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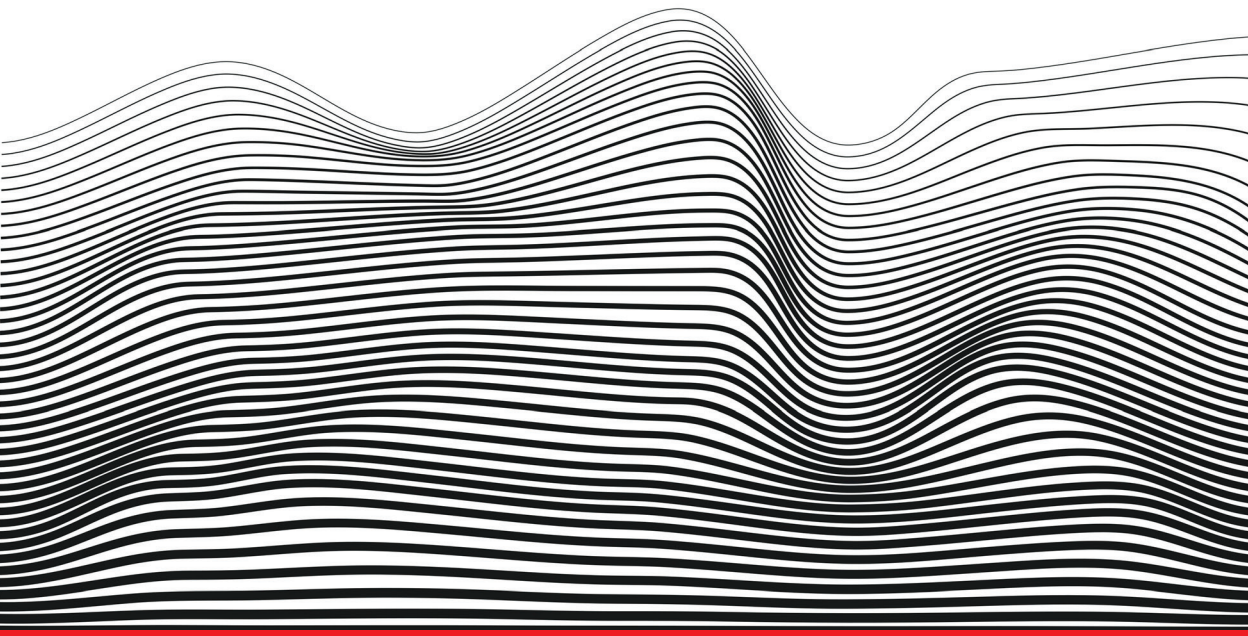
Dissertation in Disability Research

Healthy Ageing in Hearing Aid Users

How hearing and cognition shape everyday functioning in later life

Francesca Molinari Luccini



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To my grandparents

Gone but not forgotten

POPULÄRVETENSKAPLIG SAMMANFATTNING

Att kunna höra och förstå vad andra säger är viktigt för att kunna delta i sociala sammanhang och utföra vardagliga aktiviteter. När vi blir äldre kan både vår hörsel och vissa kognitiva förmågor, såsom minnet och förmågan att bearbeta information, förändras. Dessa förändringar kan påverka hur vi uppfattar tal, deltar i sociala aktiviteter samt går och förflyttar oss i vardagen. Denna avhandling undersöker hur hörsel och kognition hänger samman med hörselfunktion och vardagsfunktion hos äldre vuxna, med särskilt fokus på personer som använder hörapparater. Arbetet bygger på Världshälsoorganisationens (WHO) ramverk för hälsosamt åldrande, som sätter förmågan att utföra vardagliga aktiviteter och delta i samhället i centrum.

Avhandlingen består av fyra vetenskapliga studier som undersöker de faktorer som påverkar upplevelsen av hörselproblem och förmågan att förstå tal i bullriga miljöer, samt granskar hur hörsel och kognitiva förmågor hänger samman med förmågan att gå och socialt deltagande.

Resultaten från en av studierna visade att hörselnedsättning, mätt genom hörseltester, var den faktor som hade det tydligaste sambandet med självrapporterade hörselproblem, medan kognitiv flexibilitet–förmågan att anpassa sitt tänkande och växla mellan olika uppgifter–inte gav någon ytterligare förklaring. I en longitudinell studie försämrades deltagarnas förmåga att förstå tal i buller och att de som hade sämre hörsel vid studiens början uppvisade en större försämring. Förändringar i hörselnivå och arbetsminne–förmågan att tillfälligt lagra och bearbeta information–förklarade dock inte förändringen i förmågan att förstå tal i buller.

I en av studierna undersöktes även sambanden mellan hörsel, kognition och förmåga att förflytta sig. Resultaten visade att personer med bättre visuospatialt arbetsminne–förmågan att tillfälligt lagra och bearbeta information om former och rumsliga relationer–förflyttade sig snabbare. Deltagare med normal hörsel gick dessutom snabbare än de som använde hörapparater, men sambandet mellan arbetsminne och förmågan att gå var likartat i båda grupperna.

När det gäller socialt deltagande visade resultaten att personer som hade lättare att förstå tal i bullriga miljöer upplevde färre begränsningar i sitt sociala deltagande. Hörselstatus var förknippad med vissa aspekter av dessa begränsningar, medan det verbala arbetsminnet – förmågan att tillfälligt lagra och bearbeta språklig information – inte visade något signifikant samband.

Sammantaget visar avhandlingen att hörsel och kognitiva förmågor har olika samband med hörselfunktion, gånghastighet och socialt deltagande bland äldre vuxna. Resultaten understryker vikten av att betrakta hörsel och kognition som en del av ett bredare sammanhang när man försöker förstå hur äldre vuxna kan bibehålla sin förmåga att fungera i vardagen. Kunskap om dessa samband kan bidra till en bredare förståelse av åldrandet och av hur äldre människors behov, inte minst hos hörapparatsanvändare, kan tillgodoses för att stödja ett aktivt och självständigt liv.

ABSTRACT

Age-related hearing loss can affect communication, mobility, and social participation, but its impact on functional ability in everyday life varies considerably among older adults with similar levels of hearing impairment. Hearing aids, while improving audibility, do not eliminate all the challenges associated with hearing loss. The WHO Healthy Ageing framework defines healthy ageing as "the process of developing and maintaining the functional ability that enables well-being in older age", regardless of impairment and disability. In hearing aid users, functional ability results from the interactions between the individual's intrinsic capacities–including hearing and cognition–and their environment. This thesis aims to investigate the relationship between hearing sensitivity, cognitive abilities and different aspects of everyday functioning in hearing aid users.

This thesis is comprised of four papers: Paper I examined hearing sensitivity and cognition as predictors of self-reported hearing difficulties; Paper II examined differences in hearing sensitivity and cognition as predictors of gait performance in two groups, hearing aid users and normal hearing individuals; Paper III investigated differences in hearing sensitivity, speech-in-noise perception and cognition as predictors of social participation restrictions in two groups, hearing aid users and normal hearing individuals; Paper IV investigated hearing sensitivity and cognition as predictors of changes over time in speech-in-noise perception. The findings of the studies can be divided into two different themes: (1) hearing sensitivity and cognition as predictors of auditory functioning (Paper I and IV) and (2) hearing sensitivity, auditory functioning, and cognition as predictors of functional ability (Papers II and III). In Paper I, hearing sensitivity was the most consistent predictor of self-reported hearing difficulties, whereas cognitive shifting did not explain additional variation. In Paper IV, speech-in-noise perception deteriorated over time, and poorer baseline hearing sensitivity predicted greater deterioration. However, neither changes in hearing sensitivity nor changes in working memory were associated with changes in speech-in-noise perception. In Paper II, better visuospatial working memory independently predicted faster walking regardless of hearing status, and adults with normal hearing walked faster than hearing aid users. In Paper III, better speech-in-noise perception was associated with fewer social participation restrictions across both hearing-status groups, whereas verbal working memory was not a significant predictor.

Overall, the findings suggest that the relationship between hearing sensitivity, cognition, auditory functioning, and functional ability varies across the different aspects examined in this thesis. In relation to the Healthy Ageing framework, these findings highlight the importance of understanding how hearing sensitivity and cognitive abilities contribute differently to maintaining functional ability in hearing aid users as they age.

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1 List of Papers

This thesis is based on the following papers, referred to in the text by their Roman numerals:

I. Molinari Luccini, F., Danielsson, H., Stenbäck, V., Ng, E.H.N., & Holmer, E. (2026) Cognitive Shifting Ability Does Not Predict Self-Perceived Hearing Difficulties in Adult Hearing-Aid Users.*Trends in Hearing, 30*. https://doi.org/10.1177/23312165261433705

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II. Molinari Luccini, F., Danielsson, H., Stenbäck, V., Ng, E.H.N., & Holmer, E. (2026) Visuospatial working memory as a predictor of gait performance in adults with normal hearing and hearing aid users. *Discover Psychology 6, 169*. https://doi.org/10.1007/s44202-026-00764-x

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III. Molinari Luccini, F., Danielsson, H., Stenbäck, V., Heffernan, E., Ng, E.H.N., & Holmer, E. Predictors of social participation restrictions in hearing aid users. *In manuscript*.

IV. Molinari Luccini, F., Danielsson, H., Stenbäck, V., Ng, E.H.N., & Holmer, E. Longitudinal associations between changes in speech-in-noise perception, hearing sensitivity and working memory in hearing aid users. *In manuscript*.

2 Introduction

The proportion of older adults in the global population is increasing at an unprecedented rate. In 2020, there were an estimated 1 billion people aged 60 or older worldwide, a number expected to rise to 2.1 billion by 2050 (World Health Organization, 2025). By the late 2070s, the global population aged 65 and older is expected to surpass the number of children under age 18 (United Nations, 2024). This demographic shift highlights an important challenge for ageing societies: not only prolonging life but also ensuring that those added years are lived with health, independence, and the ability to do what is valued.

Ageing is associated with functional decline in body functions and an increased risk of diseases due to cellular and molecular damage that accumulates over time. This functional decline is neither linear nor uniform across individuals, resulting in diverse health trajectories and varying consequences for the individuals (World Health Organization, 2020, 2021). While some individuals maintain a high level of physical, cognitive, and social functioning well into later life, others experience substantial declines that affect their ability to carry out everyday activities and participate in society. This variability highlights the need for approaches to ageing that focus not only on disease and impairment, but also on how people function in their everyday lives.

In an effort to address the demographic changes and the consequent needs of the ageing population, both at the individual and at the societal level, the World Health Organization (WHO) has developed a public health framework to guide policies and interventions that support well-being in later life: the WHO Healthy Ageing framework (World Health Organization, 2020). Within this framework, healthy ageing is defined as "the process of developing and maintaining the functional ability that enables well-being in older age" (World Health Organization, 2020, p. 8). Importantly, this framework reframes the concept of healthy ageing. As ageing is associated with functional decline and an increased risk of illnesses, a framework focusing on healthy ageing as a state devoid of diseases or impairments excludes a majority of the ageing population. Instead, in this framework, the emphasis is shifted towards the ability to live a meaningful life despite the health changes that accompany older age.

The Healthy Ageing framework conceptualises functioning through the interaction of three key components: intrinsic capacity, the environment, and functional ability. Intrinsic capacity refers to the composite of genetic inheritance, health characteristics, and personal characteristics. While the genetic inheritance and some personal characteristics—such as biological sex and ethnicity—are fixed, the health characteristics are dynamic and can change over time as a result of the ageing process, health behaviours, environmental influences, diseases, and injuries (World Health Organization, 2020). The environment consists of all the external conditions that shape a person's life, and therefore encompasses the physical infrastructures, social relationships, and economic resources, as well as the broader policy systems (World Health Organization, 2020). Lastly, functional ability is determined by a combination of a person's intrinsic capacity, the characteristics of their environment, and how the individual interacts with that environment. It reflects their everyday functioning, what people are actually able to do in their everyday life, taking into account both their physical and mental capabilities as well as the environment in which they live (World Health Organization, 2020). Functional ability encompasses five domains: the ability to meet basic needs; the ability to learn, grow, and make decisions; the ability to be mobile; the ability to build and maintain relationships; and the ability to contribute to society (World Health Organization, 2020). These domains highlight how healthy ageing extends beyond physical health to include autonomy, social participation, and the ability to engage in activities that are meaningful to the individual. In other words, intrinsic capacity describes the individual's physical and mental capacities, whereas functional ability describes what the individual is actually able to do through the interaction between those capacities and the environment.

