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Jon B. Prince

Helen L. Davis

Jane Tan

Katrina Muller-Townsend

Shaun Markovic
*Edith Cowan University*

*See next page for additional authors*



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## Authors

Jon B. Prince, Helen L. Davis, Jane Tan, Katrina Muller-Townsend, Shaun Markovic, David M. G. Lewis, Brianne Hastie, Matthew B. Thompson, Peter D. Drummond, Hakuei Fujiyama, and Hamid R. Sohrabi

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# Cognitive and neuroscientific perspectives of healthy ageing☆

Jon B. Prince [a,b,*], Helen L. Davis [a,b], Jane Tan [a,b], Katrina Muller-Townsend [a,b], Shaun Markovic [a,b,g], David M.G. Lewis [a,b], Brianne Hastie [a], Matthew B. Thompson [a,f], Peter D. Drummond [a,b], Hakuei Fujiyama [a,b,c], Hamid R. Sohrabi [a,b,d,e,*]

[a] School of Psychology, Murdoch University, WA, Australia
[b] Centre for Healthy Ageing, Health Futures Institute, Murdoch University, WA, Australia
[c] Centre for Molecular Medicine and Innovative Therapeutics, Murdoch University, WA, Australia
[d] School of Medical and Health Sciences, Edith Cowan University, WA, Australia
[e] Department of Biomedical Sciences, Macquarie University, NSW, Australia
[f] Centre for Biosecurity and One Health, Harry Butler Institute, Murdoch University, WA, Australia
[g] Discipline of Psychology, Counselling and Criminology, Edith Cowan University, WA, Australia

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ABSTRACT

With dementia incidence projected to escalate significantly within the next 25 years, the United Nations declared 2021–2030 the Decade of Healthy Ageing, emphasising cognition as a crucial element. As a leading discipline in cognition and ageing research, psychology is well-equipped to offer insights for translational research, clinical practice, and policy-making. In this comprehensive review, we discuss the current state of knowledge on age-related changes in cognition and psychological health. We discuss cognitive changes during ageing, including (a) heterogeneity in the rate, trajectory, and characteristics of decline experienced by older adults, (b) the role of cognitive reserve in age-related cognitive decline, and (c) the potential for cognitive training to slow this decline. We also examine ageing and cognition through multiple theoretical perspectives. We highlight critical unresolved issues, such as the disparate implications of subjective versus objective measures of cognitive decline and the insufficient evaluation of cognitive training programs. We suggest future research directions, and emphasise interdisciplinary collaboration to create a more comprehensive understanding of the factors that modulate cognitive ageing.

## 1. Introduction

Human life expectancy has risen by over eight years since 1990 (United Nations Department of Economic and Social Affairs Population Division, 2019). Psychology, as a discipline, has contributed to this increased longevity by highlighting the importance of mental health in ageing (e.g., psychological resilience, psychotherapeutic interventions, and suicide prevention; Diehl and Wahl, 2020). Another major contribution of psychology to healthy ageing is via the study of cognition. Albeit a crude measure, one objective indicator of the contribution of the field to improving our understanding of age-related cognitive changes and potential preventive/ameliorative interventions is the number of publications on various aspects of cognitive geropsychology. A search of PubMed, using a combination of keywords relevant to age-related cognitive impairments, cognitive function in the elderly and older adults, and cognition and ageing, yielded over 22,000 papers published in the last 60 years (see Fig. 1).

Additionally, the United Nations General Assembly announced 2021–2030 as the Decade of Healthy Ageing. This initiative is aimed at promoting the quality of life of older adults, their families and communities at large, with cognition as a major pillar (World Health Organization, 2020). Such initiatives encourage further research within the field of psychology focused on maintaining mental, cognitive, and physical wellbeing later in life.

Although lifespan has increased significantly, there has not been an accompanying increase in the *health* span (Garmany et al., 2021). Ageing can produce unwanted outcomes, such as age-related cognitive decline. Such conditions have significant and chronic impact on older adults, as well as their family members and caregivers. Until we can mitigate age-related pathology and associated functional decline through disease

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* Correspondence to: School of Psychology, Building 440, Murdoch University, 90 South Street, Murdoch, WA 6150, Australia.
*E-mail addresses:* Jon.Prince@murdoch.edu.au (J.B. Prince), Hamid.Sohrabi@murdoch.edu.au (H.R. Sohrabi).

