2019; Pichora-Fuller, 2003).

1.4.1 Auditory processing

As previously outlined, hearing difficulties can be attributed to a CAP disorder rather than a sensory impairment, particularly when normal hearing thresholds are observed in PTA, but poor performance is found in speech understanding in noisy situations. Auditory processing relies on different functions that allow to analyze and extract the various types of information contained in sounds. Indeed, it is important to understand the sound's origin (spatial information), how it changes in time (temporal envelopment and temporal fine structure), as well as its pitch and timbre (spectral information) (Brotto et al., 2023). One of the most studied functions is temporal resolution, which is the ability to perceive time-related changes in ongoing auditory stimuli (Nixon et al., 2019). Given that different temporal cues are important to detect particular aspects of speech processing, a decline in this domain may explain some difficulties that older adults experience in speech perception, especially in complex conditions (Pichora-Fuller, 2003). Age-related differences in temporal processing may be related to difficulties at the segmental level, where gap and duration cues determine phonemic contrasts and influence words identification (Pichora-Fuller & Singh, 2006). Although the role of duration and gap cues varies in the phonologies of different languages, detecting brief changes in sound over time is important for recognizing short sounds like consonants, particularly stop consonants. Temporal resolution is typically assessed using either the gap detection test or the gap-in-noise test, where participants are asked to detect the smallest possible gap present in a continuous sound or a noisy background (Brotto et al., 2023; Nixon et al., 2019). Different studies shown that gap detection and duration discrimination performance is poorer (i.e., longer) in many older adults compared to younger listeners (Pichora-Fuller, 2003). It seems that older adults require a gap size nearly twice as large as the smallest detectable gap for younger adults (approximately 6 vs 3 msec) (Pichora-Fuller & Singh, 2006). These authors stated that although age-related differences in gap detection ability may negatively affect speech perception, it also seems that older adults may compensate through phonological knowledge.

1.4.2. Cognitive factors

Recently, there has been an increasing awareness of the role of cognition on speech understanding. In response, Cognitive Hearing Science has emerged as a new field acknowledging the critical role of cognition in hearing and speech understanding. Measures across various cognitive domains have been linked to age-related differences in speech understanding performance in noise, even when controlling for differences in hearing sensitivity (Gordon-Salant et al., 2020). However, there is great variability across published studies in the choice of Speech-in-Noise (SiN) and cognitive tasks, as well as in the clinical characteristics of the samples. SiN tests can vary based on foreground signals (e.g., syllables, words or sentences), background signals (e.g., white noise, multiple talkers, one or two competing speakers), type of response (open and closed set), intelligibility level (Signal-to-Noise Ratio, that is the ratio of target signal intensity to background noise), as well as adaptive or nonadaptive paradigm (Dryden et al., 2018).

Each of these variations can change the manner or the extent to which cognitive processes are engaged. Dryden et al. (2018) attempted to summarize published studies to better understand the association between SiN performance and different cognitive domains in older listeners. They found an overall association between cognitive performance and SiN perception measures (r = .31). Regarding specific cognitive subdomains, they found associations between speech-in-noise performance and measures of inhibitory control (r = .34), working memory (r = .28), episodic memory (r = .26), crystallized intelligence (r = .13), and processing speed (r = .39). Depending on the type of data available, correlations were also performed between cognitive subdomains and specific speech target (words or sentences). When the SiN target was more complex (i.e., sentences), working memory (r = .34), crystallized intelligence (r = .29), and processing speed (r = .43) showed stronger correlations.

Beyond the variability that characterizes these studies, some trends can be found. Indeed, among the theories of cognitive aging, some can account for the difficulties older listeners encounter in speech understanding. According to some authors, the hypothesis of a general slowing in brain function could explain these difficulties, as cognitive slowing reduces older adults' ability to manipulate and integrate information (Pichora-Fuller, 2003). In adverse listening conditions, which increase processing demand, the listener struggles to disambiguate input, especially if there is little contextual support. As a result, the rate at which information is processed slows down, causing the person to miss pieces of information. Consistent with the general slowing hypothesis of processing speed (Salthouse, 1996), older adults' listening difficulties in noise may reflect an age-related decline in the rate at which various cognitive operations can be performed. This decline reduces the amount of information that can be fully processed and understood before it decays (see subparagraph 1.3.1).

These difficulties in SiN can be explained also through the inhibitory deficit hypothesis proposed by Hasher & Zacks (1988). Inhibitory control, as part of a broader executive system, prevents mental or external sources from interfering with goal-relevant information. Listening difficulties in noise among older adults may be attributed to an age-related decline in the efficiency of inhibition, which impairs their ability to focus on target speech and ignore irrelevant stimuli, leading to taking-up of resources from not pertinent information (Pichora-Fuller & Singh, 2006). Indeed, to achieve accurate speech understanding, the phonemes perceived must match the listeners' mental lexicon. This process can be more difficult depending on the number of words in the lexicon that have overlapping phonemes with the target word (i.e., neighborhood density) (Gordon-Salant et al., 2020). Because older adults may have inefficient inhibitory processes, resulting in less control over the activation (and suppression) of similar-sounding lexical candidates, they may require more time to distinguish a target word from similar-sounding alternatives (Ben-David et al., 2011). These aspects may be further exacerbated by the presence of noise that causes increased ambiguity in the identification of sounds. Therefore, alongside the general slowing account, inefficiency in inhibition could delay the recognition of words. This delay can occur because both the computation of auditory input and the capacity to discriminate a target word from alternative lexical candidates are slowed (Ben-David et al., 2011).

Another important factor that studies found to be involved in speech understanding in noise is working memory. Models of WM propose that when its capacity limits are exceeded because processing is too demanding (e.g., effortful listening conditions), comprehension will be slowed or errors will occur (Pichora-Fuller & Singh, 2006). In this context, Rönnberg (2003) and Rönnberg et al. (2008, 2013) proposed a unifying framework through the Ease of Language Understanding (ELU) model to clarify the role of WM and its interaction with other cognitive functions in supporting speech understanding in adverse conditions. According to this model, features of linguistic information are Rapidly, Automatically, and Multimodally Bound to form a PHOnological representation in an episodic buffer called RAMBPHO. In ideal listening conditions, RAMBPHO input matches a corresponding phonological representation in the mental lexicon stored in semantic Long-Term Memory (LTM). Then, lexical access can proceed rapidly and automatically (implicit process). In adverse listening conditions, information may not be precise enough to match phonological representations unambiguously (mismatch) because of signal distortion. This situation interrupts the RAMBPHO mechanism, delaying lexical access and increasing dependence on WM capacity (explicit process). Both implicit and explicit processes interact in parallel with phonological and semantic information. Indeed, the fast, implicit RAMBPHO mechanism continuously operates until a mismatch interrupts it. When this occurs, the mechanism restarts the analysis of the speech signal with the available information. At the same time, the mismatch triggers the system to engage the explicit, WM capacity-dependent, processing loop to "repair" discrepancies and infer missing information through top-down semantic and phonological knowledge. The output of the system is some level of understanding or gist (*Figure 4*). The prediction of this model is that in effortful listening conditions, individuals with high WM capacity will be better able to inhibit the mismatched representation and compensate for the distorted signal than those with low WM capacity.