This understanding of functioning is closely related to the concept of disability. While impairment refers to a problem with a body function or structure, disability is a difficulty that the individual faces arising from the interaction between an individual's impairment and their environment. Thus, disability is not solely an inherent characteristic of an individual but may result from environmental barriers, such as inaccessible buildings, lack of appropriate support, or discriminatory attitudes, which can restrict a person's ability to perform activities and participate in everyday life (World Health Organization, 2001). The Biopsychosocial model provides a conceptual framework for understanding disability. Originally proposed by Engel (Engel, 1977) as an alternative to the medical approach to health and illness, the Biopsychosocial model recognises that health and functioning are influenced by the dynamic interplay between biological, psychological, and social factors. Importantly, these factors do not operate independently, but rather, they interact continuously and can either support or hinder an individual's functioning (Waddell & Aylward, 2010). For example, the consequences of a sensory impairment may be reduced through effective coping strategies, social support, rehabilitation, or assistive technologies. Conversely, environmental barriers, limited support, or restricted access to resources may increase the impact of the same impairment (Waddell & Aylward, 2010). Therefore, disability can be understood as a dynamic outcome that emerges from the interaction between changes in individual functioning and the contexts in which those changes are experienced.

Normal ageing is associated with gradual changes in sensory, cognitive, and physical capacities (Paraskevoudi et al., 2018), and while some age-related changes may constitute impairments, they do not necessarily lead to disability. Nevertheless, as these capacities change with age, older adults may be at increased risk of experiencing disability. However, the extent to which age-related changes result in difficulties in everyday life varies considerably between individuals. Importantly, within the Healthy Ageing framework, the presence of impaired capacity does not preclude healthy ageing. Individuals may experience limitations in functioning while still maintaining functional ability, well-being, and meaningful participation through supportive environments and appropriate interventions (World Health Organization, 2020). Thus, disability and health cannot be understood solely as a consequence of biological decline, but must be considered in relation to the broader context in which an individual lives.

Building on this Biopsychosocial perspective, the International Classification of Functioning, Disability and Health (ICF) provides a structured framework for describing functioning and disability (World Health Organization, 2001). Within the ICF, functioning is conceptualised as the outcomes of the dynamic interaction between interconnected domains, including body functions and structures, activities, and participation, while also recognising the influence of environmental and personal factors. In doing so, it operationalises the principle that disability is not determined solely by a health condition, but arises through the interaction between the individual and their environment (World Health Organization, 2001). The ICF therefore provides a useful framework for examining the processes underlying Healthy Ageing, particularly how age-related changes in intrinsic capacity interact with environmental factors to shape functioning and participation in everyday life.

Age-related hearing loss provides a relevant example of how age-related changes in intrinsic capacity may affect everyday functioning. However, the extent to which hearing loss affects functional ability may depend not only on hearing sensitivity itself, but also on other individual capacities, such as cognitive ability, and the availability of environmental supports, such as hearing aids. In this thesis, auditory functioning refers to an individual's ability to perceive and understand auditory information in everyday listening situations, encompassing both speech-in-noise perception and perceived hearing difficulties. Although auditory functioning is an aspect of everyday functioning in its own right, it may also influence broader aspects of functional ability. For example, difficulties in auditory functioning may affect an individual's ability to build and maintain relationships, to learn, grow, and make decisions, and to contribute to society. Understanding how these factors interact is therefore important for examining how individuals maintain functional ability and participation in everyday life. The present thesis investigates the interplay between cognition and hearing loss in shaping everyday life among adults with age-related hearing loss who are hearing aid users. In particular, it examines how hearing sensitivity and cognitive ability–as aspects of intrinsic capacity–interact with hearing aid use–as an environmental support–to influence auditory functioning and broader functional ability in everyday life. By adopting the perspective of the Healthy Ageing framework and the Biopsychosocial model of disability, this thesis seeks to contribute to a better understanding of how individual capacities and environment together shape functioning and participation as people age.

3 Background

3.1 Age-related hearing loss

Age-related hearing loss (ARHL), also known as presbycusis, is the progressive sensorineural hearing loss associated with ageing. It typically affects both ears symmetrically and frequently begins at the high-frequency range and gradually extends to lower frequencies over time (Bowl & Dawson, 2018; Huang & Tang, 2010). ARHL is the most prevalent sensory impairment, and its prevalence increases substantially with advancing age. More than 65% of individuals over 60 years old experience some degree of hearing loss (World Health Organization, 2021), and it is estimated that over 25% of individuals over 60 years old are affected by disabling hearing loss (World Health Organization, 2026). With the growing ageing population, ARHL represents a growing public health concern worldwide (World Health Organization, 2021).

Hearing loss is commonly assessed using pure-tone audiometry, which measures hearing sensitivity by determining the quietest sounds (thresholds) an individual can detect at different frequencies. Hearing thresholds are typically summarised using the pure-tone average (PTA), which represents the average hearing threshold across frequencies. The four-frequency pure-tone average (PTA4) is commonly calculated by averaging hearing thresholds at 500, 1000, 2000, and 4000 Hz. A hearing threshold of 25 dB HL has historically served as a conventional boundary between normal hearing and hearing loss in audiological research (Dillard et al., 2025; Gatlin & Dhar, 2021). The aetiology of ARHL is complex and multifactorial, involving age-related changes throughout both the peripheral and central auditory systems. Degeneration of cochlear structures, located in the inner ear and responsible for converting sound vibrations into electrical signals, has been identified as a major contributor to declining hearing sensitivity with age. These structures include sensory hair cells, spiral ganglion neurons, and the stria vascularis (Zhao et al., 2025). In addition to these intrinsic physiological age-related changes, cumulative environmental and lifestyle-related exposures may influence the onset and progression of hearing loss. For example, long-term noise exposure (Dillard et al., 2025), cardiovascular disease and smoking (Helzner et al., 2011), and the use of ototoxic medications (Rizk et al., 2020) have been

linked to decreased hearing sensitivity. Thus, ARHL results from a combination of age-related physiological changes in the auditory system and environmental and lifestyle-related factors that contribute to declining hearing sensitivity.

Although standard pure-tone audiometry provides an objective measure of peripheral hearing sensitivity, it primarily captures sound-detection thresholds and does not fully reflect the complexity of real-world listening environments (Gatehouse & Noble, 2004; Musiek et al., 2017). Consequently, individuals with similar hearing thresholds may report substantially different levels of hearing difficulty, defined as the perceived difficulties in hearing sounds, understanding speech and following conversations in everyday listening situations. Self-reported hearing difficulty therefore provides an important complementary perspective, capturing aspects of hearing that may not be reflected in hearing sensitivity alone, and it is commonly assessed using standardised patient-reported outcome measures, such as the Speech, Spatial and Qualities of Hearing Scale questionnaire (SSQ; Gatehouse and Noble, 2004). Thus, audiometric and self-reported measures provide complementary information. While pure-tone audiometry primarily characterises hearing sensitivity, self-reported measures capture how individuals experience the functional consequences of their hearing in everyday life. This distinction is consistent with the Healthy Ageing framework (World Health Organization, 2020) and the Biopsychosocial perspective (Waddell & Aylward, 2010), which emphasise that an individual's capacity alone does not fully determine their functioning, as this also depends on the interaction between individual characteristics and their environment. In relation to this perspective, self-reported hearing difficulties are a needed complement to audiometric assessment.

3.1.1 Consequences of hearing loss

The impact of hearing loss is wide and far-reaching, affecting various aspects of everyday life (Henderson et al., 2025). The most immediate impact is experienced in the perception of sound and, with the progressive decline in hearing sensitivity, in communication. Individuals with hearing loss often experience significant difficulties understanding speech, particularly in the presence of background noise or multiple talkers (Helfer et al., 2017). These difficulties reflect not only reduced audibility, but also changes in the temporal and spectral processing of sound that can further degrade the clarity of the speech signal (Anderson & Karawani, 2020; Fogerty et al., 2024). The additional effort required to understand speech may increase listening-related fatigue, particularly during challenging listening situations (Huizinga et al., 2026; Motala et al., 2024). Thus, hearing loss can have consequences that extend to multiple aspects of everyday functioning.

Beyond these immediate communication challenges, hearing loss can also affect individuals' social participation. Social participation refers to an individual's involvement in activities and interactions within their community and wider society, encompassing a range of activities shaped by personal preferences, available resources, and the social context in which participation takes place (Levasseur et al., 2010, 2022). Hearing loss may restrict social participation by making it more difficult to engage in activities that rely on communication, and over time, these challenges may affect the ability to maintain social connections and contribute to an increased risk of social isolation and loneliness (Fu et al., 2025; Shukla et al., 2020). Such restrictions are particularly relevant in later life, when social participation is an important contributor to well-being and healthy ageing (Monteiro et al., 2025), with higher levels of social participation linked to better physical health, reduced cognitive decline, and a lower risk of depression and functional decline (Chiao et al., 2011; Lin et al., 2024; Zhou et al., 2020). Additionally, hearing loss has been linked with poorer motor function and mobility (Chen et al., 2014; Mikkola et al., 2015; Polku et al., 2015). Older adults with hearing loss exhibit reduced gait performance, referring to characteristics of walking such as speed, stride, and stability, as well as impaired balance compared to their normal-hearing peers (Frosolini et al., 2026). Moreover, hearing loss has been identified as a risk factor for falls (Yeo et al., 2025). Proposed explanations for this phenomenon include limited access to auditory cues, which has been linked to reduced postural sway and gait vari-

ations (Yeo et al., 2025), or the increased cognitive load that the degraded auditory input may impose on shared cognitive resources (Wunderlich et al., 2024). Taken together, this suggests that hearing loss may have implications for healthy ageing by influencing multiple domains of functional ability and participation in later life. Within a Biopsychosocial perspective, the impact of hearing loss is shaped not only by the degree of auditory impairment, but also by individual characteristics and the social and physical environment in which everyday activities take place (Waddell & Aylward, 2010). Consequently, similar levels of hearing impairment may result in different experiences of functional limitation across individuals, depending on factors such as communication demands, social support, and environmental conditions.

3.1.2 Hearing aids

Hearing aids are the most common intervention for individuals with hearing loss and are designed to improve audibility and support speech understanding in everyday listening environments. Modern hearing aids are digital devices that capture, process, and amplify incoming acoustic signals using advanced signal processing strategies. These include wide dynamic range compression to accommodate reduced dynamic range, as well as directional microphones and noise reduction algorithms aimed at improving listening in complex acoustic environments (Morvan et al., 2024). Evidence shows that the use of hearing aids can provide a range of benefits for adults with mild-to-moderate hearing loss (Ferguson et al., 2017). Specifically, the use of hearing aids has been linked to reduced self-perceived difficulties (e.g., Cañete et al., 2024), increased access to auditory cues important for balance (e.g., Ninomiya et al., 2021), improved speech perception (e.g., Dörfler et al., 2020), and improved social outcomes (e.g., Hamada et al., 2026). However, the extent to which these benefits translate into improved everyday functioning may vary across individuals and listening environments.