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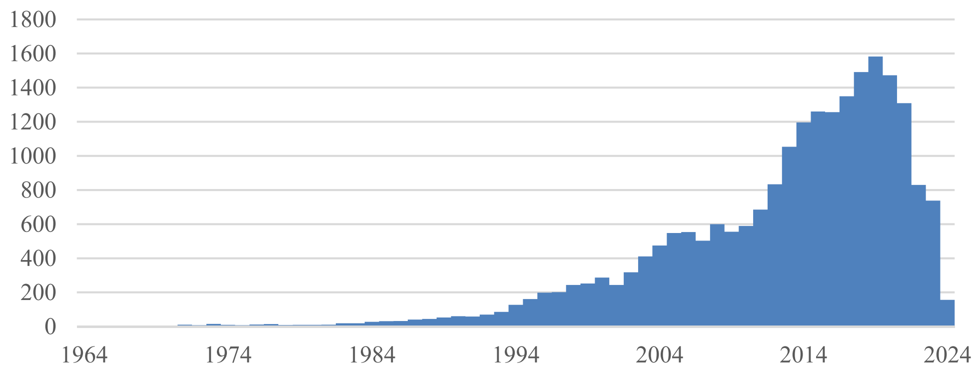


**Fig. 1.** Number of publications referring to cognition and ageing since 1964. The surge in publications on age-related cognitive decline began in the early 2000 s and peaked in 2019.[1] Keywords were as follows: ((age-related cognitive impairments) OR (cognitive function in elderly) OR (cognitive function in older adults) OR (cognitive decline in older adults) OR (age-related cognitive problems) OR (cognition and aging)), with the following filters: Clinical Trial, Meta-Analysis, Observational Study, Randomized Controlled Trial, English, Middle Aged: 45–64 years, Aged: 65+ years, 80 and over: 80+ years, Humans, from 1964/1/1. Search was conducted on 14 March 2024 on PubMed.

[1] The decline in publications since 2019 has several possible explanations. For instance, publication lag alone could account for the last 2–3 years, leaving 2020–2021 to explain. This period overlaps with the worst of the COVID-19 pandemic, which interfered with the research productivity of many academics. The pandemic also hindered access to older participants through lockdowns and travel restrictions, as well as reduced their willingness to participate in research (due to exposure risk). Further, the increased focus on dementia (and prevention) research may have diverted research efforts on healthy ageing.

modifying-treatments, older adults' quality of life will be primarily preserved through management strategies, rather than cures. Indeed, promoting better quality of life is the primary aim of the Decade of Healthy Ageing (World Health Organization, 2020). As a behavioural health discipline, psychology is central to the biopsychosocial model of health and thus has the capacity to contribute to quality of life (health span) among older adults. Indeed, psychology researchers now have methods that can be readily employed to improve the quality of life and health span of older adults. Some of these approaches show considerable clinical utility when tailored to older adults, such as novel health assessment methodologies combined with modern cognitive and behavioural interventions such as acceptance and commitment therapy (Petkus and Wetherell, 2013) or mindfulness-based therapy (Hazlett-Stevens et al., 2019).

Age-related cognitive impairment and dementia are major concerns for older adults, their family members and health providers (World Health Organization, 2022), and dementia incidence is projected to increase substantially over the next 25 years (Nichols et al., 2022). Cognition is integral to a range of essential daily functions and the maintenance of independent living capacity with age. Older people have other psychological health concerns as well; the risk of successful suicide attempts in older adults is far higher than in younger individuals (Conejero et al., 2018). The high risk of mental health conditions (Ausín et al., 2017) and limited support for older adults' psychological well-being (Stargatt et al., 2017) could partially explain this pattern. Furthermore, physical, medical, social, environmental, and financial limitations provide additional roadblocks to maintaining a high quality of life during older adulthood. Accordingly, older adults and their caregivers can significantly benefit from psychological research on healthy ageing, including preventive approaches and interventions. Importantly, despite concerns about the universality of cognitive decline among this age group, cognitive decline with advancing age is not inevitable; there are individual differences in the trajectories of both developmental gain and decline, with some individuals maintaining relatively high levels of cognitive function into older age (Zhao et al., 2020).

The aim of this article is to review the current literature on age-related change from a cognitive and neuroscientific perspective. Through a critical analysis of current knowledge and theories about age-related cognitive decline, we synthesise the existing state of the literature, identify knowledge gaps, and develop suggestions for ways that psychology can contribute to healthy ageing. Although systematic reviews provide a rigorous analysis of a narrow research question, this specificity inherently limits their capacity to capture the full spectrum of available information on a broad topic such as healthy ageing. Given the diverse nature of the approaches and findings in the field, we therefore opted to provide a holistic overview of cognitive healthy ageing, employing a narrative approach to offer a more interpretive and nuanced exploration of diverse perspectives, theories, and evidence. In the following sections, we focus on age-related cognitive changes, subjective versus objective changes in cognition, the role of cognitive reserve in cognitive decline, the interaction between lifestyle and cognitive reserve, interventions to slow cognitive decline, neuroscientific perspective on ageing and cognition, and unifying theoretical approaches to cognitive ageing, before summarizing and identifying future research directions.