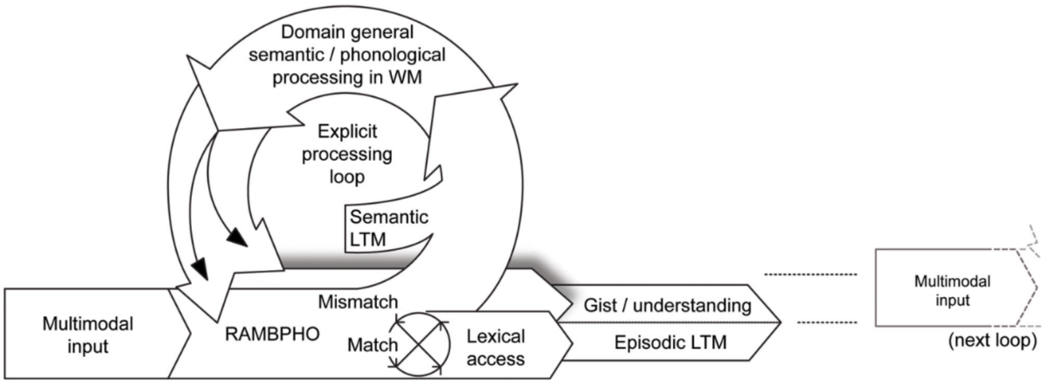

Figure 4: *The Ease of Language Understanding (ELU) model.* From Rönnberg et al., 2013.

Hence, optimal listening conditions with clear auditory signal typically demand minimal effort and seems to be quite automatic. However, when the quality of the signal is suboptimal, the effort required for successful recognition of speech increases. Additional top-down processes become necessary to compensate for signal distortion, leading to a greater demand for cognitive resources (Pichora-Fuller et al., 2016). Difficulties in understanding speech in noise may worsen in older adults due to age-related changes in fundamental cognitive mechanisms (i.e., processing speed, inhibitory control, and working memory). Additionally, aging itself implies a decline in the amount of available resources, which can be rapidly exhausted.

These studies outlined the importance of taking a holistic approach in studying speech understanding, considering the significant connection between auditory and cognitive performance in the perspective provided by the Cognitive Hearing Science.

CHAPTER 2 – THE EXPERIMENTAL STUDY

2.1 The aim of the study

This study aimed to investigate the relationship between cognitive functioning and central auditory processes in aging. The goals were twofold: 1) to identify the specific cognitive domains involved in speech-in-noise understanding in a sample of older adults with normal hearing, and mild hearing loss, and 2) to explore how decline in these cognitive domains may affect speech understanding in noise.

The prevailing framework in cognitive aging literature suggests that aging is typically accompanied by a decline in available cognitive resources, leading to rapid depletion as tasks become more challenging. Main changes in cognitive functioning with aging are primarily observed in the so-called "fundamental cognitive mechanisms", which include processing speed, inhibitory control, and working memory. In the case of pathological aging (i.e., neurodegenerative disorders), further resource depletion and worsened functioning in these domains may occur. Aging may also bring changes in CAP. Difficulties in these processes can interfere with a listener's ability to understand speech, especially in challenging listening conditions. In the context of speech understanding, cognition plays an important role. Key cognitive mechanisms, such as processing speed and executive functions, can be particularly involved in the processing of auditory information. As these cognitive abilities decline with age, and as listening in noisy environments significantly increases cognitive demand, understanding speech in noise can become further compromised for older adults.

Building on these assumptions, we hypothesized that poorer performance in specific cognitive tasks would be associated with difficulties in recognizing sentences in noise, particularly among those experiencing cognitive decline. According to recent models of speech understanding, we expected that processing speed and executive functions would play a significant role in speech recognition in noise. To the best of our knowledge, this is the first clinical Italian study to investigate this association by assessing CAP through the Italian Matrix Sentence Test in older adults.

2.2 Materials and methods

2.2.1 Participants

This clinical observational study was carried out thanks to the collaboration between the Geriatrics Division (Department of Medicine – DIMED, University of Padua) and the Complex Operative Unit of Otolaryngology (Padua University Hospital).

Participants were recruited among individuals referring to the Geriatrics Division, the Otorhinolaryngology Unit (University of Padua) or from other research team's acquaintances. The sample was composed of 38 participants (25 women and 13 men) with a mean age of 76.95 years. It was sorted into two groups: mild to moderate cognitive decline group (n = 21) and control group (n = 17).

2.2.2 Inclusion and exclusion criteria

Sample selection was conducted by referring to the inclusion/exclusion criteria listed below. The presence of such criteria is investigated through a semi-structured interview.

Inclusion criteria:

- Age ≥ 60 years.
- Capability to provide informed consent to participate.
- Being a healthy older adult or with a previous diagnosis of mild to moderate cognitive decline.
- Being an Italian native speaker.

Exclusion criteria:

- Severe cognitive/sensory/motor impairments that could interfere with the neuropsychological evaluation.
- Total score on Mini-Mental State Examination < 18.
- Current or past neurological or psychiatric diseases (diagnosed by a specialist).
- Current or past drugs/alcohol abuse.
- Presence of disabling hearing loss (> 35 dB).

2.2.3 Data collection

Participants were provided with an information sheet outlining the research project. Furthermore, they signed the written informed consent for participation and data treatment before starting the experimental procedures, in accordance with the Declaration of Helsinki. Data collection occurred confidentially (name-code) to guarantee the anonymity of participants. Some of the data was retrospectively obtained from past neuropsychological evaluations of participants (conducted no more than 1 month prior to the audiological assessment). The remaining data was extracted from participants' clinical records (socio-demographic variables, medical history, and any comorbidities).

2.2.4 Procedure

After recruitment, participants underwent two sequential sessions during which a neuropsychological assessment and an audiological evaluation took place.

The former occurred in the Geriatric Clinic where participants were cognitively assessed using, in a randomized order, the Cognitive Reserve Index Questionnaire (CRI-q) (Nucci et al., 2012), the Mini-Mental State Examination (MMSE) (Folstein et al., 1975; Magni et al., 1996), the Brief Neuropsychological Examination-2 (ENB-2) (Mondini et al., 2011) and two Reaction Time tests from the Vienna Test System (VTS) (www.schuhfried.at). During the first three tests, participants were seated in front of the examiner in a comfortable, quiet room. For a better management of digital administering (VTS) during the last tests the examiner was seated beside the patient.

In this study diagnosis of cognitive decline was carried out according to *Diagnostic and Statistical Manual of Mental Disorders* 5th edition criteria (APA, 2013) by specialists expert in the management of Neurodegenerative Disorders (geriatricians and neuropsychologists).

In the Otolaryngology Unit took place the audiological examination (with audiometric tests) which consisted of pure tone audiometry and the Italian Matrix Sentence Test (IMST; OLSA test) (Puglisi et al., 2015; Houben et al., 2014). The evaluation was conducted by skilled audiologists and technicians experienced in hearing care.

Further details of the materials and tools used will be provided below.

2.2.4.1 Neuropsychological Assessment

The Neuropsychological Assessment included both digital and paper-and-pencil tests. The administration lasted around one hour and a half overall.

Cognitive Reserve Index Questionnaire (CRI-q) (Nucci et al., 2012).

The CRI-q is used to estimate the amount of Cognitive Reserve (CR) accumulated by an individual during the lifespan (Nucci et al., 2012). It was administered in its digital version (free and available here: http://cvi.math.unipd.it/CRIq/). Through a semi-structured interview, main demographic data are collected, followed by 20 items assessing the three primary markers of CR: level of education (i.e., years of schooling and training course; CRI-Education), working activity (types and number of years of employment from 18 years; CRI-Working Activity) and leisure time (frequency for different cognitively stimulating activities; CRI-Leisure Time). Each of these three sections returns a sub-score, whereas the total CRI-q score is the average of the three sub-scores, standardized and transposed to a scale with a mean of 100 and a standard deviation of 15 (Nucci et al., 2012). Since the CRI-q can be administered to family members, to reduce potential inaccuracies related to the clinical characteristics of a subset of the sample, in some cases suspect information was integrated administering the questionnaire to caregivers. The estimation of cognitive reserve using the CRI-q was carried out also for supporting diagnosis, aiming to gain a deeper understanding of cognitive functioning, which may not necessarily reflect the underlying degenerative process.