In fact, while hearing aids can substantially improve access to sound and speech, outcomes remain highly variable across users. Improved audibility does not necessarily restore normal auditory processing, and amplification alone may not fully resolve the complex listening difficulties associated with ARHL. It is therefore not uncommon for hearing aid users to continue reporting substantial challenges in everyday listening environments, especially in acoustically demanding situations such as with background noise, in group conversations, and in reverberant environments (Nicoras et al., 2026; Petersen, 2024). Despite these limitations, hearing aid use has been associated with positive social outcomes, including greater engagement in social activities and improved social quality of life (Beadle et al., 2026; Holman et al., 2021; Hori et al., 2025). Nevertheless, persistent listening effort and communication difficulties may continue to restrict participation in challenging social situations (Alhanbali et al., 2017). Similarly, although hearing aid use has been linked to improvements in balance and gait performance, findings remain inconsistent across studies (Borsetto et al., 2020; Ernst et al., 2021; Mahafza et al., 2022; Martinez-Amezcua et al., 2021; Mohanathas et al., 2024; Shayman et al., 2017; Weaver et al., 2017). Taken together, these findings suggest that factors beyond audibility may contribute to how hearing loss affects everyday functioning and may help explain the variability in outcomes observed among hearing aid users.

3.2 Cognitive models of listening

Understanding speech, particularly in complex listening environments, involves several processes that enable listeners to interpret and make use of incoming auditory information. Cognitive functions are thought to play an important role in these processes, supporting the interpretation of speech when listening conditions place greater demands on the listener (Dryden et al., 2017). Cognition encompasses the mental processes involved in acquiring, processing, storing, and using information (American Psychological Association, n.d.). Cognitive abilities encompass a broad range of functions, including attention, which involves selectively focusing on relevant information (Posner & Petersen, 1990), fluid intelligence, which refers to the ability

to reason and solve problems (Ferrer et al., 2009), and working memory, which involves temporarily storing and manipulating information (Baddeley, 2012). Working memory is closely related to executive functions, which are higher-order cognitive processes that regulate thought and behaviour to support goal-directed activities (Diamond, 2013; Miyake et al., 2000). Executive functions encompass three related but distinct components: shifting, or cognitive flexibility, which involves flexibly switching between tasks; inhibition, which involves suppressing dominant or irrelevant responses; and updating, which involves monitoring and revising the contents of working memory (Miyake et al., 2000). In the context of listening, these cognitive processes may support the selection of relevant information, the holding of relevant spoken material, and the integration of information to facilitate speech understanding.

These cognitive processes may be particularly important when listening conditions make speech more difficult to understand. Consistent with this, a large body of research has demonstrated associations between cognitive abilities and speech perception outcomes in challenging listening conditions. Studies of older adults have shown that cognitive and auditory factors jointly contribute to individual differences in speech understanding, with cognitive factors playing an important role in aided listening conditions (Humes et al., 2013). Higher-order cognitive processes—including attention, fluid intelligence, and working memory—have also been shown to contribute to improved speech-in-noise perception (Dryden et al., 2017). Specifically, working memory capacity has been linked to speech-in-noise performance (e.g., Gafoor & Uppunda, 2026; Lad et al., 2020). Consistent with this, individuals with greater working memory capacity—particularly hearing aid users—tend to achieve better outcomes in speech-in-noise tasks (Foo et al., 2007; Lunner et al., 2009). These findings suggest that successful speech perception under challenging listening conditions depends not only on the quality of the incoming auditory signal, but also on the cognitive resources available to process and interpret that signal.

The role of cognition in listening has been described in several theoretical models. Among these, hearing-specific frameworks provide explanations of how cognitive processes contribute to listening and speech understanding, particularly under challenging listening conditions. Two prominent models are the Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al., 2016) and the Ease of Language Understanding (ELU; Rönnberg et al., 2022) model. Although both models emphasise the role of cognitive resources, they address different aspects of listening. The FUEL provides a broader framework for understanding how cognitive resources are allocated in response to listening demands (Pichora-Fuller et al., 2016), whereas the ELU model focuses more specifically on the processes involved in understanding speech when the available auditory information is degraded (Rönnberg et al., 2022).

The FUEL is based on Kahneman's Capacity Model of Attention (Kahneman, 1973), which conceptualises cognitive capacity as limited and dynamically allocated according to the demands of a task. Within the FUEL, listening effort is understood as the mental resources a person deliberately allocates to overcome challenges and achieve successful understanding during a listening task. (Pichora-Fuller et al., 2016). The amount of effort invested therefore depends not only on the characteristics of the listening environment, but also on the individual's available cognitive capacity and their motivation to engage with the task. From this perspective, listening emerges from an interaction between task demands and factors that influence the listener's engagement with those demands. Acoustic characteristics of the environment, such as background noise, can increase the difficulty of extracting relevant speech information. Hearing impairment can similarly alter the demands placed on the listener because poorer access to the speech signal may require greater reliance on cognitive resources. However, the FUEL also recognises that source allocation is not determined by task demand alone, but also by the listener's current state and motivation to engage with the task. Consequently, a listener may reduce their effort despite having sufficient cognitive capacity to continue, particularly when fatigue increases, or the perceived value of the task decreases (Pichora-Fuller et al., 2016). This emphasis on the interaction between demands, available capacity, and motivation makes the FUEL particularly

relevant to listening in everyday environments, where the demands of communication can vary continuously.

Although the FUEL provides a general framework of the factors influencing listening effort, it does not specify in detail how degraded speech is processed during comprehension. The ELU model addresses this more specific process by proposing that speech understanding normally relies on rapid, automatic matching between incoming phonological information—the sound properties of speech that allow words to be distinguished from one another—and linguistic representations—the knowledge of how words sound and what they mean—stored in long-term memory (Rönnberg et al., 2022). Through a mechanism called Rapid Automatic Multimodal Binding of Phonology (RAMBPHO), the incoming phonological information is rapidly integrated into a phonological representation of the incoming speech signal, and it is then matched against linguistic representations stored in long-term memory. When the incoming information is sufficiently clear to correspond with existing representations, language processing can proceed rapidly and efficiently, with limited demands on additional cognitive resources. The situation changes when the incoming signal is ambiguous, incomplete, or degraded. Noise, hearing impairment, and other forms of signal degradation (Mattys et al., 2012) can make it more difficult for the incoming information to correspond directly with existing linguistic representations. Such discrepancies require additional, more explicit processing, rather than relying primarily on rapid automatic matching. Thus, the listener must recruit other cognitive resources to interpret the available information and establish a meaningful representation of the message. This may involve retrieving relevant information from long-term memory, generating inferences, directing attention towards relevant information, suppressing competing information, and maintaining information temporarily in working memory while interpretation takes place (Rönnberg et al., 2022).

The relationship between these additional processing requirements and working memory is particularly relevant to speech-in-noise perception. Working memory has a limited capacity, meaning that the resources available for processing information are limited. When processing and temporary storage are required at the same time, resources must therefore be distributed between these functions, creating a trade-off between processing and storage (Daneman & Carpenter, 1980). In challenging listening situations, increased requirements for explicit processing may consequently reduce the resources available for maintaining information (Lunner et al., 2009). Importantly, the ELU model (Rönnberg et al., 2022) suggests that these demands are not restricted to situations involving background noise. Hearing impairment can also reduce the fidelity of the speech signal and therefore increase the likelihood that additional processing will be required. Individuals with hearing loss may therefore encounter situations in which comprehension cannot rely as readily on rapid and automatic processing. From this perspective, improving access to the auditory signal may reduce the extent to which additional cognitive processing is required. Hearing aids may consequently influence not only the perceptual quality of speech but also the cognitive demands associated with understanding it.

3.3 Hearing loss, cognition, and everyday functioning

3.3.1 Cognitive ageing and hearing loss

Age-related changes in cognitive functioning are highly variable between individuals and across cognitive domains. Normal cognitive ageing is generally characterised by the gradual reduction in fluid cognitive abilities, including processing speed and aspects of working memory and executive functions, whereas crystallised abilities and accumulated knowledge tend to be relatively preserved into later life (Naveh-Benjamin & Cowan, 2023; Salthouse, 2019; Tucker-Drob et al., 2022). Importantly, age-related cognitive changes are distinguished from pathological cognitive decline. This distinction between normal and pathological cognitive ageing is based not only on the presence of cognitive decline, but also on its magnitude, rate of progression,

pattern across cognitive domains, and impact on everyday functioning (Salthouse, 2019). This distinction is particularly relevant when considering that other age-related conditions may co-exist with cognitive change, for example, ARHL. To explain how hearing and cognition interact across the lifespan, several theoretical models have been proposed, such as the Common Cause hypothesis, the Information Degradation hypothesis, the Cognitive Load on Perception theory, the Sensory Deprivation theory, and the Cascade hypothesis.

The Common Cause hypothesis posits that age-related declines in both hearing and cognition arise from shared neurobiological deterioration rather than a direct causal pathway between the two (Uchida et al., 2019; Wayne & Johnsrude, 2015). In contrast, the Information Degradation hypothesis proposes that degraded auditory input requires the allocation of additional cognitive resources to processing speech, resulting in fewer resources left available for higher-order cognitive functions and thereby negatively affecting cognitive performance (Wayne & Johnsrude, 2015). The Cognitive Load on Perception theory emphasises the opposite direction of influence, proposing that individuals with declining cognitive capacity due to ageing are less able to compensate for degraded sensory input, resulting in poorer speech understanding and auditory perception outcomes (Uchida et al., 2019; Wayne & Johnsrude, 2015). The Sensory Deprivation hypothesis argues that long-term reductions in auditory stimulation may lead to structural and functional changes in the brain, contributing to cognitive decline over time. According to this view, persistent hearing loss results in underutilisation of neural systems involved in auditory and cognitive processing, potentially accelerating age-related cognitive deterioration (Wayne & Johnsrude, 2015). Lastly, the Cascade hypothesis extends the perspective of the Sensory Deprivation hypothesis by proposing that hearing loss initiates a chain of downstream consequences, including increased listening effort, communication difficulties, social withdrawal, loneliness, reduced engagement in cognitively stimulating activities, and ultimately cognitive decline (Uchida et al., 2019). Taken together, these models provide different explanations for the observed association between hearing and cognition in ageing, and they differ in the direction and mechanism of the proposed relationship. Thus, there is general agreement that declines in hearing and cognition are related in older populations, but no consensus on whether one domain influences the other, or if there is a common cause responsible for a general deterioration.

3.3.2 Cognition and everyday functioning

Most evidence for the relationship between working memory and speech-in-noise perception is derived from cross-sectional studies, while longitudinal evidence remains limited. Results from a longitudinal study investigating hard-of-hearing children found that working memory was not a predictor of speech recognition in noise (Walker et al., 2019). Additionally, results from intervention studies show that, while improvements in speech-in-noise perception through working memory training are present in young adults (Ingvalson et al., 2015), the same is not observed consistently in older adults (Wayne et al., 2016). Thus, while an association between working memory and speech-in-noise performance has been observed in multiple cross-sectional studies and populations, the role of working memory regarding changes in speech-in-noise perception over time is unclear, especially in individuals with hearing loss. The limited availability of longitudinal studies, particularly in older individuals and populations with hearing loss, limits the understanding of how changes in working memory relate to changes in speech perception over time, and how these processes interact with changes in auditory function. From the perspective of the ELU model (Rönnberg et al., 2022), working memory is assumed to play a key role in compensating for degraded speech input by supporting the integration of contextual cues, prior knowledge, and available speech information when the incoming signal is unclear or mismatches stored phonological representations.

In addition to objective speech-perception performance, cognitive abilities have also been linked to subjective hearing experiences. Studies have shown associations between cognitive abilities and self-reported hearing difficulties (Humes et al., 2013; Perron et al., 2022; Zekveld et al., 2013), suggesting that individuals with lower cognitive resources may experience greater lis-

tening effort in everyday situations. From the perspective of the FUEL (Pichora-Fuller et al., 2016), greater perceived hearing difficulty may reflect the additional cognitive demands that arise when available auditory information is insufficient for effortless communication. Sustained allocation of cognitive resources to support listening may increase perceived listening effort and fatigue, particularly when communication remains demanding over time. In turn, fatigue or reduced motivation may affect engagement with the listening task. The FUEL therefore provides a conceptual link between the demands imposed by hearing difficulties and broader experiences of communication and participation in everyday life.