### 1.1. Age-related cognitive changes

Cognitive function is an important contributor to healthy ageing, predicting self-perceived health (McHugh and Lawlor, 2016) and aspects of mental health, such as lower pessimism, in old age (Taylor et al., 2017). Among older adults, there are robust associations between cognitive function and educational outcomes, socioeconomic attainments, health, longevity (Deary et al., 2010), and daily living tasks such as medication use, financial management, and food preparation (Allaire and Marsiske, 2002).

Although much current research uses screening tools to dichotomise the ageing population into pathological and non-pathological ("healthy") individuals (in the tradition of medical diagnosis), this approach neglects the more subtle, gradual cognitive changes detected by more sensitive measures in healthy individuals over time (Rodrigues and Moreno, 2023). Generally, cognitive test performance declines during adulthood (Tucker-Drob, 2019). However, the age at which decline is detected depends on the balance of a test's demands between "crystallised" accumulated knowledge, which increases through adulthood, and "fluid" knowledge-free information processing, which declines through adulthood (Lindenberger, 2014). Thus, processing speed (fluid) peaks early in adulthood and steadily declines thereafter, whereas vocabulary (crystallised) peaks late in adulthood; tasks such as verbal fluency, reasoning, and long-term memory, which require both crystallised knowledge and fluid ability, peak at intermediate ages

(Hartshorne and Germine, 2015; Hedden and Gabrieli, 2004; Salthouse, 1996; Swagerman et al., 2016). Ageing trajectory estimates vary between study designs, with cross-sectional studies showing downward linear trends with age, but longitudinal studies showing more optimistic patterns of initial increase or protracted stability before decline (Salthouse, 2019). The discrepancy is likely attributable to practice effects in longitudinal studies (Rabbitt et al., 2008b; Salthouse, 2019), which can be interpreted as showing the same test requiring less fluid and more crystallised ability with repeated exposures. Although practice effects represent an unwanted confound for researchers, from the perspective of healthy ageing, they demonstrate the capacity to benefit for years after even a small amount of test exposure, albeit a capacity that varies among individuals and diminishes with advancing age (Rabbitt et al., 2008b; Salthouse, 2019).

A point of debate among researchers is whether the non-pathological ageing population should be regarded as homogeneous, with age groups' average cognitive performance providing a meaningful normative trajectory against which to compare individuals and assess interventions (Salthouse, 2019), or as heterogeneous, with constituent individuals' abilities following idiosyncratic trajectories before a rapid terminal decline (Lindenberger, 2014; Rabbitt et al., 2008a), poorly represented by the group mean. Central to this debate is the question of whether performance variability remains constant with age (Salthouse, 2011) or whether variability increases but is systematically underestimated, due to selection bias and selective attrition (i.e., only unusually healthy and capable older people participate in demanding cognitive studies; Rabbitt, 2011). Inter-individual variability is partly a function of intra-individual variability, representing increasingly erratic cognitive processes (Rabbitt, 2011) but may also reflect the myriad hazards and protective factors affecting different individuals in different ways (Lindenberger, 2014). Rodrigues and Moreno propose two intertwining approaches for the conceptualisation and investigation of healthy cognitive ageing: population subtyping and trajectory analysis (Moreno et al., 2023; Rodrigues et al., 2022; Rodrigues and Moreno, 2023).

Subtyping involves categorising groups of individuals according to genotype and/or phenotype features, with the aim of better understanding the inter-individual heterogeneity of age-related changes (Rodrigues and Moreno, 2023). An example is the examination of sex effects on cognitive ageing: older females show lower rates of decline compared to males in several cognitive abilities including memory, executive function, and global cognition (Zaninotto et al., 2018). Potential causes for this difference include various lifestyle risk factors that are more prevalent in older males (e.g., higher rate of smoking, alcohol consumption, lower likelihood of seeking medical care as preventive or treatment measures). Other examples of subtyping include structural brain atrophy, where individuals with higher atrophy rates in the cortex and hippocampus have lower episodic memory (Nyberg et al., 2023). The “Orchid and Dandelion theory” has also been proposed as a subtyping framework for understanding the nuances of ageing through stratification analysis (Moreno et al., 2023). According to the theory, older adults with average cognitive scores exhibit notable resistance to the effects of negative environment lifestyle factors such as smoking or drinking, however the impact of these factors is significantly more pronounced among older adults with more extreme scores (both high and low; Rodrigues et al., 2022). This theory underscores the diverse responses within the ageing population, where some individuals prove more resilient (akin to a dandelion) whereas others (orchids) are more susceptible to external influences.

Subtyping is also relevant to cognitive trajectories (Rodrigues and Moreno, 2023). Using longitudinally collected cognitive assessments, the patterns (trajectories) of cognitive function provide indicators of both the natural process of cognitive ageing and intra-individual heterogeneity (Wu et al., 2020). To account for both inter- and intra-individual heterogeneity, some studies have performed subtyping analysis to identify latent classes of trajectories through the classification and clustering of individuals with similar cognitive trajectories, typically identifying three to four classes (Wu et al., 2020). An analysis of subtypes showed that the association between cognitive performance and modifiable factors varied across class; for example, higher education was the strongest predictor of membership in the highest performing group, whereas frailty was the strongest predictor of membership in the lowest-performing group (Wu et al., 2022).