Mini-Mental State Examination (MMSE) (Folstein et al., 1975; Magni et al., 1996)

The MMSE is a widely used screening test to assess global cognitive function in the elderly through items that evaluate orientation to time and place, memory, attention, language, and visuospatial abilities. The maximum total score is 30 and a cut-off value < 24 indicates cognitive impairment. It takes only 5-10 minutes to administer.

In this study the MMSE was used as a rapid cognitive assessment tool for a standardized and efficient screening process. It facilitated the selection of participant by excluding those with severe cognitive decline (the cut-off value of MMSE < 18 was chosen).

Brief Neuropsychological Examination-2 (ENB-2) (Mondini et al., 2011)

The ENB-2 is a neuropsychological paper-and-pencil screening battery that provides a more comprehensive evaluation of cognitive functions. It consists of sixteen tests that assess different cognitive domains. By combining the scores of each test, the ENB-2 provides a total score that represents a comprehensive measure of an individual's cognitive state. The maximum total score is 100, which is obtained by summing the weighted score of each test in the battery. The cut-off value (for both the global score and the individual test scores) depends on age and education level, the latter categorized as either "low" or "high" level. The entire protocol takes approximately one hour to administer.

A brief description of these tests will be provided below.

Digit span – This test assesses attention and short-term memory capacity. The subject is asked to repeat orally presented sequences of digits of increasing length. It is measured the number of digits an individual can immediately repeat in the same order as presented by the examiner (forward order). The maximum achievable score is eight. The subject's memory span corresponds to the number of the last series of digits correctly reported.

Immediate and delayed recall prose memory – These tests primarily assess long-term memory capacity, but they also evaluate verbal comprehension and the ability to organize information to create a coherent and meaningful discourse. After listening to a short story, the person is asked to recall what he/she remembers both immediately and after a 5-minute distracting visual task. The total number of items that can be reported for each recall is 28.

Interference memory test (10 or 30 seconds) – These tests evaluate working memory capacity while the subject is engaged in an interfering task that impedes subvocal rehearsal. The subject is asked to read and memorize three visually presented consonants in the correct order. Then, they count by twos from a given number for a duration of 10 seconds (first test) or 30 seconds (second test). Afterward, the subject must recall the triplet of letters. This procedure is repeated three times for each test, and it is identical for both tests except for the duration of interference. One point is awarded for each correctly recalled letter in the right position, with a maximum of nine points per test.

Trail Making Test–A (TMT-A) – This test serves as a measure of visuospatial search, selective attention, and psychomotor speed. Subjects are instructed to connect, in ascending order, 25 numbers randomly arranged on a page as quickly as possible without lifting the pencil. The time taken to complete the task is recorded.

Trail Making Test–B (TMT-B) – Beyond the processes measured in TMT-A, this test also assesses working memory, divided attention, switching attention, and cognitive flexibility. Subjects alternate linking between numbers in ascending order and letters in alphabetic order. This requires constantly maintaining and updating attention on these two alternating series (numbers and letters). The time taken to complete the task is recorded.

Token test – This is a shorter version of the original task commonly used in language test batteries to evaluate verbal comprehension. The ENB-2 version assesses the subjects' ability to execute simple and precise verbal orders in the absence of pragmatic information. The subject is asked to perform five different orders from the examiner using ten tokens of different colors. One point is given for each correctly executed order.

Phonemic fluency test – It evaluates lexical access and retrieval, as well as executive functions through the ability to develop an effective search strategy without making intrusions or repetitions. The person has to produce as many words as possible that begin with a given letter (C, P, and S) within one minute. Names of people or cities are not allowed. The maximum score is based on the total number of correct words reported within the allotted time.

Abstract reasoning – This test aims to evaluate abstract thinking and reasoning. Subjects must identify the semantic category shared between two terms (e.g., pasta and milk). Three pairs of words are presented, and the maximum achievable score is six, with two points awarded for each correctly identified category.

Cognitive estimation – This test evaluates various components of executive functions, including reasoning, problem-solving, and cognitive flexibility. The subject is presented with five questions that lack definitive and precise responses, requiring answers to be estimated based on personal experience and general knowledge. Each answer has an acceptable range within which the response is considered correct. The maximum total score is five.

Overlapping figures test – This test evaluates visual perceptual function by assessing subjects' ability to discriminate figures from background. It also measures their ability to monitor performance and inhibit provided responses. Subjects are instructed to identify as many shapes as possible within a complex image of overlapping figures within four minutes.

Spontaneous drawing – This test is used to evaluate access to the mental representation of an object and praxis abilities. The task requires drawing a daisy with a stem and one leaf. A maximum of two points can be assigned for this test.

Copy drawing – Through this task is possible to assess praxis and visuospatial constructional abilities. In this test is required to copy a drawing house, which is a complex but extremely familiar figure. A maximum of two points can be assigned for this test.

Clock Drawing Test (CDT) – This well-known and useful test assesses executive functions (e.g., planning, reasoning), visuospatial and praxis abilities, as well as access to the mental representation of a clock. Subjects are asked to draw a clock with all the numbers and to place the hands at a specific time. The maximum achievable score is ten, determined by points obtained in three main categories: presence of all numbers, organization of numbers in the quadrant, and accuracy of placed hands.

Praxis test – It evaluates a person's ability to perform gestures with and without specific meanings, thereby assessing potential presence of apraxia. The examiner may ask the subject to pantomime common actions, perform meaningful gestures, or copy the examiner's meaningless gestures using hands or arms. A maximum of six points can be assigned based on performance in this test.

In this study the ENB-2 was chosen as a comprehensive tool for swift and efficient administration, updated for the current Italian population, enabling an accurate overview of an individual's cognitive functioning.

Reaction Time Tests (from the VTS) (www.schuhfried.at)

The Reaction Time tests (RT) were used in order to evaluate information processing speed in its two components of cognitive and motor reaction times. To achieve a comprehensive assessment of reaction time two different forms of the task were selected: the Simple Reaction Time test (RT/S1) and the Complex Reaction Time test (RT/S3).

These tests were administered using the Vienna Test System, a specific software developed by Schuhfried for digital psychological testing. Participants were seated in front of a 17.3-inch monitor of a Toshiba Satellite Pro notebook. All device's technical requirements were followed in accordance with the instructions provided by the user manual of the company. For a precise measurement Schuhfried developed an ergonomic, user-friendly response panel (*Figure 5*). This input device is particularly suitable for respondents with little computer experience (Schuhfried, 2006), that is older adults' population in most cases. The panel is composed of different colored buttons, but the ones relevant to the selected RT tests are the rectangular black button (reaction button) and the gold touch-sensory key (rest button). Participants were instructed on how to use these buttons when a relevant stimulus appeared on the monitor. At the beginning the respondent is requested to place the index finger of the dominant hand on the gold sensor key and to press the black button moving the same finger when the target stimulus appears. Then he/she must promptly return the finger to the rest button. Participants were exhorted to react as quickly and accurately as possible. Instructions were the same for both tasks, with the only difference being the target stimulus to which participants must pay attention. Furthermore, the system provides a practice phase in order to ensure that the participant has fully understood the instructions.

Figure 5: *The Universal Response Panel developed by Schuhfried used in this study for the administration of RT tests (S1 and S3 forms).*

A detailed description of RT tests administered in this study is provided below.