The relevance of cognitive abilities extends beyond auditory processing and communication to other everyday activities that require the coordination of cognitive and motor demands. For example, working memory has been associated with balance and gait. Experimental studies have shown that when individuals perform a secondary cognitive task while walking (i.e., under dual-task conditions), gait performance often deteriorates, suggesting that locomotion partly relies on cognitive resources (Camp et al., 2023; Smith et al., 2017). Notably, visuospatial working memory (VSWM), which involves the temporary storage and manipulation of spatial information (Baddeley & Hitch, 1974), appears to be especially important for effective locomotion (Camp et al., 2023; Smith et al., 2017). Evidence from dual-task paradigms indicates that gait is more adversely affected when walking is combined with visuospatial tasks compared to other working memory demands (Menant et al., 2014; Pavlou et al., 2023; Qu, 2014). These findings demonstrate that cognitive resources are relevant not only to speech processing in challenging situations, but also to other everyday activities that require the simultaneous coordination of cognitive and motor demands. For hearing aid users, this relationship may be particularly relevant, as hearing loss can place additional demands on cognitive resources during everyday listening, potentially leaving fewer resources available for other concurrent tasks. Although the FUEL was developed to explain listening effort, its broader principle of limited and flexibly allocated cognitive resources may also help explain why demanding listening situations could affect performance in other concurrent activities, such as in the case of walking.

Cognitive abilities have also been linked to social functioning in later life. Longitudinal findings indicate that older adults with higher levels of cognitive functioning tend to engage more in social activities over time (Moorman & Goldman, 2026). Supporting this, studies have reported positive associations between working memory capacity and the size of individuals' real-world social networks (Ishiguro et al., 2024). Conversely, reduced cognitive capacity has been associated with smaller social networks and lower levels of community engagement (Kotwal et al., 2016). For individuals who use hearing aids, the FUEL provides a relevant framework for understanding this relationship, as it proposes that listening effort depends on the allocation of limited cognitive resources. If listening in everyday situations requires substantial cognitive effort, fewer resources may be available for other demands, including those involved in social interaction. This may be particularly relevant for hearing aid users, for whom improved audibility does not necessarily eliminate the cognitive demands of listening.

3.3.3 Individual differences in everyday functioning

Individual differences in age, sex, and educational attainment may contribute to variation in how individuals with hearing loss experience and manage everyday activities. These factors may be particularly relevant when examining everyday functioning in individuals who use hearing aids, as everyday experiences can reflect not only hearing difficulties but also differences in cognitive abilities, health, and social circumstances.

Age is associated with both hearing impairment and cognitive decline, which may increase difficulties in complex listening situations and everyday activities (Choi et al., 2019; Kamil et al., 2015; Kim et al., 2017; Lin et al., 2011; Salthouse, 2019; Tsimpida et al., 2020). Longitudinal evidence further suggests that age-related changes in auditory and cognitive function may occur concurrently, with declines in auditory temporal-order processing associated with declines

across several cognitive domains, even after controlling for age (Humes, 2021). In addition, age-related changes in physical health, functional abilities, and social roles may influence opportunities for and engagement in everyday activities, including social participation (Huang et al., 2025; Pinto & Neri, 2017; Zhou et al., 2025). Consequently, age may be associated with both hearing-related difficulties and broader aspects of everyday functioning, making it an important factor to account for when investigating these relationships.

Educational attainment may also be associated with differences in hearing, cognitive functioning, and everyday experiences. Higher educational attainment has been linked to better hearing health and a greater ability to manage hearing impairment (He et al., 2018; Rahimi et al., 2023), and education may also serve as a protective factor against cognitive decline (Alattar et al., 2020; Chen & Lu, 2020). Moreover, higher education levels have been associated with greater social participation in older age, potentially reflecting differences in access to social resources and networks (Augustsson et al., 2025; Townsend et al., 2021). Educational attainment may therefore help explain individual differences in cognitive performance and everyday functioning among people with hearing loss.

Biological sex may likewise be relevant to hearing-related everyday functioning. Biological differences, including hormonal influences and structural differences in the cochlea and auditory pathways, may contribute to variation in auditory processing and hearing outcomes (Aloufi et al., 2023; Hämäläinen et al., 2019; Nolan, 2020). Previous studies have also reported sex differences in the progression of hearing loss and in hearing aid use (Aloufi et al., 2023; Hansen et al., 2023; Reavis et al., 2023), as well as in hearing difficulties (Badache et al., 2024). Moreover, sex differences have been reported in cognitive functioning (Reynolds et al., 2022), gait performance (Sialino et al., 2021), and social participation, including the types of activities individuals engage in and changes in participation over time (Ong et al., 2024; Vogelsang & Moorman, 2025). These findings suggest that biological sex may be associated with differences in hearing-related outcomes and broader patterns of everyday functioning.

Taken together, age, sex, and educational attainment may be associated with individual differences in hearing-related experiences and everyday functioning. Accounting for these characteristics may therefore help distinguish the relationships of interest from variation associated with demographic factors. Accordingly, age, sex, and education were included as control variables in the analyses across studies.

3.4 Aims

The overall aim of this thesis was to investigate the relationships between hearing sensitivity, cognitive abilities, and different aspects of everyday functioning in individuals with age-related hearing loss, specifically in hearing aid users.

Specifically, this thesis aimed to:

- Examine the associations between hearing sensitivity, cognition, and auditory functioning (Papers I and IV).
- Examine the associations between hearing sensitivity, cognition, and gait performance (Paper II).
- Examine the associations between hearing sensitivity, cognition, auditory functioning, and social participation restrictions (Paper III).
- Investigate whether associations between cognitive abilities and functional outcomes differ between hearing aid users and individuals with normal hearing (Papers II–III).
- Examine associations between hearing sensitivity, working memory, and longitudinal changes in speech-in-noise perception (Paper IV).

4 Methods

The data included in this thesis are a selection of the data available from the first (T1) and second (T2) waves of testing of the N200 study (Rönnberg et al., 2016). The N200 is a longitudinal study examining the relationship between hearing, cognition, and speech recognition in normal-hearing and hearing-impaired individuals. The data were collected at the hearing clinic at Linköping University Hospital by clinical audiologists and trained research assistants.

Paper I includes data from the first wave of testing. Papers II and III include data from the second wave of testing. Paper IV is a longitudinal study and therefore includes data from both waves of testing. An overview of the variables included is shown in Table 4.1.

Table 4.1: Overview of the variables included in the studies

Study nr	T1	T2
Paper I	Age	
	Sex	
	Years of education	
	PTA4	
	Shifting cost	
	SSQ12	
Paper II		Age
		Sex
		VSWM
		Hearing status
		2MW test
Paper III		Age
		Sex
		Years of education
		Reading span
		HINT
		Hearing status
		SPaRQ
Paper IV	Age	
	Sex	
	PTA4	PTA4
	Reading span	Reading span
	Hagerman	Hagerman

4.1 Participants

The participants included in this thesis were native Swedish speakers, with good self-reported health, normal or corrected-to-normal vision, and no diagnosis of neurological deficits. In Papers I and IV, we included only a group of hearing aid users. In Papers II and III, we included both a group of hearing aid users and a group of normal hearing individuals. Participants ranged in age from 33 to 80 years at T1 and from 41 to 85 years at T2.

The participants included in the hearing aid group were recruited from the clinical population at the hearing clinic at Linköping University Hospital. They were experienced hearing aid users with at least 1 year of hearing aid use at T1, with bilateral mild-to-severe sensorineural hearing loss, and bilateral hearing aids. In the present study, hearing loss was operationally defined as a PTA4 of > 25 dB HL, calculated by averaging hearing thresholds at 500, 1000, 2000, and 4000 Hz. The participants included in the normal hearing group were age-matched to the hearing aid group and were recruited via voluntary participation from the general population in Linköping. They had PTA4 $\leqslant$ 25 dB HL in the better ear.

In Paper I, 203 participants with hearing loss using hearing aids were included in the data analysis (mean age=61.2, SD=8.05; 89 females).

In Paper II, we included 190 individuals (mean age = 67.5, SD = 8.01) in the analysis. Participants included 104 adults with hearing loss using hearing aids (mean age = 68.3, SD = 8.17; 40 females) and 86 adults with normal hearing (mean age = 66.5, SD = 7.75; 40 females).

In Paper III, 225 individuals (mean age = 67.5, SD = 8.05; 95 females) were included in the data analysis: 127 participants with hearing loss using hearing aids (mean age = 68.2, SD = 8.33; 51 females), and 98 participants with normal hearing (mean age = 66.5, SD = 7.60; 44 females).

In Paper IV, 121 participants with hearing loss using hearing aids were included in the analysis (mean age at T1= 60.3, SD = 8.29; 51 females).

The sample sizes differed across papers because each paper addressed different research questions and included different variables and measures. Consequently, the number of participants available for analysis varied depending on missing data in the variables of interest and the exclusion criteria specific to certain tests or analyses. Thus, the final analytical sample for each paper was determined by the availability of relevant data and the eligibility criteria applicable to the analyses conducted.

4.2 Measures

4.2.1 Hearing measures

All hearing measures were conducted inside a CA Tegnér sound-attenuated booth (Brüel & Kjær, type 4232) (Rönnberg et al., 2016).

Hearing thresholds

Air-conduction pure-tone audiometry was performed at frequencies of 125, 250, 500, 750, 1000, 2000, 4000, 6000, and 8000 Hz to assess unaided hearing thresholds. The pure-tone average across four frequencies (PTA4) was calculated using thresholds at 500, 1000, 2000, and 4000 Hz. For statistical analyses, the PTA4 value from the better-hearing ear was used as the indicator of hearing loss severity, with higher PTA4 values reflecting greater degrees of hearing loss.

Hearing in Noise test

Speech recognition thresholds in noise were assessed using the Swedish Hearing in Noise Test (HINT; Hällgren et al., 2006). Testing was conducted using individually fitted linear amplification settings in the presence of steady-state noise. The standard HINT protocol was employed to determine the signal-to-noise ratio (SNR) required for 50% correct sentence recognition using sentence lists containing 20 items. Speech and background noise were initially presented at 65 dB SPL, after which the noise level was adaptively adjusted based on participant responses. The participants completed a practice list prior to the main test. The dependent variable from the task was the final SNR threshold, calculated as the mean presentation level across the last 15 sentences. Lower SNR thresholds reflected better speech-in-noise recognition performance, indicating the ability to understand speech under less favourable listening conditions, whereas higher SNR thresholds indicated poorer performance.

Hagerman sentence test

Another task of speech-in-noise perception was the Hagerman sentence test (Hagerman, 1982), which consists of five-word sentences containing a proper noun, verb, numeral, adjective, and noun (e.g., "Ann had five red boxes"). An adaptive procedure was used to estimate the signal-to-noise ratios (SNR) corresponding to 50% and 80% correct word recognition (Brand, 2000). To investigate aided speech perception under cognitively demanding listening conditions, hearing aid processing features and background noise characteristics were experimentally manipulated (Foo et al., 2007; Lunner & Thorén, 2007; Ng et al., 2013, 2015). Two hearing aid processing parameters were examined: amplification type and noise reduction (NR). Amplification was

individually prescribed according to each participant's audiometric thresholds to ensure speech audibility. Two amplification settings were implemented: (1) linear amplification and (2) fast-acting non-linear amplification, as well as two types of background noise: (1) slightly amplitude-modulated (10%) speech-weighted noise and (2) multi-talker babble consisting of four talkers (two male and two female voices). The linear amplification setting was based on the voice-aligned compression (VAC) rationale (see Ng et al., 2013 for technical details) and provided linear gain with a 1:1 compression ratio for input levels between 30 and 90 dB SPL. All speech and noise stimuli used in the Hagerman test fell within the linear gain region and were therefore unaffected by compression knee-points or output limiting. The setup enabled individualised frequency-response shaping based on the VAC linear prescription to ensure adequate audibility of speech stimuli.

For the purpose of this study, we focused on two conditions: (1) linear amplification without NR in slightly amplitude-modulated noise and (2) linear amplification without NR in multi-talker babble. The dependent variable for this task was the SNR threshold for 80% correct word recognition. Higher SNR thresholds were associated with poorer speech perception in noise, reflecting greater difficulty understanding speech under challenging listening conditions, whereas lower thresholds indicated better performance in noisy environments.