Age-related cognitive changes should also be viewed with a multidisciplinary lens: the trajectory of developmental growth and subsequent age-related deterioration differs among people, potentially due to variations in premorbid IQ, life experiences, lifestyle factors, neurodegenerative changes, and cognitive reserve or resilience. For example, those living in regions characterised by a high frequency of centenarians, known as Blue Zones (Fastame et al., 2021; Poulain et al., 2004), demonstrate more favourable outcomes on a variety of health indicators, such as life expectancy and cognitive decline, compared to other geographical locations. These benefits are attributed to a healthy and active lifestyle and better mental health indices including social connections and having a purposeful life (Buettner and Skemp, 2016; Fastame et al., 2021; Hitchcott et al., 2018). Another example: although females have lower rates of cognitive decline than males (Zaninotto et al., 2018), over 66% of dementia cases are females (Beam et al., 2018) – suggesting the involvement of contributing factors other than cognitive decline to dementia. A developmental approach is well-suited to understanding such differences, by first scrutinising various lifestyle factors and early life experiences/opportunities for their impact on the development of various cognitive abilities that, in turn, may partially account for higher risk of dementia in females (Tucker-Drob, 2019). For example, a recent large population-based cohort study reported differing risk profiles for dementia amongst men and women, where physical inactivity and lower education was a stronger predictor of dementia development in women (Sindi et al., 2021). These lifestyle-based factors also intersect with biological underpinnings (e.g., hormonal differences) to modify the risk of other chronic health conditions such as cardiovascular disease, which in turn, can contribute to accelerated cognitive decline (Volgman et al., 2019). From a psychosocial perspective, women are also more likely to assume the role of primary caregiver for a spouse or family member with a chronic condition (Swinkels et al., 2019), which can have downstream effects on their own sleep quality, and mental and cognitive health (Dassel et al., 2017). These studies echo the large body of literature highlighting the complex nature of healthy ageing, along with the role that factors such as sex can play in determining an individual's ageing trajectory (Rovio et al., 2005; Virta et al., 2013).

### 1.2. Subjective versus objective changes in cognition

People are often cognisant of subtle changes to their memory and thinking skills before clinically identifiable cognitive decline becomes apparent. Between 50% and 80% of older individuals (aged 70 years and older) who perform within normal ranges on cognitive tests nevertheless report some form of perceived decline in cognitive functioning (Jessen et al., 2020). This is known as Subjective Cognitive Decline (SCD) – a decline in cognitive performance, subtle memory loss or increased confusion, reported by the individual themselves or an informant (e.g., spouse, child, or medical practitioner). Personal insight into memory failings may be more sensitive than informant reports and cognitive assessments alone (van Harten et al., 2018). Even at the earliest stages of SCD, a person may have already begun accumulating underlying neuropathology (Hanseeuw et al., 2019). Indeed, SCD may be one of the earliest and most subtle symptoms of dementia (Sohrabi and Weinborn, 2019) because it corresponds to the advanced preclinical phase of the Alzheimer's disease (AD) and non-AD dementia spectrum, representing the period between the cognitively unimpaired stage and the phase of cognitive impairment (Jansen et al., 2014; Jessen et al., 2020; Sohrabi and Weinborn, 2019). Longitudinal studies (e.g., van Harten et al., 2013;

Wolfsgruber et al., 2017) have shown that individuals without a clinical diagnosis of cognitive impairment who self-report cognitive decline and test positive for neuropathological markers of AD (as measured by the levels of misfolded amyloid beta and total/phosphorylated tau in cerebrospinal fluid, plasma, or brain imaging) have a 40–62% risk of progressing either to mild cognitive impairment (MCI) or dementia within three years. Individuals with more severe SCD show a faster decline in objectively assessed cognition than those with less severe subjective concerns (Amariglio et al., 2018; Vogel et al., 2017).

SCD also has inherent links with social factors such as isolation, a fact which has become more apparent in recent years during the COVID-19 pandemic. Santangelo et al. (2021) reported increased self-reported SCD (particularly reduced cognitive efficiency) during periods of isolation associated with COVID-19 lockdowns. An increase in self-reported cognitive failures was associated with lower educational levels and fewer people in the house (i.e., greater isolation – see Santangelo et al., 2021). This aligns closely with other studies on changes to objective cognitive performance in response to social isolation or, conversely, engagement (Ertel et al., 2008). Although further work is needed to quantify how the COVID-19 pandemic and social isolation impacted the cognitive health of ageing populations, it is plausible that it (and social isolation in general) can accelerate cognitive decline and memory impairment for many people, especially those at higher risk of dementia.