- The **RT/S1** is a simple Reaction Time task. Participants are requested to react as fast as possible when a yellow light appears on the screen (visual target). In this test only the relevant stimulus is presented, thus incorrect reactions are not possible, and all stimuli require a reaction (Prieler, 2012). The practice phase consists of five stimuli, whereas during the test phase 28 stimuli are presented.

The presentation of each stimulus lasts 1 second, but the time inter-stimulus changes (ranging from 2.5 to 6.5 seconds). The administration takes approximately seven minutes, including instructions.

- The **RT/S3** is a choice Reaction Time task. In this more complex version of RT tests a sequence of yellow and red lights, a tone (at 2000 Hz) and combinations of these stimuli is presented (e.g., yellow light alone, red light and tone simultaneously). Participants are instructed to respond only when a combination of yellow light and tone appears simultaneously (visual and acoustic targets). This version of the test includes an inhibition component, requiring participants to withhold responses to other combinations of stimuli (non-target stimuli) and react only to the target combination. Consequently, in this test format incorrect reactions are possible. A minimum of nine practice stimuli precedes the test phase. The latter consists in the presentation of 48 stimuli, of which 16 require a reaction. Each stimulus is presented for 1.2 seconds, whereas the length of pause between stimuli changes (ranging from 1.5 to 4.0 seconds). The administration takes approximately nine minutes, including instructions.

Thanks to the use of a rest key and a reaction key in these two forms of RT tests is possible to distinguish Cognitive reaction time from Motor time. The former is the time (msec) that elapses between the presentation of the target and when the finger leaves the rest button (*Figure 6A*). The latter measures the time (msec) between the moment the finger leaves the rest button and the time the reaction button is pressed in response to the relevant stimulus (*Figure 6B*) (Prieler, 2012). In this way the two main variables automatically calculated for each test and of main interest for this study were the Mean Reaction Time and the Mean Motor Time.

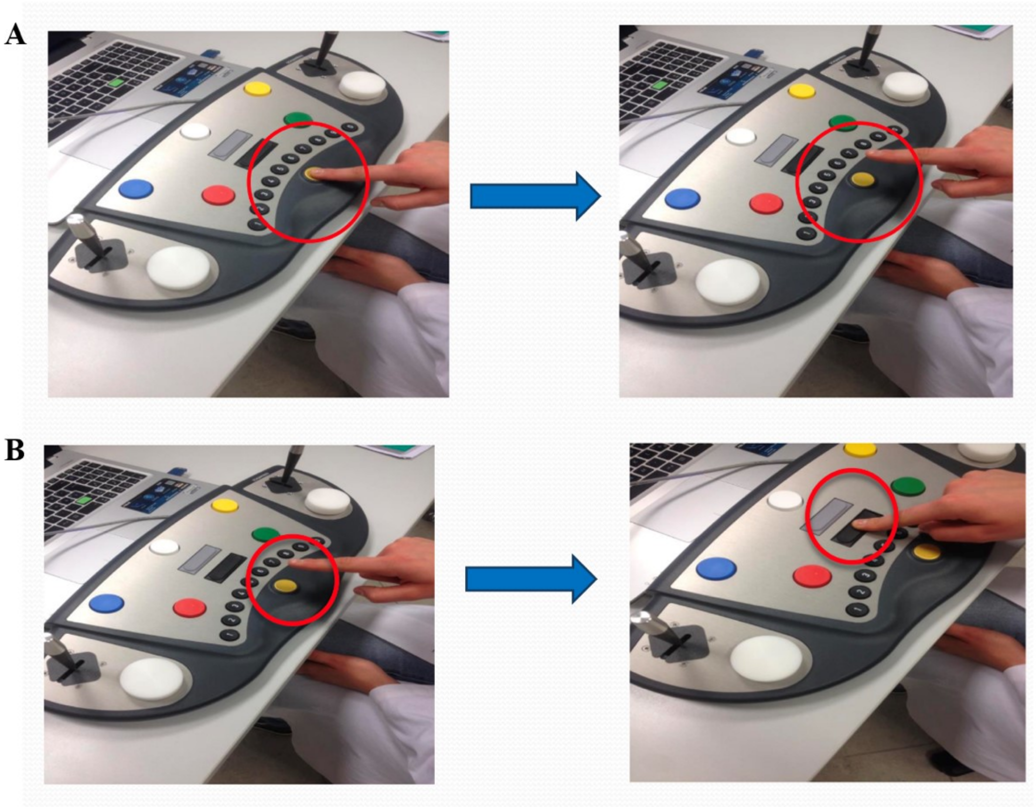

Figure 6: *The figures illustrate the distinct phases of Cognitive and Motor response time. Figure **A** depicts the interval from target stimulus presentation to the finger leaving the rest button (gold key), representing Cognitive reaction time. Figure **B** shows the interval from the finger's departure from the gold key to pressing the reaction button (black button), representing Motor reaction time.*

2.2.4.2 Audiological Assessment

All tests were performed in a soundproof audiometric booth. The assessment lasted around one hour overall.

Pure Tone Audiometry

Pure Tone Audiometry is a subjective and behavioral measure that was performed to assess peripheral hearing functioning. It was administered using the Otometrics MADSEN® Astera^2 audiometer, the Otosuite software (Natus Medical, Taasrup, Denmark) and a set of TDH39 standard headphones. Pure tone audiometry for air conduction tests different frequencies (Hz) at different intensities (dB HL). It consisted of pure tones emitted at specific frequencies (ranging from 250 to 8000 Hz) in octave intervals. The test is conducted for each ear separately. For the estimation of hearing threshold is followed “the method of limits”. Testing started at 1000 Hz (center frequency) and the tone is emitted at a clearly audible level (dB) of this frequency (Walker et al., 2013). Then the intensity is progressively reduced by steps of 10 dB until the subject no longer reports the presence of the acoustic stimulus (Lovato, 2023). After the test is repeated in an ascending sense (increasing intensity) until the subject responds. This process is repeated for each frequency (high and low ones, respectively). By this way, the minimum intensity perceived by the patient is identified for each frequency (hearing threshold level). In this study participants responded by rising a hand. Results are graphically represented in an audiogram (frequency and intensity are recorded on the horizontal and vertical axis, respectively.)

The Pure Tone Average (PTA) is an outcome measure calculated by averaging hearing thresholds for mid frequencies (500, 1000, 2000 and 4000 Hz). This value outlines an individual’s hearing level for each ear. Although, according to the WHO (2021) classification, mild hearing loss stars from 20 to 35 dB hearing level, in this study the cut-off for hearing impairment was set at a PTA in the better ear higher than 35 dB. This choice was made considering definitions of the WHO (2021) and the concept of socially useful hearing. Indeed, with a hearing loss under 35dB, most everyday speech sounds can be still perceived without significant difficult.

In addition, for the sake of completeness, in this study speech audiometry was performed qualitatively to confirm results from pure tone audiometry. Simple two-syllables Italian words were used as verbal stimuli (Turrini et al., 1993). By this way, it was possible to ascertain hearing threshold emerged during tonal investigation.

Italian Matrix Sentence Test (IMST) (Puglisi et al., 2015)

The IMST is an adaptive speech audiometry test with competing noise. It measures the Speech Reception Threshold (SRT), defined as the Signal-to-Noise-Ratio (SNR, in dB) capable of eliciting 50% of intelligibility (Soi et al., 2017). Since both previous tests are performed in a silent booth, they do not accurately reflect a real-life situation. The IMST, otherwise, aims to reproduce real-life speech perception conditions within a clinical setting.

The reference software is the Oldenburg Measurement Application (OMA), developed by the University of Oldenburg (Germany), used with standardized Italian language acoustic material. The standardization in Italian language was conducted by Puglisi et al.