Hearing difficulties

The Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse and Noble, 2004) was used to assess self-reported hearing difficulties across a range of everyday listening situations. The SSQ is designed to evaluate hearing in three domains that are central to understanding the everyday consequences of hearing impairment: Speech, Spatial, and Quality. The Speech subscale assesses the ability to understand speech in demanding listening environments, such as situations involving background noise, competing talkers, or rapid and complex conversations. The Spatial subscale evaluates spatial hearing abilities, including sound localisation, perception of distance, and tracking moving sound sources. The Quality subscale measures the perceived clarity, naturalness, and richness of sounds and speech, as well as the ability to discriminate among different sound sources, such as distinguishing voices in group conversations or perceiving musical detail (Gatehouse & Noble, 2004).

The abbreviated 12-item Swedish version of the SSQ (SSQ12; Ahlberg et al., 2024; Noble et al., 2013) was used in our study. Participants responded to the questionnaire using a scale ranging from 0 ("not at all") to 10 ("perfectly"), based on their hearing experiences while using hearing aids. Higher scores indicated better perceived hearing and fewer subjective hearing difficulties.

4.2.2 Cognitive measures

Cognitive shifting ability

Cognitive shifting ability, defined as the capacity to flexibly switch between different tasks or mental operations, was assessed using a number-letter task (Rogers & Monsell, 1995). In this task, participants were presented with a series of number-letter pairs displayed sequentially in one of the four corners of a computer screen. Depending on the location of the stimulus, participants applied one of two decision rules: when the pair appeared in the upper half of the screen, participants judged whether the number was odd or even; when it appeared in the lower half, they judged whether the letter was lowercase or uppercase. Switching between these two rules imposed a cognitive shifting cost, reflecting the efficiency of task-switching processes (Rogers & Monsell, 1995).

Before the experimental task, participants completed 16 practice trials and were required to achieve at least 50% accuracy before proceeding. During the main task, the first stimulus pair appeared in the upper-left corner of the screen, after which the stimuli followed a clockwise se-

quence. A total of 38 stimulus pairs were presented, including 18 shifting trials. Each stimulus remained on the screen until a response was made using designated response buttons or until a maximum duration of 10 s had elapsed. The dependent variable was the shifting cost, calculated as the difference between the mean reaction time for shifting trials and the mean reaction time for non-shifting trials. Higher scores reflected greater switching costs, indicating poorer cognitive flexibility and slower adaptation to changing task demands.

Visuospatial working memory

Visual-spatial working memory (VSWM) was assessed using a task described in Rönnberg et al. (2016). In each trial, pairs of ellipsoid shapes were presented sequentially at different locations within a 5 × 5 grid displayed on a computer screen. For each pair, participants made a self-paced judgment about whether the two ellipsoids were identical before the next pair appeared. After the final pair in each sequence, participants recalled the spatial locations of the ellipsoids by marking the corresponding grid squares on a blank paper grid in the correct serial order. Sequence length ranged from two to five items, with three trials administered at each length. Before the test, participants completed two practice trials using a 4 × 4 grid. The dependent measure in the present study was the total number of ellipsoids correctly recalled in their respective grid locations, irrespective of order (maximum score = 42). Higher scores indicated better VSWM performance.

Verbal working memory

Verbal working memory was assessed using the reading span test (RST) (Baddeley et al., 1985; Daneman & Carpenter, 1980; Rönnberg et al., 1989). Participants were presented with sets of two to five sentences (e.g., "The dog drives a car") and completed two simultaneous tasks: determining whether each sentence was semantically plausible and recalling either the first or final word of each sentence in the correct serial order after the entire set had been presented (Lunner, 2003). Sentences were displayed on a computer screen one word at a time, with each word presented for 800 ms. Half of the sentences were semantically anomalous (e.g., "The car drinks milk"), whereas the remaining sentences were meaningful (e.g., "The farmer builds a house"). Following each sentence, participants were given 5000 ms to indicate whether the sentence was meaningful ("yes") or not ("no") (cf. Ng et al., 2013, 2015). At the end of each sequence, participants recalled either the initial or final words from the sentences in their original order of presentation. Two trials were administered at each list length, yielding a maximum possible score of 28. The dependent variable was the total number of correctly recalled words, with higher scores indicating better verbal working memory performance.

4.2.3 Gait performance

Gait performance was assessed using the 2-minute walk test (2MWT; Bohannon et al., 2015). Participants were instructed to walk as quickly as possible, without running, along a 15-meter course marked at 3-meter intervals for a duration of 2 minutes. Upon reaching the end of the course, participants turned around and continued walking back and forth along the same route as many times as possible within the allotted time. Participants were allowed to use visual aids if necessary and could pause to rest at any point during the test. All participants in the HA group performed the assessment while wearing their hearing aids. The total walking distance covered during the 2-minute period was recorded. Gait performance was operationalised as walking speed, calculated by dividing the total distance walked (in meters) by the test duration (in seconds), yielding a measure expressed in meters per second (m/s).

4.2.4 Social participation restrictions

Perceived restrictions in social participation were assessed using the Social Participation Restrictions Questionnaire (SPaRQ; Heffernan et al., 2019). The SPaRQ is a self-report instrument comprising 19 items divided into two subscales: Social Behaviours and Social Perceptions. The Social Behaviours subscale assesses everyday social challenges, such as difficulties communicating with staff in shops, cafés, or banks. The Social Perceptions subscale evaluates negative emotional reactions related to these social challenges, including experiences of stress or discomfort in social situations (Heffernan et al., 2019). Participants rated each item on an 11-point Likert-type scale ranging from 0 to 10, where 0 indicated "do not agree at all" and 10 indicated "completely agree." Participants were instructed to respond based on their typical experiences in everyday life, with participants in the hearing aid group asked to consider their experiences while wearing their hearing aids. Lower scores reflected fewer perceived social participation restrictions.

4.3 Statistical analysis

Statistical analyses in the papers were performed using R version 4.5.1 (R Core Team, 2025) in RStudio (Posit team, 2025). Hierarchical multiple regression was used in Paper I, hierarchical robust regression in Papers II and III, and linear mixed modelling (LMM) in Paper IV.

Prior to the analyses, the datasets were examined for missing data in the variables of interest. Missing data were addressed using multivariate imputation by chained equations (MICE), implemented with the *mice* package (van Buuren & Groothuis-Oudshoorn, 2011), where appropriate. Papers I–III report results based on imputed data. In Paper IV, the primary analyses were conducted using non-imputed data; analyses using imputed data yielded consistent results.

4.4 Ethics

As the studies included in this thesis involved secondary analyses of anonymised data from a previously approved study, no additional ethical approval was required for the analyses presented here. The original study received ethical approval from Regionala etikprövningsnämnden i Linköping, the regional ethics committee (Dnr: 55-09 T122-09 and Dnr: 55-09 2016/418-32).

4.5 Use of AI

Throughout my PhD, I have used AI as a supporting tool, primarily to search for relevant literature and obtain feedback on my writing. For this thesis, I have used AI to search for relevant literature and to get feedback on the clarity and flow of my writing. In writing my papers, I have also used AI to explore alternative phrasings and assist with coding for data analysis. In both cases, the suggestions were treated as a starting point and critically evaluated, with AI-assisted code checked by an experienced researcher before use.

5 Summary of the papers

5.1 Paper I

Objective: To investigate whether hearing loss and cognitive shifting ability predict self-reported hearing difficulties among adult hearing-aid users. The study also examined whether sex moderates these relationships while controlling for age and education.

Methods: Data were drawn from 203 adults with bilateral hearing impairment participating in the longitudinal N200 study, including 89 females. Participants had a mean age of 61.2 years and had used hearing aids for more than one year. Hearing loss was measured using the better-ear pure-tone average across 500, 1,000, 2,000, and 4,000 Hz (PTA4), with higher values indicating greater hearing loss. Cognitive shifting ability was assessed using a number–letter task, in which greater shifting costs represented poorer cognitive flexibility. Self-reported hearing difficulties were evaluated using the 12-item Speech, Spatial and Qualities of Hearing Scale (SSQ12). Its three subscales assessed speech understanding, spatial hearing, and sound quality; higher scores indicated better perceived hearing and fewer difficulties. Hierarchical multiple regression models were fitted separately for each outcome. Age, education, and sex were entered as control variables, followed by PTA4 and shifting cost. Interaction terms tested whether associations involving hearing loss and shifting differed by sex. Exploratory models also examined whether sex moderated associations between education and hearing difficulties. Missing values were addressed using multiple imputation, and robustness analyses were conducted.

Results: Greater hearing loss independently predicted lower scores on all three SSQ12 subscales, indicating greater perceived difficulties with speech understanding, spatial hearing, and sound quality. Education was also an independent predictor of the Speech and Spatial subscales: participants with more years of education reported fewer difficulties in these domains. Cognitive shifting ability did not independently predict any SSQ12 outcome. Although sex-stratified correlations suggested some differences between females and males, none of the interactions between sex and hearing loss, cognitive shifting, or education significantly improved the re-

gression models. Thus, the relationships between the predictors and hearing difficulties did not differ by sex. Age and sex were not significant independent predictors. The models explained a relatively small proportion of variance, suggesting that additional factors contribute to self-perceived hearing difficulties.

Conclusions: Audiometric hearing loss emerged as the most consistent predictor of self-reported hearing difficulties among adult hearing-aid users, while education showed smaller associations with speech and spatial hearing. Cognitive shifting ability did not explain perceived hearing difficulties beyond demographic characteristics and hearing loss, and sex did not moderate the examined relationships. The findings highlight the importance of combining audiometric assessment with self-reported measures and investigating other cognitive, demographic, environmental, and hearing-aid-related factors that may explain persistent difficulties despite amplification.

5.2 Paper II

Objective: To investigate whether visuospatial working memory (VSWM) predicts gait performance in adults with normal hearing and hearing-aid users. The study also examined whether the relationship between VSWM and gait differs according to hearing status while controlling for age and sex.

Methods: Data were drawn from 190 adults participating in the second wave of the longitudinal N200 study. The sample comprised 104 adults with hearing loss who used bilateral hearing aids and 86 adults with normal hearing, with an overall mean age of 67.5 years. VSWM was assessed using a task in which participants recalled the locations of ellipsoid pairs presented sequentially within a grid. Gait performance was measured using the two-minute walking test. Participants walked as quickly as possible without running along a 15-metre course, and walking speed in metres per second was calculated from the total distance covered. Hearing-aid users completed the test while wearing their devices. Hierarchical robust regression models were fitted with walking speed as the outcome. Age and sex were entered as control variables, followed by VSWM and hearing status. An interaction term was then included to determine whether the association between VSWM and walking speed differed between the hearing-status groups. Missing walking-speed data were addressed using multiple imputation.

Results: Better VSWM independently predicted faster walking after age, sex, and hearing status were taken into account. Hearing status was also an independent predictor: adults with normal hearing walked faster than hearing-aid users, despite the latter wearing their hearing aids during testing. Adding VSWM and hearing status significantly improved model fit, and the selected model explained approximately 29% of the variance in walking speed. Increasing age independently predicted slower walking, whereas sex was not a significant predictor. The interaction between VSWM and hearing status was not statistically significant and did not improve model fit. Thus, the association between VSWM and gait performance did not differ reliably between hearing-aid users and adults with normal hearing.

Conclusions: VSWM and hearing status emerged as independent predictors of walking speed, suggesting that both cognitive and sensory factors contribute to mobility. However, hearing-aid users did not appear to rely more heavily on VSWM for walking than adults with normal hearing. Future research should use controlled auditory conditions, more detailed gait measures, broader cognitive assessments, and comparison groups with aided and unaided hearing loss.

5.3 Paper III

Objective: To investigate whether speech-in-noise perception and verbal working memory are associated with behavioural and subjective social participation restrictions among hearing-aid

users and adults with normal hearing. The study also examined whether these relationships vary according to hearing status.