### *1.3. The role of cognitive reserve in cognitive decline*

People at higher risk of dementia have varying trajectories of cognitive and functional decline. That is, the severity, rate, and speed of the decline differs substantially across individuals despite sharing significant AD-related neuropathological changes in the brain. Boyle et al. (2019) examined brain pathologies in people from the Religious Orders Study and the Rush Memory Aging Project; although neurodegenerative processes accounted for 43% of the variability in neuropathologies, 50% of the variance could not be explained. One potential explanation for this variance may lie in cognitive reserve, which originally referred to individual differences in the degree of cognitive and neural dysfunction experienced following brain damage (Stern, 2009). More recent definitions specify cognitive reserve as a property of the brain that allows performance to be better than the expected norms in the presence of brain changes and brain injury or disease throughout life (Stern et al., 2023).

Cognitive reserve might explain the substantial variability in the onset and trajectory of cognitive dysfunction seen in older adult populations, via resilience (Stern et al., 2023, 2020). This perspective contends that the ability to cope with neuropathological disease or insult will vary based on individual differences in cognitive processes which are, in turn, a function of lifetime experiences, intellectual activities, and other environmental factors – years of education, occupational attainment, and physical leisure activities (Bordignon et al., 2021; Stern et al., 2020). For instance, the dentate gyrus, a subregion of the hippocampal formation that is critical for memory formation, is a neurogenic network that can be modulated by behaviour and experience (Piatti et al., 2013). Cognitive experiential factors also promote neuroplasticity and resistance to cellular apoptosis (Whalley et al., 2004). By contrast, the phrase 'use it or lose it' summarises the result of a cognitively sedentary lifestyle, where acceleration of atrophy in various brain structures is associated with early clinical manifestations of cognitive decline (Bordignon et al., 2021). Isolation and reduced social interaction often increase with age, which can impact problem solving abilities and other higher order cognitive skills (Cacioppo and Cacioppo, 2014). In fact, the stress of social isolation may invoke stress-induced inflammation, resulting in brain injury and dysfunction (Friedler et al., 2015). Regardless, underutilised cognitive processes may progressively deteriorate due to neurodegeneration and the gradual loss of synapses.

In accordance with the cognitive reserve perspective, social interaction provides mental stimulation (Bennett et al., 2006) and promotes neuroplasticity (Perry et al., 2022), potentially through the use of complex communication. However, there is no clear consensus on the definition of complex social connection, and there are many varying approaches to the assessment and definition of cognitive outcomes (Holwerda et al., 2012; Simning et al., 2014). It is important to emphasise that there are often disparities (potentially owing to differing cognitive reserve profiles) between an individual's trajectory of ageing and what is 'typically' seen in larger cohort studies. Moreover, it is still unclear from current research how we might forestall (or even reverse) cognitive decline in a prescriptive manner tailored to individual patterns of cognitive performance. As such, continued research aimed at clarifying the roles of internal (e.g., biological) and external (e.g., social connectedness) processes and factors that contribute to healthy ageing at an individual level is essential (Livingston et al., 2020).

Another potentially promising research area concerns "super-agers" – adults over 80 years of age who perform similarly to adults 20–30 years younger on episodic memory tests (Harrison et al., 2012). Although research from the same lab suggests that such individuals exist and are seemingly less prone to AD neuropathological changes (Dang et al., 2018), others have not been able to replicate these results (Gardener et al., 2021). Variations in the definitions of super-ageing and inclusion/exclusion criteria could partially explain these differences, but more research with larger groups is essential to provide insight into the differences between normal age-related decline (as per age, education and sex-stratified norms) and preserved (non-decremented) performance (Rogalski et al., 2013).

#### *1.3.1. Lifestyle contributions to cognitive reserve and healthy ageing*

A wide range of variables could feasibly contribute to an individual's cognitive reserve profile and thus influence their subsequent disease risk, particularly those relating to lifestyle. There is compelling evidence that physical activity can provide a degree of protection against cognitive decline. For instance, Erickson et al. (2011) found that a 12-month walking-based exercise intervention led to significant increases in hippocampal size in previously sedentary older adults; high-intensity interval training has been associated with improved memory performance over a 12-week period (Kovacevic et al., 2020).

Northey et al., (2018) conducted a comprehensive meta-analysis of the exercise and cognition literature, finding that exercise improved cognitive function in adults aged 50 and above, regardless of the mode used (e.g., aerobic or resistance), cognitive domain assessed or cognitive status of participants. Nevertheless, other equally robust studies have failed to find a clear link between exercise or physical activity engagement and cognitive function (Brown et al., 2021; Ciria et al., 2023). In fact, people may experience vast differences in their neurological 'response' to exercise (e.g., based on genotype or baseline cardiorespiratory fitness), which speaks to the need for a broad, multi-domain approach to healthy ageing and quantifying cognitive reserve.