(2015) from the Polytechnic University of Turin. For this test was used an open-set response format in free field. Participants were positioned 1 m away from a frontal loudspeaker, which emits both the speech material and the background noise.

The speech material consists of a matrix of 50 phonetically balanced two- and three-syllabic words, from which possible everyday life-related sentences are derived (Soi et al., 2017). The automated system generates 5-word sentences that have the same fixed grammatical structure (name, verb, numeral, noun, adjective), are syntactically correct but semantically unpredictable (Brotto et al., 2023) (*Figure 7*). In this study, before the measurement session, listeners were familiarized with the speech material by presenting five trial sentences. Then, a total of 20 random sentences were presented to the participant together with a competing noise that was kept constant at 65 dB sound pressure level, thus the SNR was determined by the speech signal level. The masking noise derives from a 30-fold overlapping of all the sentences, and it has the same long-term spectrum of the speech material (Puglisi et al., 2015). Subjects were asked to repeat the words/phrases they detected. Responses were recorded using word-scoring (each word of a sentence is scored separately). This test is defined "adaptive" because the speech material varies in intensity based on the subject's responses: speech signal intensity increases if more than 50% of responses are incorrect, whereas it decreases if more than 50% of responses are correct. Thus, the test difficulty increases as the participant understands more words.

Thanks to the main features of this test (e.g., the unpredictability of sentences and the high number of possible words combinations), the repetitive training effect associated with the memorization of verbal material (often observed in audiometric tests with limited verbal material) can be prevented, avoiding an overestimation of results (Soi & Ambrosetti, 2017).

The test provides three main parameters: (1) the SNR in dB at which the subject recognizes 50% of the listened words, even if not in the same sentence (SNR-SRT); (2) the slope of the discrimination function at SRT, which is the ratio between the percentage of recognized words and the intensity of the signal at SRT (%/dB); (3) the intelligibility score, expressed as a percentage of whole sentences understood.

For the purpose of this study, only the SNR value will be considered. This value is automatically obtained by subtracting the intensity of the noise from that of the words. It can be positive or negative: the more negative the value, the better speech discrimination in noise. According to Brotto et al. (2019), in this study the mean reference level of the SNR dB (SRT) for the older population corresponded to -0.4 dB.

Names	*Verbs*	*Numerals*	*Nouns*	*Adjectives*	*English translation*
Sofia	compra	due	**scatole**	azzurre	*Sofia buys two light-blue boxes.*
Marco	vuole	poche	matite	piccole	*Marco wants a few small pencils.*
Anna	prende	quattro	tazze	normali	*Anna takes four normal cups.*
Sara	**dipinge**	cinque	pietre	nuove	*Sara paints five new stones.*
Chiara	vede	**molte**	tavole	belle	*Chiara sees many nice desks.*
Maria	cerca	sette	palle	bianche	*Maria looks for seven white balls.*
Luca	trascina	otto	macchine	grandi	*Luca drags eight big cars.*
Andrea	regala	nove	sedie	**utili**	*Andrea donates nine useful chairs.*
Matteo	possiede	dieci	bottiglie	nere	*Matteo owns ten black bottles.*
Simone	manda	venti	porte	rosse	*Simone sends twenty red doors.*

Figure 7: *Basic word matrix of the Italian Matrix Sentence Test. Bolded words indicate an example of one randomly built-up sentence.* From Puglisi et al., 2015.

CHAPTER 3 – DATA ANALYSIS AND RESULTS

3.1 Statistical Analysis

All participants completed the neuropsychological (CRI-q, MMSE, ENB-2, RT tests) and audiological evaluations (Pure tone audiometry and IMST). Therefore, analyses were performed on these variables. However, to address the main objectives of this study and in accordance with current literature on speech-in-noise understanding in adult aging, an a priori selection of variables was performed. As a measure of cognitive function ENB-2 total score was chosen. Among the ENB-2 tests included in the analysis there are *Digit Span*, which assesses attention and phonological short-term memory storage; *Trail Making Test–A*, which measures attention and psychomotor speed; *Interference Memory test* (10" and 30"), which evaluates WM capacity and susceptibility to interference under two different levels of difficulty; *Phonemic Fluency test*, which assesses lexical access and retrieval; and *Clock Drawing test*, which measures executive control functions. These specific variables were chosen because, along with RT tests, they represent a reliable measure of those functions (i.e., executive functions, working memory and processing speed) that may be involved in understanding speech in noise. Additionally, CRI-q was included in the analysis, as we hypothesized that cognitive reserve could be an important factor in supporting cognitive effort. Thus, this a priori selection aims to identify a subset of cognitive predictors that can help explain performance on the IMST.

The main descriptive indices were calculated. Demographic and clinical characteristics of participants are expressed as Mean (*M*) and Standard Deviation (*SD*) for continuous variables, and as frequencies and percentages for categorical variables. The normality of each variable was evaluated by means of histograms and the Shapiro-Wilk test. Independent sample Welch's t-tests were then performed to verify the existence of significant differences in the main continuous variables between groups (cognitive decline group and control group). To investigate the association between the IMST and selected cognitive variables that will be included in the regression model, Spearman's correlation coefficient was calculated due to the non-normal distribution of data. Multiple regression analysis with stepwise selection was performed to identify the best subset of predictors among the selected cognitive variables to explain IMST scores. All variables included in this model were standardized to a mean of zero and a standard deviation of one, in order to permit a comparison among their values. Lastly, to detect potential multicollinearity problems among the variables selected by stepwise regression in the best model, the Variance Inflation Factor (VIF) was computed. The smallest possible value for VIF is one (i.e., complete absence of collinearity). Typically, a VIF value that exceeds five or ten indicates a problematic amount of collinearity (James et al., 2017).

All analyses were carried out using R Software (version 4.3.1; R Core Team, 2023). All statistical analysis were two sided; a significance level (α) of 0.05 was considered.

3.2 Results

3.2.1 Demographic and clinical characteristics of the sample

The final sample consisted of 38 participants (25 women and 13 men) with a mean age of 76.95 years (*SD* = 5.33). The mild to moderate cognitive decline group (n = 21; females = 13) had a mean age of 77.33 years (*SD* = 4.95) and a mean education of 11.10 years (*SD* = 5.17). The control group (n = 17; females = 12) had a mean age of 76.47 years (*SD* = 5.89) and a mean education of 9.59 years (*SD* = 4.84).

The normality of variables was evaluated by observing distribution plots (histograms) and using the Shapiro-Wilk test to ensure that the appropriate statistical methods are chosen.

Independent sample Welch's t-tests were performed to ensure the comparability of groups. No significant differences emerged between the control group and the cognitive decline group in terms of age ($p = .633$), education ($p = .360$), and CRI-q ($p = .082$). This indicates that the two groups were comparable in key demographic variables, reducing the risk of confounding variables influencing the results.