Methods: Data were drawn from 225 adults participating in the second wave of the longitudinal N200 study. The sample comprised 127 bilateral hearing-aid users and 98 adults with normal hearing, with an overall mean age of 67.5 years. Speech-in-noise performance was measured using the Swedish Hearing in Noise Test (HINT), in which higher signal-to-noise-ratio thresholds indicate poorer performance. Verbal working memory was assessed using a reading-span task. Social participation restrictions were evaluated with a Swedish translation of the 19-item Social Participation Restrictions Questionnaire (SPaRQ). The Social Behaviours subscale assessed difficulties carrying out everyday social actions, whereas the Social Perceptions subscale measured negative thoughts and feelings associated with social situations. Hierarchical robust regression models were fitted separately for the two outcomes. Age, sex, and education were entered as control variables, followed by hearing status, HINT performance, and reading-span scores. Interaction terms were then included to determine whether associations differed between the hearing-status groups. Missing values were addressed using multiple imputation.

Results: Poorer speech-in-noise performance independently predicted greater restrictions on both SPaRQ subscales after demographic characteristics, hearing status, and verbal working memory were taken into account. For Social Behaviours, adding hearing status, HINT, and working memory significantly improved model fit, with the selected model explaining 14% of the variance. Hearing-aid users reported greater Social Perceptions restrictions than adults with normal hearing, indicating more negative subjective experiences of social situations. However, hearing status did not independently predict Social Behaviours restrictions. Neither the association between HINT performance and social participation restrictions nor the association between working memory and social participation restrictions differed significantly by hearing status. Although working memory was related to participation restrictions in initial correlations, it was not an independent predictor in the final models. Age, sex, and education were also not significant independent predictors.

Conclusions: Speech-in-noise ability emerged as the most reliable predictor of social participation restrictions across both hearing-status groups. The results suggest that clinical assessment should consider functional communication in noisy settings and the individual's subjective social experiences, rather than relying solely on hearing status or cognitive ability.

5.4 Paper IV

Objective: To investigate whether longitudinal changes in speech-in-noise perception are predicted by longitudinal changes in hearing sensitivity or verbal working memory in adult hearing aid users

Methods: Data were drawn from 116 adults participating in both waves (T1 and T2, separated by, on average, 8.14 years (SD = 2.18)) of the longitudinal N200 study. Participants had a mean age of 60.26 years at T1 and had used hearing aids for more than one year at T1. Speech-in-noise perception was measured using the Hagerman task, a matrix sentence test, in which semantically unpredictable sentences were presented in two background noise conditions (speech-shaped noise and 4-talker babble), and the speech-reception threshold (SRT) for 80% correct performance was used as the dependent variable. Verbal working memory was assessed using a reading-span task, and hearing sensitivity was assessed with four-frequency pure-tone average (PTA4). Linear mixed-effects analysis was used to investigate changes in speech-in-noise perception over time, and whether changes in hearing sensitivity or in verbal working memory capacity emerged as predictors. Additionally, time between test occasions, noise conditions (speech-shaped noise and 4-talker babble), and hearing sensitivity and verbal working memory capacity at T1 were included as predictors. Age at T1 was included as a covariate.

Results: Speech-in-noise perception worsened between T1 and T2, as indicated by an elevated SRT by 3.95 dB SNR. (SD = 3.52). Hearing sensitivity at T1 emerged as a significant predictor of changes in speech-in-noise perception, with participants with a worse PTA4 at T1 showing a greater increase in SRT over time. However, changes in hearing sensitivity and in verbal working memory were not significant predictors of changes in SRT.

Conclusions: Speech-in-noise perception worsened over the follow-up period in hearing-aid users, with a greater decline observed among those with poorer hearing sensitivity at baseline. This association suggests that initial hearing sensitivity may be linked to the trajectory of speech-in-noise performance over time. However, the longitudinal decline was not explained by changes in hearing sensitivity or verbal working memory capacity during the study period. Although baseline hearing sensitivity was associated with differences in subsequent performance trajectories, the factors underlying longitudinal changes in speech-in-noise perception remain unclear.

6 General discussion

The overarching aim of this thesis was to examine the relationships between hearing sensitivity, cognition, and everyday functioning in later life, with particular focus on hearing aid users. Across four studies, hearing and cognitive measures were considered in relation to self-reported hearing difficulties, gait performance, social participation restrictions, and longitudinal changes in speech-in-noise perception.

The findings of the studies can be divided into two different themes: (1) hearing sensitivity and cognition as predictors of auditory functioning (Papers I and IV) and (2) hearing sensitivity, auditory functioning, and cognition as predictors of functional ability (Papers II and III). The results suggest that hearing sensitivity and cognition were not uniformly associated with aspects of auditory functioning. Additionally, hearing sensitivity, auditory functioning, and cognition were not uniformly associated with functional ability. Rather, the associations between hearing sensitivity, cognitive abilities, auditory functioning, and functional ability differed across the studies and the outcomes examined. In Paper I, better hearing sensitivity was associated with fewer self-reported hearing difficulties. In Paper IV, poorer hearing sensitivity at baseline was associated with greater deterioration in speech-in-noise perception over time in hearing aid users. In Paper II, higher age and worse VSWM were associated with slower walking speed, and hearing aid users had slower walking speed compared to individuals with normal hearing. Lastly, in Paper III, hearing status was associated with perceived social participation restrictions, and better speech-in-noise perception was associated with fewer perceived and behavioural social participation restrictions, regardless of hearing status. Taken together, these findings suggest that hearing sensitivity is an important component of functional ability in adults and older adults, whereas cognitive contributions are domain-specific. In addition, demographic characteristics similarly showed outcome-specific associations: age was relevant to gait performance and changes over time in speech-in-noise performance, while education was associated with selected aspects of perceived hearing difficulty and social participation restrictions. Lastly, sex did not emerge as a significant predictor in any study, suggesting that sex may have limited explanatory value for the outcomes examined in the present studies.

6.1 Intrinsic capacity and functional ability

6.1.1 Hearing sensitivity as a component of intrinsic capacity

The WHO Healthy Ageing framework (World Health Organization, 2020) is particularly relevant to ARHL because hearing impairment is not equivalent to a functional limitation. A reduction in hearing sensitivity represents one aspect of intrinsic capacity, but the extent to which this reduction affects everyday life depends partly on the person's cognitive resources and other individual characteristics, the demands of their environment, communication partners, and opportunities for participation (Granberg et al., 2014). This perspective aligns with the Biopsychosocial model of disability, which conceptualises disability as arising from the interaction between health conditions, individual factors, and contextual influences (Waddell & Aylward, 2010). Hearing loss can therefore be understood as one component of a much broader system of functioning rather than as an isolated condition.

The findings of Paper I illustrate how hearing sensitivity relates to, but does not fully explain, perceived hearing difficulties. Hearing thresholds were associated with self-perceived hearing difficulties in all three subscales of the SSQ12, indicating that hearing sensitivity remains relevant to how individuals experience their auditory functioning, even among hearing aid users. At the same time, hearing thresholds did not account for all variation in perceived hearing difficulties, suggesting that other factors also influence the experience of auditory functioning. Therefore, an individual with better hearing sensitivity may experience a higher level of difficulty compared to an individual with a more severe hearing loss, depending on their environment, social support, and use of hearing technology. In capturing this functional dimension of hearing, the SSQ12 is particularly useful as it assesses auditory functioning in everyday situations, thereby reflecting listening environments that cannot be captured by laboratory-based measurements of auditory function conducted in controlled conditions. Thus, the degree of hearing impairment alone does not fully capture the extent of perceived hearing difficulties; how hearing loss is experienced in everyday listening situations needs to be considered when assessing auditory functioning.

The findings from Paper IV provide a longitudinal perspective on auditory functioning by examining how auditory sensitivity relates to changes in speech-in-noise perception over time. Baseline hearing thresholds predicted longitudinal changes in speech-in-noise perception, with individuals with poorer initial hearing thresholds showing a greater decline in speech-in-noise perception. This extends the cross-sectional findings of the thesis by suggesting that hearing sensitivity is relevant not only to differences in current auditory functioning but also to its subsequent changes. However, changes in hearing thresholds were not associated with changes in speech-in-noise performance, indicating that deterioration in peripheral hearing did not directly account for the observed decline in speech-in-noise perception. This is important because speech-in-noise perception also depends on cognitive abilities and the demands of the listening situation (Dryden et al., 2017; Schneider et al., 2007). Previous longitudinal research has similarly found associations between changes in speech-in-noise perception and cognitive functioning, suggesting that these relationships may be bidirectional, with both cognitive changes influencing auditory functioning and changes in auditory functioning relating to subsequent cognitive changes (Pronk et al., 2019). This highlights the complex interplay between hearing sensitivity and cognitive abilities in shaping auditory functioning. From the perspective of the Healthy Ageing framework, hearing sensitivity represents an aspect of intrinsic capacity that, together with other individual capacities and environmental factors, contributes to auditory functioning and, in turn, broader functional ability in everyday life.

The findings from Papers II and III extend the discussion beyond auditory functioning to examine how differences in hearing sensitivity relate to gait and social participation, two aspects relevant to functional ability in later life (World Health Organization, 2001). In Paper II, hearing aid users walked more slowly than participants with normal hearing, suggesting an associa-

tion between hearing sensitivity and gait performance. This finding is consistent with previous research linking hearing loss to poorer gait performance, poorer physical performance, and greater gait variability (Martinez-Amezcua et al., 2021; Sakurai et al., 2021). It is worth noting that participants in the hearing aid group wore their own hearing aids during the gait assessment, which have been reported to have potential benefits on gait performance (Shayman et al., 2017). Nevertheless, hearing aid users walked more slowly than participants with normal hearing; this pattern may reflect the fact that gait is a complex motor task that relies on the integration of multiple sensory inputs, including auditory, visual, and somatosensory information (Rossignol et al., 2006). Although hearing aids can improve access to environmental sounds, they may not fully restore the sensory information or processing required for effective postural control and locomotion. Taken together, the results from Paper II highlight the importance of considering hearing sensitivity in relation to mobility within the Healthy Ageing framework, as gait performance provides insight into an aspect of everyday functioning that extends beyond auditory functioning alone.

In Paper III, hearing status emerged as a significant predictor in the Social Perceptions subscale of the SPaRQ, but not in the Social Behaviours subscale. One possible explanation for this finding is that hearing loss may affect individuals' subjective experiences of social situations without necessarily preventing them from attending or engaging in social activities. Qualitative studies have highlighted how people with hearing loss can experience frustration, exclusion, and loneliness during social interactions, particularly when communication becomes challenging (Heffernan et al., 2022; Smith et al., 2024). Thus, hearing loss may impact social participation not only by creating barriers to social engagement, but also by shaping how individuals perceive their ability to participate in social situations. From the perspective of the Healthy Ageing framework, these findings highlight how hearing sensitivity, as an aspect of intrinsic capacity, may relate to different dimensions of functional ability, including social participation.

Hearing aids demonstrate an aspect of the interaction between intrinsic capacity and environmental support. By improving access to auditory information, hearing aids can reduce the functional consequences of hearing loss, yet they do not restore hearing sensitivity nor eliminate all associated difficulties (Ferguson et al., 2017). The findings across the papers illustrate this: in Paper I, hearing thresholds remained associated with self-perceived difficulties among hearing aid users; in Paper II, hearing aid users walked more slowly than participants with normal hearing despite wearing their own aids during assessment; and in Paper III, hearing aid users reported more perceptual social participation restrictions compared to normal hearing participants. Together, these findings suggest that hearing aids support everyday functioning without fully compensating for reduced intrinsic capacity; however, at the same time, they cannot establish the extent to which hearing aids compensate for reduced intrinsic capacity, as functioning in the absence of hearing aid use was not assessed. Nevertheless, these findings should not be interpreted as evidence that hearing aids are ineffective. Rather, hearing aid use indicates that an individual has received an intervention intended to support everyday functioning by reducing the functional consequences of hearing loss, while the degree of benefit varies between individuals and across listening situations (Jansen et al., 2024; Neher et al., 2016). In Healthy Ageing terms, hearing aids modify the environment in which a person functions, but the resulting functional ability still depends on the person's intrinsic capacity and the demands of the environment.