The potential benefits of multi-domain approaches underscore the complex array of factors contributing to an individual's broader lifestyle patterns. For example, diets such as the Mediterranean diet and the hybrid Mediterranean-DASH (MIND) diets have received substantial attention as modifiable methods of reducing dementia risk (Abbatecola et al., 2018). Broadly, dietary patterns emphasising the consumption of legumes, olive oil, fish, whole grains and fresh fruits and vegetables, in combination with reduced fat, sugar and red meat, together promote antioxidant mechanisms, neuronal plasticity, inflammation regulation, and cardiovascular health (Koloverou et al., 2016). Morris et al., (2015) demonstrated that even moderate adherence to the MIND diet was sufficient to reduce AD risk, and a recent study combining three major longitudinal cohort projects reported that incremental increases in MIND diet scores (i.e., higher adherence) resulted in a 17% decrease in the risk of dementia (Chen et al., 2023). Another example of lifestyle factors is sleep, which is a widely recognised modifiable therapeutic target to improve cognition and quality of life (Sadler et al., 2018). Chronic sleep deficiencies have emerged as a key driver of dementia-related neuropathological processes (mediated by mechanisms such as the glymphatic clearance and hormonal regulation; Nedergaard and Goldman, 2020). Despite the promising steps taken in lifestyle-based research for cognitive ageing, the degree to which each aspect of lifestyle influences an individual's ageing trajectory is highly variable and multi-faceted. Cultural, social, familial, experiential, and innate biological intra-individual differences can often lead to heterogenous samples which reduce generalisability and impact the strengths of the lifestyle-based recommendations made at a population level. Although an experiential variable like education is widely seen as protective, there is still longitudinal evidence to the contrary (Sala et al., 2023). Moreover, well-designed systematic reviews and meta-analyses have reported null findings and small effect sizes when examining the link between dietary pattern adherence, cognition, and dementia incidence (Fu et al., 2022). Similar criticisms have been levelled at recommending physical exercise to improve cognitive abilities (e.g., see Ciria et al., 2023), which are reflective of the important questions remaining on optimal protocol length, exercise type, and intensity to best activate neuroprotective pathways (Stillman et al., 2020).

Accordingly, the increasing use of large, longitudinal datasets provides an opportunity to better understand healthy ageing across a broader spectrum of the population. Studies utilising data from initiatives such as the UK Biobank have recently demonstrated robust associations between physical activity, grey matter volume (Hamer et al., 2018), and specific dietary elements such as meat consumption and incident dementia risk (Zhang et al., 2021). From a psychological ageing perspective, the advent of big data may provide the statistical power to identify subgroups of 'responders' and individuals who benefit the most from varied, multi-domain lifestyle-based interventions designed to promote healthy ageing.

### 1.4. The interaction between lifestyle and cognitive reserve

The benefits associated with lifestyle-related protective behaviours (e.g., physical activity, sleep) extend well beyond cognition, given the interconnection between lifestyle, psychological, and experiential factors in contributing to a person's cognitive reserve profile (Song et al., 2022). A review by Bauman et al. (2016) suggested that physical activity assists in improving cognitive functioning, preventing physical disease, reducing falls, and reducing depression. Almeida et al. (2006) demonstrated positive relationships between physical activity and mental health (cognitive functions and preserved mood) in a longitudinal study of 601 males in their 80 s. Similar benefits for depression were found in a scoping review of the effects of walking, although the authors noted issues with the quality of trials available for metrics such as subjective well-being (Kelly et al., 2018).

In the context of cognitive reserve, it is also important to consider the intersection between more traditional lifestyle-based variables of interest (e.g., exercise) and psychological perspectives. Personality traits such as extraversion and openness to experience influence the relationship between physical activity and subjective wellbeing (Long Chan et al., 2018). Similarly, there are also well-established bi-directional relationships between sleep deficits, mood disturbance (e.g., major depressive disorder) and physical activity engagement (Firth et al., 2020; O'Leary et al., 2017; Sewell et al., 2021). As such, cognitive health trajectories are modified by the interconnection between lifestyle-related behaviours, personality, psychological health and a multitude of other experiential factors which can contribute to cognitive reserve (Song et al., 2022). Although it is not possible to characterise all of the possible modulatory factors that impact the level of cognitive reserve for any given person, there is clear value in integrating multiple perspectives and ideas related to optimising physical, cognitive and mental health to build intrinsic capacity and resilience to disease (World Health Organization, 2015).