Neuropsychological assessment

Welch's t-tests were also conducted to compare the means of the two groups on neuropsychological examination tests. Predictably, the cognitive decline group had significantly lower total scores on MMSE (*M* = 25.29; *SD* = 2.59) compared to the control group (*M* = 27.88; *SD* = 1.65), $t_{(34)} = 3.76$, $p = .001$. A similar result was found for ENB-

2, where the cognitive decline group (*M* = 58.90; *SD* = 11.72) significantly differed from healthy-matched controls (*M* = 69.91; *SD* = 8.18), $t_{(35)}$ = 3.40, *p* = .002 (*Figure 8*). Additionally, sub-tests of ENB-2 that also showed significant differences, with the cognitive decline group performing lower than the control group, included Interference Memory – 30" $t_{(30)}$ = 4.03, $p < .001$ (*M* = 3.10; *SD* = 1.89 for the cognitive decline group and *M* = 5.94; *SD* = 2.36 for the control group), and Clock Drawing Test $t_{(36)}$ = 2.46, *p* = .019 (*M* = 6.02; *SD* = 3.44 for the cognitive decline group and *M* = 8.41; *SD* = 2.53 for the control group). Other included ENB-2 tests and RT tests did not show any significant differences between groups. However, in RT/S1 and RT/S3, the cognitive decline group exhibited higher average response times (mean score is 378.05 ± 113.18 for RT/S1 and 647.90 ± 173.42 for RT/S3) compared to the control group (mean score is 324.65 ± 47.40 for RT/S1 and 566.65 ± 93.74 for RT/S3). These differences, however, did not reach statistical significance for either RT/S1 (*p* = .060) or RT/S3 (*p* = .075).

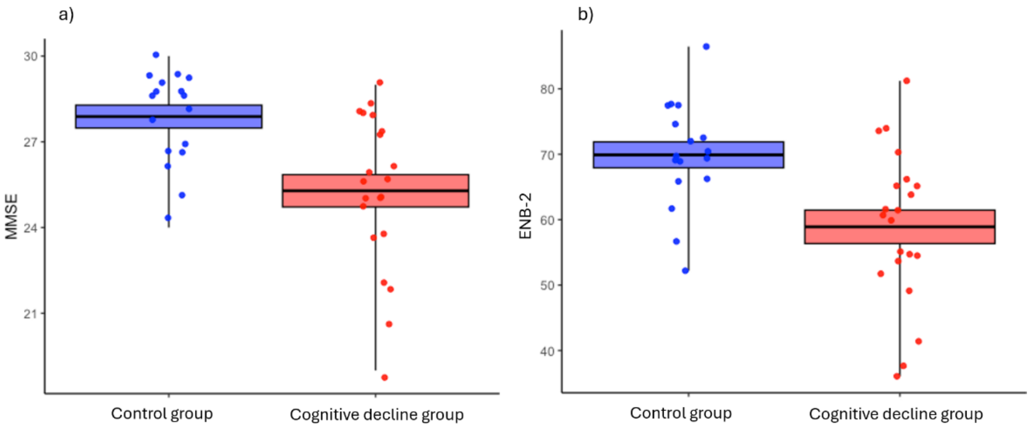

Figure 8: *Box plots showing the distribution of global cognitive functioning assessed with* ***(a)*** *MMSE and* ***(b)*** *ENB-2 in the control group and the cognitive decline group. The cognitive decline group had significantly worse performance than the control group.*

Audiological assessment

Audiological measures were compared between the two groups. No significant differences emerged between the control group and the cognitive decline group in PTA (dB HL) for the right ear (p = .319) and the left ear (p = .077), suggesting that the mean hearing threshold was similar in both groups. Additionally, there were no significant differences in hearing levels between the right and left ears within the control group (p = .682) and the cognitive decline group (p = .760). Lastly, participants with cognitive decline showed significantly higher scores on the IMST (M = -1.39; SD = 1.91) compared to those with normal cognitive functioning (M = - 2.76; SD = 0.86), thus performing worse, $t_{(29)} = -2.94$, p = .006. Indeed, the cognitive impairment group needed higher SNR values for hearing in noise (*Figure 9*).

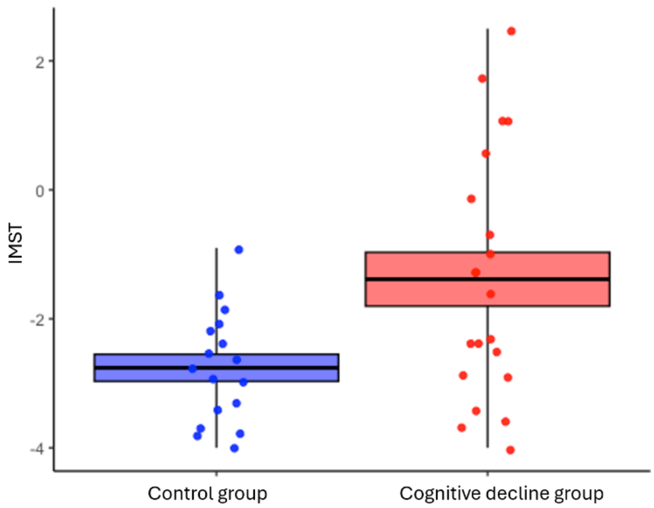

Figure 9: *Box plot showing the distribution of scores on the Italian Matrix Sentence Test (IMST), expressed as Signal-to-Noise Ratio (dB), in the control group and the cognitive decline group. On average, participants with cognitive decline showed significantly higher scores on the IMST than controls.*

The means and standard deviations for the main demographic, cognitive and audiological characteristics of the sample, as well as significance level on t-test, are reported in *Table 1*.

Table 1. *Descriptive demographic and clinical characteristics of the sample.*
Continuous variables are showed as Mean ± Standard Deviation, while frequencies as numerosity (%).

	Cognitive decline group n = 21	**Control group n = 17**	**P-value t-test**
Demographic characteristics (M ± SD)			
Age	77.33 ± 4.95	76.47 ± 5.89	0.633
Sex, ♀ (n, %)	13 (59.09)	12 (70.59)	
Education (years)	11.10 ± 5.17	9.59 ± 4.84	0.360
CRI-q	109.14 ± 19.81	97.88 ± 18.84	0.082
Neuropsychological assessment			
MMSE	25.29 ± 2.59	27.88 ± 1.65	**0.001**
ENB-2	58.90 ± 11.72	69.91 ± 8.18	**0.002**
Digit Span	4.95 ± 1.07	5.00 ± 0.87	0.880
Trial Making Test–A (sec.)	57.67 ± 24.82	50.59 ± 18.29	0.319
Interference Memory–10”	5.38 ± 2.38	5.88 ± 2.26	0.511
Interference Memory–30”	3.10 ± 1.89	5.94 ± 2.36	**< 0.001**
Phonemic Fluency test	9.53 ± 4.37	10.77 ± 3.20	0.319
Clock Drawing Test	6.02 ± 3.44	8.41 ± 2.53	**0.019**
RT/S1 (msec.)	378.05 ± 113.18	324.65 ± 47.40	0.060
MT/S1 (msec.)	337.33 ± 89.37	292.65 ± 109.32	0.184
RT/S3 (msec.)	647.90 ± 173.42	566.65 ± 93.74	0.075
MT/S3 (msec.)	354.52 ± 85.39	299.65 ± 114.56	0.112
Audiological assessment			
PTA dB HL Right Ear	23.15 ± 7.21	20.96 ± 6.20	0.319
PTA dB HL Left Ear	23.85 ± 7.34	20.15 ± 5.15	0.077
IMST, SNR (dB)	-1.39 ± 1.91	-2.76 ± 0.86	**0.006**

Notes. n: sample size; F: females; CRI-q: Cognitive Reserve Index questionnaire; MMSE: Mini-Mental State Examination; ENB-2: Brief Neuropsychological Examination-2; RT: Reaction Time; MT: Motor Time; PTA: Pure Tone Average at 0.5, 1, 2, and 4 kHz (mean in dB Hearing Level); IMST: Italian Matrix Sentence Test; SNR: Signal-to-Noise Ratio. Bolded values indicate significant results.