The ICF provides a complementary perspective to the Healthy Ageing framework by distinguishing between impairments of body functions and structures, activity limitations, participation restrictions, and contextual factors (World Health Organization, 2002). This distinction is relevant to the present findings because hearing loss represents an impaired body function, whereas self-perceived hearing difficulties, reduced gait performance, and reduced speech-in-noise perception represent activity limitations, and social participation restrictions reflect limitations in participation. Across the papers, hearing impairment was consistently associated with outcomes at the activity and participation level, but explained only part of each, suggesting

that other factors beyond hearing impairment influence these outcomes. The ICF therefore reinforces the importance of distinguishing hearing impairment from its consequences in everyday functioning, while the Healthy Ageing framework places these relationships within the broader concept of functional ability.

6.1.2 Cognitive ability as a component of intrinsic capacity

Cognitive capacity represents another component of intrinsic capacity and was examined in different ways across the studies: in Paper I, we investigated the role of cognitive shifting ability in self-reported hearing difficulties; in Paper II, we examined the role of VSWM in gait performance; in Paper III, we investigated the role of verbal working memory in social participation restrictions; lastly, in Paper IV, we examined the role of verbal working memory in longitudinal changes in speech-in-noise perception. An important finding of the thesis is that cognitive abilities did not show a uniform relationship with different aspects of everyday functioning. Instead, the relevance of cognition appeared to depend on the cognitive function measured and the aspect considered.

This is particularly important when interpreting the findings in relation to the theories guiding this thesis. Hearing loss can increase the cognitive demands associated with listening, particularly under adverse conditions, as illustrated by the ELU model (Rönnberg et al., 2022) and by the FUEL (Pichora-Fuller et al., 2016). However, these frameworks primarily concern speech perception and listening; they describe how cognitive resources are allocated in response to listening demands (FUEL) and how explicit processing is recruited when the incoming signal cannot be matched to stored linguistic representations (ELU model), and they do not imply that hearing loss will result in increased reliance on the same cognitive resources during unrelated functional activities. Similarly, associations between hearing-related outcomes and cognition may differ depending on the type of hearing-related outcome and the specific cognitive ability being considered (Danielsson et al., 2019). The findings across the papers are consistent with this domain-specific interpretation, although an alternative interpretation is that the role of cognition in these outcomes is generally limited. In any case, the results of the papers do not support the interpretation that hearing loss leads to increased reliance on cognitive resources across different functional activities. Paper II provides the best example of this. Better VSWM was associated with faster walking speed, which is consistent with the idea that walking involves more than motor capacity alone (Woollacott & Shumway-Cook, 2002). For both hearing aid users and normal hearing individuals, everyday walking requires individuals to adapt their walking patterns to changing environmental and task demands (Dasgupta et al., 2021), for which visuospatial processing is particularly important (Higuchi, 2013; Kim et al., 2018). However, the interaction between VSWM and hearing status was not significant, therefore not supporting the hypothesis that adults with hearing aids would rely more strongly on VSWM for gait performance compared to normal-hearing individuals. This suggests that VSWM may be relevant to gait performance in general, rather than representing a cognitive resource specifically recruited to offset reduced access to auditory cues due to hearing loss. Additionally, in Paper I, cognitive shifting ability was not significantly associated with self-reported hearing difficulties, indicating that variations in this component of executive functions did not account for variations in perceived hearing difficulties. The results of Paper III similarly support this interpretation. Verbal working memory was not a significant predictor of social participation restrictions, whereas speech-in-noise perception showed a strong association. Thus, the association between hearing loss and social participation restrictions was not explained by the particular measure of verbal working memory used in the study. Paper IV shows a similar pattern longitudinally. Verbal working memory capacity declined over time, but neither baseline verbal working memory nor changes over time in verbal working memory significantly predicted trajectories of speech-in-noise perception. Thus, the findings of this thesis support a multidimensional interpretation of cognition. Cognitive capacity should not be treated as a single resource that either compensates for hearing loss or explains functional consequences across domains. Rather, particular cognitive abilities may be relevant to particular tasks.

6.1.3 Demographic factors as components of intrinsic capacity

Demographic factors such as age, sex, and level of education as components of intrinsic capacity were also included in the papers.

Age emerged as a significant predictor of both gait performance (Paper II) and speech-in-noise performance (Paper IV), suggesting that age is associated with different aspects of functional ability. The association between increasing age and slower walking speed (Paper II) is consistent with previous research (Bohannon et al., 2015) and may reflect gradual declines in physiological and neurological functions involved in locomotion and postural control, including reductions in lower-limb strength and range of motion (Aboutorabi et al., 2016) and age-related changes in motor cortical regions (Seidler et al., 2010). In Paper IV, longitudinal changes in speech-in-noise performance suggest that auditory functioning may change over time beyond what is captured by measures of hearing sensitivity alone. At baseline, older age was associated with poorer speech-in-noise performance, consistent with previous research demonstrating age-related differences in speech-in-noise perception and longitudinal associations between hearing and cognition (Goderie et al., 2020; Pronk et al., 2019). These findings suggest that age-related changes in speech perception may reflect the combined influence of peripheral hearing loss and cognitive processes; however, the mechanisms underlying this association remain unclear.

Despite these associations with objective measures, age was not a significant predictor of self-reported hearing difficulties (Paper I) or self-reported social participation restrictions (Paper III). The discrepancy between speech-in-noise performance and self-reported hearing difficulties is consistent with evidence that these measures assess related but distinct aspects of auditory functioning. Previous studies have shown that older adults may experience difficulties with speech-in-noise perception without reporting hearing problems, and that self-reported hearing difficulties show limited agreement with objectively measured hearing loss (Pronk et al., 2018; Tsimpida et al., 2020). Similarly, the absence of an association between age and self-reported social participation restrictions may reflect the fact that the functional consequences of age-related changes are shaped by factors beyond intrinsic capacity alone. Although hearing loss can affect the ability to maintain relationships and participate in social activities, these consequences vary according to individual and environmental circumstances, including social support and strategies for managing communication difficulties (Prieur Chaintré et al., 2024). Thus, age-related declines in hearing sensitivity do not necessarily translate into greater hearing difficulties in daily life or social participation restrictions, as supportive environments, social networks, and individual strategies may help individuals maintain their functional ability despite changes in intrinsic capacity.

Educational level emerged as a significant predictor in the Speech and Spatial subscales of the SSQ12, with individuals with higher education levels reporting a lower degree of hearing difficulties (Paper I). One possible explanation is that higher educational attainment is associated with greater health literacy, which may support informed health-related decisions, awareness of preventive care, and the management of hearing difficulties (He et al., 2018; Raghupathi & Raghupathi, 2020; Rahimi et al., 2023). However, we did not see an association with level of education in the Quality subscale, and one possible explanation for this is that this subscale focuses on perceptual qualities such as sound segregation, recognition, and clarity/naturalness, which may have a weaker link to education level. Nonetheless, the reason education is associated with only two of the three subscales is not fully clear, and this is a pattern that should be followed up on in future research. Education also showed a complex relationship with social participation restrictions (Paper III). Although it was a significant predictor of the Social Perception subscale of the SPaRQ, this association became non-significant after additional predictors were included, suggesting that the relationship may partly overlap with other factors more directly related to the outcome. Furthermore, the significant interaction between education and speech-in-noise perception suggests that the association between speech-in-noise perception and perceived social participation restrictions may differ according to educational level. This is consistent with previous longitudinal research indicating that the relationship between hearing and social out-

comes may vary by education (Stam et al., 2016). However, this finding should be interpreted cautiously, as the interaction was observed in a model for which the overall improvement in fit was not statistically significant. Thus, educational attainment may be relevant to both self-reported hearing difficulties and social participation restrictions, although its associations appear to vary across functional outcomes and require further investigation.

Biological sex was included in the analyses as a control variable in all papers (I-IV) as previous research has identified sex-related differences in hearing sensitivity (e.g., Aloufi et al., 2023), gait (e.g., Sialino et al., 2021), cognition (e.g., Reavis et al., 2023), and social participation (e.g., Ong et al., 2024; Vogelsang & Moorman, 2025). However, contrary to our expectations, sex was not linked to self-reported hearing difficulties, gait performance, social participation restrictions, or changes in speech-in-noise performance. One possible explanation is that sex-related differences may be more evident for specific physiological measures, rather than for perceived hearing difficulties and broader functional outcomes. Furthermore, gait performance, speech-in-noise perception, social participation, and self-reported hearing difficulties are influenced by several interacting factors, which may limit the independent contribution of sex in the sample we examined.

6.1.4 Everyday functioning in hearing aid users

While Papers I and IV focused on hearing sensitivity and cognitive abilities as predictors of auditory functioning, Papers II and III investigated the relationship between hearing sensitivity, cognition, and everyday functioning. One of the central findings of this thesis is that hearing sensitivity as an aspect of intrinsic capacity was associated with several aspects of everyday functioning, but the observed relationships differed depending on the outcome being examined: hearing sensitivity was associated with self-reported hearing difficulties (Paper I) and with longitudinal changes in speech-in-noise perception (Paper II), and differences in hearing sensitivity (hearing status) were associated with walking speed (Paper II) and with the perceptual aspects of social participation restrictions (Paper III). Additionally, speech-in-noise perception as an aspect of auditory functioning was associated with social participation restrictions (Paper III). On the other hand, cognitive ability as an aspect of intrinsic capacity showed a much smaller influence, with VSWM associated with gait performance (Paper II), whereas cognitive shifting ability showed no association with perceived hearing difficulties (Paper I) and verbal working memory showed no significant association with social participation restrictions (Paper III) nor with longitudinal changes in speech-in-noise perception (Paper IV).

Compared with hearing sensitivity, cognitive ability showed more limited and outcome-specific associations with everyday functioning in this thesis. Cognitive abilities are a component of intrinsic capacity that may be relevant to functional ability, but their relationship with it appears to depend on the cognitive capacities and tasks being considered. Hearing sensitivity and cognition are closely connected when considering demanding listening situations, where understanding speech may require both adequate auditory information and cognitive resources to interpret it (Rönnberg et al., 2022). Research on hearing, cognition, and healthy ageing has emphasised these interrelationships while also recognising that associations between hearing and cognitive outcomes do not, by themselves, establish a causal pathway (Pichora-Fuller et al., 2015). In this thesis, the cognitive associations were not consistent across outcomes: VSWM was associated with walking speed, while verbal working memory was not significantly associated with social participation restrictions. However, these results do not imply that cognition is unimportant for healthy ageing; rather, they suggest that a single cognitive measure may not capture the cognitive demands relevant to the aspects of functional ability examined in this thesis.

Taken together, these findings suggest that the relationship between hearing sensitivity as a component of intrinsic capacity and everyday functioning cannot be understood from hearing impairment alone, but the implications of reduced hearing sensitivity may differ depending on

which aspect of everyday functioning is considered. The findings indicate that hearing sensitivity is associated with several aspects of everyday functioning, including auditory functioning, mobility, and social participation, although these associations differ depending on the outcome examined. Furthermore, the association between speech-in-noise perception and social participation restrictions highlights the relevance of considering auditory functioning as an aspect of everyday functioning in its own right. In contrast, the more limited associations observed for cognitive ability as an aspect of intrinsic capacity suggest that its contribution to everyday functioning may be more specific to certain functional domains. Overall, these findings underscore the multidimensional nature of the relationship between intrinsic capacity and everyday functioning, and the importance of considering both hearing sensitivity and cognitive ability, as well as distinct dimensions of everyday functioning, when examining the functional implications of hearing loss.