Although cognitive reserve is an area of research that incorporates several promising pathways to prevent or mitigate the impact of age and disease-related neurodegenerative processes on cognition, the fact remains that during the last two years, the number of deaths due to dementia has passed ischemic heart disease as the primary cause of death at least in one country (Australian Bureau of Statistics, 2022) and we expect similar trends to occur elsewhere (Doblhammer et al., 2022), potentially due to multiple pathways including the effects of social isolation (resulting in decreased physical activity, social interaction, and access to medical care) and the physiological and neurological effects of COVID-19 infection. This statistic highlights the importance of investigating longitudinal reserve and resilience mechanisms, as well as the need to examine methods of limiting cognitive decline for those who are already experiencing significant decline.

### 1.5. Interventions to slow cognitive decline

Similar to exercise programs designed to maintain physical health across age, there are other interventions that may improve cognitive abilities through prescribed activities. Although there are many such approaches, here we focus on three: cognitive training (Jaeggi et al., 2011; Katz et al., 2018), music training (Román-Caballero et al., 2018), and also mindfulness interventions (Mirabito and Verhaeghen, 2023). The most prevalent approach is that of cognitive training, which includes multiple object tracking and memory exercises, paper and pencil methods (e.g., Sudoku or word puzzles), single-person or group-based training and consultative methods, computerised, online, and gadget-based methods (Harvey et al., 2018). Cognitive training is non-invasive, non-pharmacological, and relatively easy to access (particularly computerised programs), making it an attractive tool for people seeking low-cost ways of preserving their neurocognitive health. Encouragingly, several studies have demonstrated that both computerised and conventional pencil and paper cognitive training programs can elicit clinically meaningful changes in various cognitive domains for older populations (Bahar-Fuchs et al., 2019; Harvey et al., 2018; Kueider et al., 2012).

However, other studies have found no benefits associated with cognitive training for older adults (Sala and Gobet, 2020; Sala et al., 2018), and a common critique centres on the lack of transferability from domain-specific training programs to general cognitive functioning (Owen et al., 2010; Sala and Gobet, 2019; Simons et al., 2016). Kane et al. (2017) reviewed 263 studies of interventions aimed at preventing or delaying age-related cognitive decline, MCI, and Alzheimer's-type dementia. Of these, 38 were studies of cognitive training. After addressing the risk of bias and assessing evidence strength, the authors concluded that cognitive training with tasks focused on memory and reasoning improved domain-specific performance for cognitively normal older adults. However, this improvement in performance did not transfer across cognitive domains, and overall, cognitive training did not prevent or delay age-related cognitive decline, MCI, or AD.

In their systematic review on how cognitive training might affect cognitive performance and incident dementia outcomes, Butler et al. (2018) specifically targeted studies of cognitive training and cognitive decline. After study selection and data extraction, they reviewed 11 studies of cognitive training interventions on cognitive performance and incident dementia outcomes for adults with normal cognition or MCI. Healthy older adults improved their performance in trained cognitive domains, but this did not translate to global cognition. Further, participants with MCI experienced no benefits at all, highlighting the lack of applicability for older adults with current prodromal AD and a limited scope for dementia prevention. A more recent review (von Bastian et al., 2022) reached similar conclusions, whereby training did not transfer, although there was evidence for gains in cognitive *efficiency* (the ability to use existing cognitive capacity via strategies, routines, and/or automaticity). One possibility is that cognitive training might be useful not by enhancing cognition per se, but rather through facilitating an active lifestyle that preserves cognitive capacity and/or efficiency.

Gates et al. (2019) initially cast a wide net in their Cochrane systematic review by considering 317 studies of cognitive training and cognitive decline. However, only one study (Corbett et al., 2015) met their inclusion criteria. Gates and colleagues noted the magnitude of low-quality evidence in the field, meaning it was impossible to determine whether computerised cognitive training is effective in maintaining global cognitive function among healthy adults in midlife through to older age. This could be partly due to the lack of rigorous scientific scrutiny in the development and validation of commercially available computerised cognitive training platforms (cf. Shah et al., 2017).

Musical training represents another possible approach to addressing age-related cognitive decline, in part because it is a cognitively demanding (yet enjoyable) activity that involves multisensory integration, reward, and emotion (Sutcliffe et al., 2020). However, these authors also note the lack of control conditions and random assignment in intervention studies. Román-Caballero et al. (2018) reviewed 13 studies on this topic, and concluded that both cognitive and neural processes likely benefit from musical training in the context of ageing. However, most of these studies were correlational, which limits the inferential utility of the research. Part of the issue stems from the fact that musical training earlier in life may moderate the effects of training in later life. Okely et al. (2023) conducted a longitudinal study of 420 participants from the Lothian Birth Cohort (1936) and found that although musical training was associated with overall *levels* of verbal ability, verbal memory, visuospatial processing, and processing speed in older age, there were no associations with *changes* in cognitive function, likely suggesting a differentiation carrying over from the early stages of life. Reviews of longitudinal studies tend to show small benefits of musical training on cognitive skills (Román-Caballero et al., 2022) or auditory processing (Neves et al., 2022), but caution about the need for well-conducted studies and the dangers of publication bias. A broader review on the effects of music training on general cognitive function (Schellenberg and Lima, 2024) concludes that the cognitive benefits of musical training are weak, benefits rarely transfer across domains, apply mostly to clinical populations (as opposed to healthy ageing), and likely are a function of the many social and emotional benefits of engaging in musical activity rather than any cognitive or neural benefits (see also Schellenberg, 2020).