3.2.2 Correlation analysis

All correlations were performed using Spearman’s correlation coefficient, given the non-normal distribution of the variables. A correlation matrix for audiological (IMST) and neuropsychological (CRI-q, ENB-2, Digit Span, Interference Memory 10” and 30”, Phonemic Fluency test, Clock Drawing test, TMT-A, RT/S1, MT/S1, RT/S3, and MT/S3) measures was carried out. As expected, significant correlations were found between IMST and various neuropsychological variables, as shown in *Figure 10*. This operation also allowed for the investigation of possible associations among the cognitive variables themselves.

The IMST was moderately negatively correlated with ENB-2 total score (*r* = -0.488; *p* = .002), Digit Span (*r* = -0.378; *p* = .019), Interference Memory 30” (*r* = -0.549; *p* < .001), and Phonemic Fluency test (*r* = -0.576; *p* < .001). Instead, IMST showed a moderate positive correlation with TMT-A (*r* = 0.373; *p* = .021), RT/S1 (*r* = 0.610; *p* < .001), and RT/S3 (*r* = 0.540; *p* < .001). These results suggest that higher scores on cognitive tests are associated with better performance on the IMST, as indicated by lower SNR values that reflect better recognition of speech in noise.

Additionally, significant correlations were observed among neuropsychological variables. Specifically, the ENB-2 total score showed significant correlations with included subtests, such as Interference Memory 10” (*r* = 0.374; *p* = .021), Interference Memory 30” (*r* = 0.646; *p* < .001), Phonemic Fluency test (*r* = 0.620; *p* < .001), Clock Drawing test (*r* = 0.647; *p* < .001), and TMT-A (*r* = -0.630; *p* < .001), but not with Digit Span. Furthermore, the ENB-2 total score was negatively correlated with RT/S1 (*r* = -0.323; *p* = .048), but not with other RT tests. Moderate correlations were found between the Phonemic Fluency test and measures of executive functioning and processing speed. For example, Phonemic Fluency was positively associated with the Clock Drawing test (*r* = 0.341; *p* = .036) and negatively associated with TMT – A (*r* = -0.564; *p* < .001), RT/S1 (*r* = -0.474; *p* = .003), RT/S3 (*r* = -0.497; *p* = 0.002), and MT/S3 (*r* = 0.406; *p* = .013). Lastly, RT tests significantly correlated with each other. The strongest associations were found between RT/S1 and RT/S3 (*r* = 0.795; *p* < .001), as well as between MT/S1 and MT/S3 (*r* = 0.742; *p* < .001). Additional correlations are not described here but can be referenced in *Figure 10*.

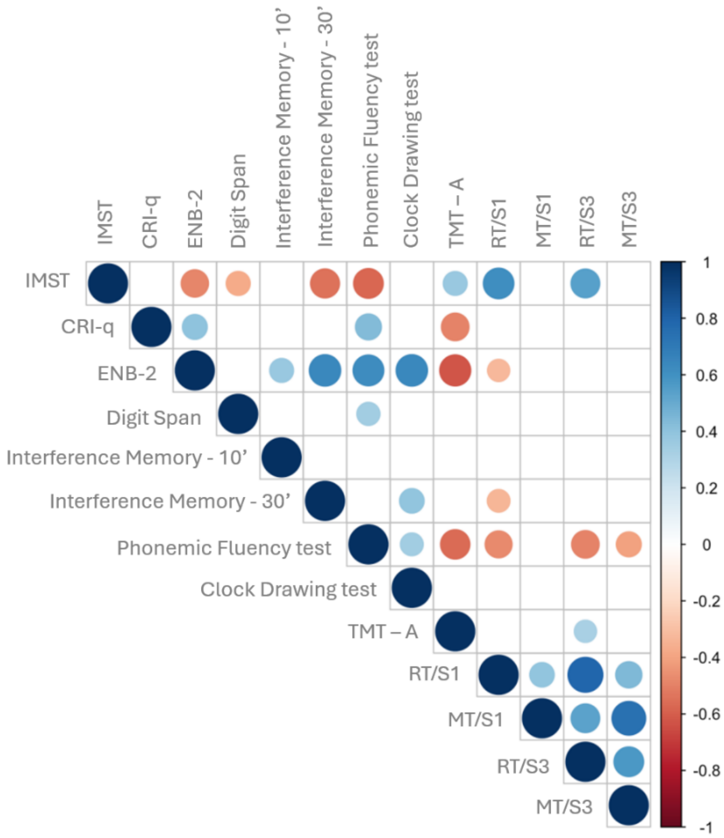

Figure 10: *Correlation matrix showing the association among different variables included in the audiological and neuropsychological assessment. Only statistically significant associations ($p < .05$) are shown. The blue-shaded dots indicate a positive correlation, while the red-shaded dots indicate a negative correlation. The color intensity and the size of each dot represent the strength of the association (Spearman's r).*

Notes. IMST: Italian Matrix Sentence Test; CRI-q: Cognitive Reserve Index questionnaire; ENB-2: Brief Neuropsychological Examination-2; TMT – A: Trail Making Test – A; RT: Reaction Time; MT: Motor Time.

3.2.3 Regression analysis

After the standardization of variables, multiple regression analysis with stepwise selection (a combination of backward elimination and forward selection) was carried out to investigate the relative contribution of selected cognitive variables in predicting performance of recognition sentences in noise. Therefore, all cognitive variables that were included in the correlation analysis were considered as predictors in this model (CRI-q, ENB-2, Digit Span, Interference Memory 10" and 30", Phonemic Fluency test, Clock

Drawing test, TMT-A, RT/S1, MT/S1, RT/S3, and MT/S3), while IMST was the dependent variable.

The regression model with stepwise selection found that performance on the IMST was predicted by RT/S3 ($\beta = 0.519$; $p < .001$), Interference Memory – 30” ($\beta = -0.350$; $p = .003$), and Digit Span ($\beta = -0.240$; $p = .030$). The results showed that this model had a significant explanatory power ($F(3,34) = 21$, $p < .001$), accounting for approximately 62% of the variance in IMST performance, with an adjusted R^2 of 0.619. Multiple regression results are reported in *Table 2*.

Table 2. Results of the stepwise multiple regression analysis for IMST.

Model Coefficients – Italian Matrix Sentence Test

Predictor	Estimate	*SE*	*t*	*p*
Intercept	1.050×10^{-16}	0.100	0.000	1
RT/S3	0.519	0.107	4.832	< .001
Interference Memory – 30”	-0.350	0.110	-3.182	0.003
Digit Span	-0.240	0.106	-2.270	0.030

Finally, multicollinearity was assessed for the predictors relevant to the best model using Variance Inflation Factor. The VIF values for RT/S3, Interference Memory – 30”, and Digit Span ranged from 1.085 to 1.173, indicating no signs of multicollinearity among best predictors of the model.

CHAPTER 4 – DISCUSSION AND CONCLUSION

4.1 Discussion

The aim of the present study was to investigate the association between cognitive functioning and central auditory abilities in a sample of older adults with normal hearing and mild hearing loss, characterized by different levels of cognitive functioning. As far as we know, this is the first clinical Italian study to explore this relationship by assessing CAP through the Italian Matrix Sentence Test.

Several studies have shown how cognitive functioning can impact speech recognition, especially in presence of background noise. In light of this, the primary aim of this work was to provide new insights into understanding which specific cognitive function measures were significantly associated with the sentences in noise recognition. Given that individuals in the cognitive decline group were expected to score lower on cognitive assessment compared to the control group, we hypothesized a worse performance in the IMST for those with cognitive impairment. Consequently, lower scores in cognitive tasks were expected to result in poorer outcomes in the sentence recognition test.