For hearing aid users, understanding functional ability may therefore require consideration not only of hearing sensitivity, but also of cognitive ability and how these capacities relate to the demands of everyday life. Hearing thresholds describe an individual's hearing sensitivity, but they do not determine how well a person manages functioning in everyday life. Similarly, hearing aid use does not necessarily indicate the degree to which challenges due to hearing loss are resolved in daily situations. The relationship between hearing sensitivity and healthy ageing therefore extends beyond auditory functioning to include the extent to which people can maintain activities, relationships, and participation as they grow older. Research on hearing health has increasingly emphasised this broader perspective, highlighting the importance of considering social, emotional, and physical well-being alongside hearing-related outcomes (Pichora-Fuller et al., 2015; Vercammen et al., 2021). Although hearing aid use may be relevant to some aspects of everyday functioning beyond auditory functioning (e.g., Holman et al., 2021; Jansen et al., 2025), it does not necessarily indicate that the broader challenges associated with hearing loss are resolved.

The findings of this thesis illustrate why it is important to distinguish intrinsic capacity from functional ability, while still considering them related concepts. The associations found in the studies suggest that hearing sensitivity may be relevant to different dimensions of everyday functioning, but they do not establish that hearing impairment by itself causes limitations in functional ability. For example, in Paper III, speech-in-noise perception–an aspect of auditory functioning–emerged as a significant predictor of restrictions in social participation, whereas hearing sensitivity was linked only to perceptual aspects of social participation restrictions. Thus, auditory functioning can be understood both as a dimension of everyday functioning in its own right and as a factor associated with other dimensions of functional ability, such as social participation. Therefore, hearing sensitivity is one component of the broader set of capacities and circumstances involved in functioning. A person's experience of an activity may also depend on the demands of the situation, available support, and opportunities to adapt to difficulties. Although environmental conditions and hearing-aid-related benefits were not directly examined in this thesis, the Healthy Ageing framework (World Health Organization, 2020) indicates why these factors matter when interpreting the relationship between intrinsic capacity and functional ability.

6.2 Methodological considerations, limitations, and future directions

An important methodological consideration is that the studies provide different levels of information about the relationships between hearing sensitivity, cognition, and everyday functioning. Papers I-III were primarily cross-sectional and therefore describe associations at a given point in time, whereas Paper IV adds a longitudinal perspective by examining change over time. The findings should consequently be interpreted according to the type of evidence provided by each design rather than as evidence of causal relationships. This is particularly rel-

evant to the overall interpretation of the thesis. The studies identify consistent relationships between hearing-related measures and different aspects of everyday functioning, but they do not establish a single direction of influence between these domains. Even the longitudinal association observed in Paper IV does not by itself establish causality. Future studies using repeated measurements of hearing, cognition, and functional outcomes could provide stronger evidence regarding the direction and development of these relationships over time. In addition, experimental studies manipulating auditory conditions could help clarify whether changes in hearing sensitivity and auditory functioning contribute to changes in functional outcomes. Such studies would complement longitudinal research by providing stronger evidence regarding potential causal relationships between hearing sensitivity, auditory functioning, and other domains of everyday functioning.

The thesis also highlights the importance of using different hearing-related measures as complementary approaches. Hearing thresholds provide a standardised measure of hearing sensitivity, while speech-in-noise perception involves the processing of complex auditory information in adverse conditions (Mattys et al., 2012; Musiek et al., 2017). Self-reported hearing difficulties capture the individual's experience of hearing in everyday life and may incorporate listening effort, communication demands, expectations, coping strategies, and environmental conditions (Vas et al., 2017). Differences between these measures should therefore not automatically be regarded as inconsistencies, but rather they reflect the multidimensional nature of hearing. A person can have relatively stable hearing thresholds but experience deterioration in speech-in-noise performance, or can have substantial hearing loss while reporting relatively few difficulties because of environmental support and effective communication strategies. The use of multiple hearing-related measures across the thesis is therefore an important strength.

Cognition was also assessed using different measures across the studies. Cognitive shifting was examined in Paper I, VSWM in Paper II, and verbal working memory in Papers III and IV. This reflects the multidimensional nature of cognition but also limits conclusions about cognition as a broad construct. The findings also illustrate why non-significant associations should be interpreted cautiously. The absence of an association between verbal working memory and speech-in-noise change or social participation restrictions does not demonstrate that cognition is irrelevant; rather, it indicates that the specific cognitive construct measured did not account for additional variation in the outcome. A possible explanation is that the tasks used failed to capture the cognitive processes most relevant to the specific auditory task. For example, auditory working memory has been associated with both speech-in-noise perception and self-perceived hearing difficulties, suggesting that it may capture cognitive processes relevant to these outcomes (Roup et al., 2025; Shokuhifar et al., 2025). Future studies should therefore consider other cognitive measures to clarify which cognitive processes are most relevant to self-reported hearing difficulties, speech-in-noise perception, and social participation restrictions.

The interpretation of hearing status group differences requires particular caution. Papers II and III compared hearing-aid users with individuals with normal hearing. These comparisons are informative because they show differences between groups with different hearing status, but they cannot determine the effects of hearing aids. Hearing-aid users differ from normal hearing individuals in their underlying hearing loss and may also differ in age, health, health-seeking behaviour, socioeconomic circumstances, communication demands, and other characteristics, and they also differ from individuals with hearing loss who are not hearing aid users. Furthermore, hearing aid users vary substantially in duration and consistency of use, fitting, rehabilitation, and subjective benefit. Consequently, the slower walking speed observed among hearing-aid users in Paper II should not be interpreted as a lack of effect of hearing aids on gait performance. Similarly, the greater social participation restrictions reported by the hearing-aid group in Paper III should not be interpreted as evidence that hearing aids do not aid social functioning. The group differences more appropriately indicate that the hearing-aid group differed from the normal hearing group on these outcomes. The distinction between hearing status and hearing-aid benefit is therefore important. A binary classification of users versus non-users does

not capture the extent to which hearing aids change access to sound or functional ability in everyday life. Future research should include duration of hearing-aid use, daily wear time, fitting characteristics, communication strategies, assistive technologies, and subjective benefit. Longitudinal designs would be particularly useful because hearing-aid use and benefit may change as hearing sensitivity and functional needs change. Furthermore, outcomes should be assessed under both aided and unaided conditions to allow comparisons between the two.

The use of self-reported outcomes in Papers I and III provides information that cannot be obtained from objective measures alone. Perceived hearing difficulties and perceived social participation restrictions reflect the individual's experience of functioning in everyday life. At the same time, self-reported outcomes may be influenced by factors related to questionnaire design and administration, as well as by individual response behaviours (Chang et al., 2019). This does not make them less valid; rather, it emphasises that subjective perspectives on functioning represent a different level of assessment. For example, an individual may have poor hearing thresholds but report relatively few difficulties because communication partners adapt and listening environments are supportive. Another person with better hearing may report considerable difficulty because their communication demands are high or because they frequently encounter adverse listening conditions. Combining objective and subjective measures is therefore likely to provide a more complete understanding of their level of functional ability. In the context of hearing loss, longitudinal studies that repeatedly assess both self-reported and objective outcomes may provide insight into whether changes in objective hearing sensitivity precede changes in perceived difficulty, whether subjective difficulties emerge before measurable changes in hearing sensitivity, or whether the two change relatively independently.

An important scope consideration is that only selected aspects of functional ability were assessed in this thesis. In the Healthy Ageing framework, functional ability encompasses five domains: the ability to meet basic needs; the ability to learn, grow, and make decisions; the ability to be mobile; the ability to build and maintain relationships; and the ability to contribute to society (World Health Organization, 2020). The thesis included auditory functioning, gait performance, and social participation restrictions, which are relevant aspects of everyday functioning, but they do not represent functional ability as a whole, and they cover different aspects of its multiple domains. It would therefore be incorrect to claim that all aspects of the domains that comprise functional ability are captured in this thesis. The findings should therefore be interpreted as domain-specific and aspect-specific rather than as a comprehensive assessment of functional ability.

A limitation of the studies included in this thesis is that they primarily measured intrinsic capacity and functional ability, with little information on the environments in which functioning occurred. This limitation is particularly relevant when considering social participation restrictions and perceived hearing difficulties. The two questionnaires–SSQ12 (Noble et al., 2013) and SPaRQ (Heffernan et al., 2019)–assess multiple aspects of their perceived experience of functioning in everyday life, but they do not characterise the environments in which these difficulties and restrictions occur. For example, listening environments vary considerably in terms of background noise, reverberation, and distance from the speaker, all variables that can affect speech perception (Bottalico et al., 2026). Social participation may also depend, among other aspects, on transportation, social support, and living arrangements (Vaughan et al., 2016). Future studies should therefore consider a wider range of contextual characteristics when investigating functional ability.

An important consideration when interpreting the findings of this thesis is the age distribution of the participants. The age range across the studies was relatively broad (33 to 80 at T1, 41 to 85 at T2), with mean ages ranging from 60 to 66 years depending on the study, meaning that the findings may not fully reflect the experiences and functional challenges of older adults. Age was included as a covariate in all four studies, and was significantly associated with speech-in-noise perception and gait performance, but not with the other outcomes examined. This may suggest that the relationships between hearing sensitivity, cognition, and functional ability observed in

this thesis were not consistently explained by chronological age. At the same time, the inclusion of participants across a broad adult age range provides insights into the relationships between hearing sensitivity, cognition, and functional ability across different stages of life. Nevertheless, further research focusing specifically on older adults would be valuable to determine whether the observed relationships apply to adults in advanced age and how they relate to everyday functioning in this population.

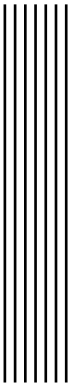
Finally, future research on adults with hearing loss should move toward more integrated models of healthy ageing. The present thesis examined hearing sensitivity, cognitive ability, auditory functioning, gait performance, and social participation restrictions across separate studies. This design allowed detailed examination of specific relationships, but a more comprehensive model could examine how multiple components of intrinsic capacity interact within the same individuals. More advanced statistical modelling could be used to investigate whether different patterns of ageing emerge. Such an approach would be consistent with the WHO Healthy Ageing framework because it recognises that maintaining functional ability does not require every component of intrinsic capacity to remain unchanged. Instead, functioning reflects the interaction among intrinsic capacities, environments, and individual circumstances.

7 Conclusion

The aim of this thesis was to investigate the relationship between hearing sensitivity, cognitive abilities, and functional ability in adults with age-related hearing loss who are also hearing aid users. Across the four studies, the findings showed that these relationships differed according to the outcome and cognitive ability examined. For auditory functioning, hearing thresholds were the most consistent predictor of self-reported hearing difficulties and of changes in speech-in-noise perception over time. On the other hand, cognition showed a more limited role, as cognitive shifting did not emerge as a predictor of self-reported hearing difficulties, and verbal working memory did not explain changes in speech-in-noise perception. Similarly, for functional ability, differences in hearing sensitivity were consistently associated with gait performance and social perception restrictions and auditory functioning was associated with social participation restrictions, whereas cognition showed a more domain-specific relationship. Verbal working memory was not a predictor of social participation restrictions, whereas VSWM emerged as an independent predictor of gait performance, regardless of hearing status. In relation to the Healthy Ageing framework, these findings can be understood in terms of functional ability, which is central to the framework's definition of healthy ageing and emerges through the interaction between intrinsic capacity and the environment. Hearing sensitivity and cognitive abilities can be understood as components of intrinsic capacity, while auditory functioning, gait performance, and social participation restrictions represent different aspects of functional ability. The findings of this thesis suggest that hearing sensitivity and cognitive abilities should not be assumed to operate in the same way across all aspects of functional ability. Although the findings highlight associations between hearing sensitivity, cognition, and functional outcomes, the role of environmental conditions in shaping these relationships remains unclear, as these were not directly examined in the present thesis.

Taken together, the findings of this thesis are relevant to understanding the broader implications of hearing sensitivity and cognitive abilities for everyday functioning, as the ability to communicate, maintain mobility, and participate in social activities are important aspects of everyday life that support independence and engagement, particularly as people age. The observed associa-

tions suggest that hearing sensitivity and cognitive abilities may be relevant to several aspects of functioning beyond auditory functioning alone. Although the study population covered a wide age range, these findings highlight the relevance of considering hearing sensitivity and cognition in relation to broader functional outcomes when seeking to understand factors that may contribute to maintaining independence and healthy ageing.



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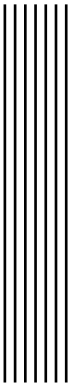

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