However, with the exception of ENB-2 total score, Interference Memory – 30", and Clock Drawing Test, other cognitive assessment measures analyzed did not show significant differences between groups. This outcome could be attributed to two main aspects: 1) The diagnosis of cognitive decline was made according to criteria outlined in the DSM-V, thus not all ENB-2 sub-tests needed to be altered for diagnosis. Indeed, other tests beyond those included in this study were used to support the diagnostic process; 2) Within the cognitive decline group, there may exist heterogeneity due the inclusion of individuals with varying degrees of cognitive decline (e.g., MCI, AD, Vascular dementia), which could potentially hide or confound the results of cognitive performance.

When comparing the outcomes of the IMST between the two groups, it was found that participants with cognitive decline required significantly higher SNR values to recognize at least 50% of words in noise (SRT) compared to the control group. As hypothesized, this result opens the possibility that cognitive functioning may influence performance on the IMST. Furthermore, pure-tone audiometry confirmed that listener's peripheral hearing thresholds did not exceed 35 dB HL, indicating that difficulties in the IMST could not be attributable to peripheral impairment (WHO, 2021).

In this context, correlation analysis revealed interesting results about the association between audiological and cognitive abilities. As expected, negative correlations emerged between the IMST and the ENB-2 total score, Digit Span, Interference Memory 30”, and Phonemic Fluency tests, suggesting that lower scores on these cognitive measures are associated with higher SNR values. Consistently, significant positive correlations were found between the IMST and TMT-A, RT/S1, and RT/S3, indicating that higher reaction times, which reflect a slowing in information processing speed, are associated with higher SNR values. These results, consistent with previous considerations, suggest that poorer cognitive performance in these tasks (lower tests scores or longer reaction times) is somehow linked to a worse performance on IMST. The cognitive variables included in the correlation analysis were also incorporated into the regression model to predict IMST performance and gain a better understanding of this relationship. The best-fitting model comprised RT/S3, Interference Memory – 30”, and Digit Span. Although these predictors together account for the variance in IMST performance, they will be discussed separately here to better understand their specific contribution.

The results of this study are consistent with theories of cognitive aging and speech understanding that have been extensively debated above. One of the most dominant theories of cognitive aging (Salthouse, 1996) posits that a generalized slowing of processing information speed occurs with age, contributing to age-related decline in various complex cognitive functions, such as language comprehension (Schneider et al., 2010). Models of language comprehension emphasize the role of information processing speed, explaining how a slowing in this process can lead to difficulties in handling the high rate of incoming information, thus making it challenging to understand language. Although high rates of speech do not characterize the speech material of the IMST, and although this study analyzed sentence recognition rather than discourse comprehension, the results obtained still confirm an association between processing speed (i.e., TMT – A, RT/S1, and RT/S3) and speech understanding in noise. A possible explanation lies in slowed lexical access, the process by which words can be recognized. Typically, this process starts with the activation of different candidates as soon as input is heard. Thus, word recognition is influenced by the number of words that share overlapping phonemes with the target word (Gordon-Salant et al., 2020). Older adults may encounter greater difficulties in managing this situation due to slower word recognition. Indeed, correlation analysis revealed an association between the Phonemic Fluency test and IMST performance, although this test was not included in the best model identified through stepwise regression. This finding could be explained with Salthouse's theory (1996), suggesting that generalized slowing of processing speed may be responsible for the decline in a variety of tasks.

Unexpectedly, no associations were found between the motor component of reaction time (MT/S1, MT/S3) and IMST performance. Indeed, some studies suggest that a decrease in processing speed may serve as a common cause to behavioral slowing in both cognitive and motor tasks (e.g., Sleimen-Malkoun et al., 2013). However, in this study only the more complex version of RT tests (RT/S3) was included in the best predicting model.

In addition to declines in information processing speed, this study found that reductions in WM capacity and increased susceptibility to interference, as measured by the Interference Memory – 30" test, also negatively impact speech recognition in noise. In this regard, the ELU model for speech processing (Rönnberg et al., 2008, 2013) is particularly relevant. Indeed, it posits that challenging listening conditions (e.g., noise) may increase the risk of phonological mismatches between the perceived signal and phonological representations in long-term memory. Additionally, slow lexical access can further heighten the risk of mismatches by disrupting the cycle of information flow. When this occurs, explicit processing is required, and WM is engaged to solve ambiguity by reconstructing or inferring speech content. Thus, the model predicts that individual WM capacity will modulate performance under mismatch conditions. In other words, in adverse listening situations, the cognitive processing load increases more for individuals with low than high WM capacity. These considerations can explain the results obtained in this study for Interference Memory 30" test.

Finally, the best-fitting model also included Digit Span as a predictor of performance in speech-in-noise understanding. Digit Span is considered a measure of attention and phonological short-term memory span. It can be hypothesized that an individual's capacity to temporarily maintain information in the phonological short-term store is linked to the length of the sentence that can be held in memory (span). For this reason, Digit Span, as a short-term memory measure, could be involved in sentence recognition. Indeed, the phonological loop component, which consists of a storage and a subvocal rehearsal process, is likely required for maintaining the phonological form of the message and thus processing the sentence (Papagno et al., 2007).

4.2 Limitations and future directions

While recognizing the contribution of the current study in understanding the role of cognitive functioning in the processing of auditory stimuli in noise, it is also important to acknowledge some limitations and suggest future directions for this research.

As previously outlined, because of the small sample size it was not possible to differentiate the cognitive decline group based on the type and/or severity of diagnosis. The heterogeneity within this group could introduce a significant variability in the study, potentially masking the specific contributions of each type of dementia. Indeed, different subtypes of cognitive decline can have distinct pathophysiological mechanisms and cognitive profiles, which can differently affect central auditory processing. It is fundamental in future to increase sample dimensions and, thus, stratify the sample based on specific dementia diagnosis to analyze the effects of cognitive functioning on CAP within each group.

Materials also pose a limitation in this study. Specifically, the neuropsychological assessment did not include a comprehensive measure of inhibitory control, a key cognitive mechanism known to decline with age and potentially relevant for understanding speech in noise by suppressing unnecessary information. Furthermore, this study only tested speech-spectrum noise as the background noise condition. Exploring the impact of cognitive functioning across different types of noise, such as multi-talker babble noise, would provide valuable insights into real-life listening conditions and enhance the generalizability of this findings.

4.3 Conclusions

In alignment with cognitive aging theories and the Ease of Language Understanding model, the present study extends results from previous research by highlighting that cognitive processes, including processing speed, working memory, and short-term memory, play an important role in older adults' ability to understand speech in noise. To our knowledge, this is the first clinical Italian study to investigate the association between cognitive functioning and Central Auditory Processing (CAP) in older adults using the Italian Matrix Sentence Test (IMST).

These findings have two main clinical implications. Currently, audiological and neuropsychological assessments are performed independently. However, there is considerable value in integrating both dimensions, particularly for older listeners. Since the results demonstrate that central auditory processing of sentences is closely linked to cognitive functioning, a comprehensive evaluation of an older individual's cognitive state become essential before interpreting their performance on speech understanding tests, such as the IMST. Incorporating routine assessment of cognitive abilities into audiology settings would help ensure that the needs of these people are adequately addressed. Furthermore, it is worth noting that questions/instructions during a neuropsychological assessment typically rely on auditory means (e.g., verbal), which necessitate intact CAP to be correctly understood (Nixon et al., 2019). The second implication concern interventions, that consequently could benefit from such a comprehensive, multidisciplinary approach. Indeed, cognitive stimulation programs that focus on those cognitive abilities specifically related to speech-in-noise understanding are needed. Some studies reported that weeks of training on specific cognitive domains (e.g., WM, attention) improved performance on tasks that rely on these functions (Wayne & Johnsrude, 2015). Interventions would aim to encourage the maintenance of stimulating social interactions to mitigate potential negative outcomes, such as social isolation.

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