Mindfulness interventions in healthy older adults also show small but significant benefits in some aspects of cognition, specifically in attention, long-term memory, and visuospatial processing, but not processing speed, language, working memory, verbal fluency, or global cognition (Mirabito and Verhaeghen, 2023). These authors compared the benefits to those of other interventions and found that mindfulness gave smaller benefits than programs focusing on exercise, cognitive training, or qigong (a traditional Chinese exercise program combining movement, meditation, and breath control) interventions. A longitudinal analysis from a study of health in retirement found meditation at least twice per week conferred some protection for cognition, but only for older adults *without* depressive symptoms prior to the intervention (Lopes et al., 2023). Importantly, there are suggestions for mechanisms by which meditation may benefit neural function, including benefits to the default mode network and neurovascular system (Pommy et al., 2023; Sevinc et al., 2021), although much research remains to be done to establish a stronger basis for mindfulness interventions.

Even though the current literature is mixed, neuroplasticity research shows that the ageing brain can repair itself to some degree by developing new synaptic nodes and promoting neuronal connectivity (Stampanoni Bassi et al., 2019). There is evidence that neurogenesis occurs in the hippocampal area (Tobin et al., 2019), which is integral to episodic memory and susceptible to neuronal loss in both normal ageing, across the spectrum of AD and other neurodegenerative disorders. In other clinical disorders, strategy-based cognitive training has been shown to improve frontoparietal functional connectivity in people with chronic severe traumatic brain injury or TBI (Han et al., 2018). As such, although current evidence for cognitive training as a method of preventing cognitive decline is lacking, there are several strong neurobiological and mechanistic bases for the continued examination of preventive and ameliorative interventions, including cognitive training. Given the lack of high-quality studies examining the efficacy of cognitive training and its clinical viability, there is an urgent need for more robust research on increasing the transferral of domain-specific improvements from cognitive training for persistent cognitive change.

There is also cause for further investigation into the combination of cognitive training with other modalities (e.g., lifestyle-based interventions). For example, a combination of physical exercise and computerised cognitive training has shown promise in improving verbal episodic memory and increasing cerebral glucose metabolism in the older adults (Shah et al., 2014).

The issue of heterogeneity also applies to this domain, as the effects of training vary across individuals (Roheger et al., 2021; van Balkom et al., 2020). Efforts to determine the variable effectiveness of cognitive training on older adults are exploring biomarkers, neuroimaging, and new technology (Gallen et al., 2016; Ziegler et al., 2022), which show promise to eventually develop individually-customised cognitive training strategies (Shatenstein et al., 2015).

### 1.6. Neuroscientific perspective on ageing and cognition

With advancing age, the brain undergoes significant structural and functional changes (Cabeza et al., 2018). After age 40, brain volume decreases approximately 5% with each passing decade (Svennerholm et al., 1997), with an accelerated rate of volume reduction after the age of 70 (Scahill et al., 2003). The volume reduction of the ageing brain comprises declines in grey matter volume (Nyberg et al., 2010; Walhovd et al., 2011), reduced coherence in white matter microstructure (Giorgio et al., 2010; Madden et al., 2010; Ouyang et al., 2021; Salat et al., 2005), cell shrinkage, dendritic regression, and reduced synaptic density (Uylings et al., 2000). In addition to changes in brain architecture, the neural activation patterns of older adults are distinct from those of their younger counterparts (Reuter-Lorenz and Cappell, 2008), which can be indicative of age-dependent changes in functional connectivity (e.g., Stumme et al., 2020; Zonneveld et al., 2019). The age-related changes in brain function and structure underlie declines in perceptual, cognitive, and motor performance (e.g., Calautti et al., 2001; Esposito et al., 1999; Fujiyama et al., 2012; Fujiyama et al., 2016; Hinault et al., 2020; Yang et al., 2016). Because these abilities are instrumental for processing important environmental information and executing accurate and coordinated actions, the age-related declines of these functions compromise the quality of life and physical independence of older adults (Swinnen et al., 2011). To address and mitigate such changes, it is imperative to advance our understanding of the neurophysiological mechanisms that mediate changes in perceptual, cognitive, and motor function in the ageing brain. We underscore here the role of age-related neurodegenerative processes in various conditions, including AD, as the most common cause of cognitive impairment and dementia, in addition to other dementia-causing conditions (Sohrabi and Weinborn, 2019).

Early neuroimaging studies investigating age-related differences in brain activation patterns during cognitive tasks (e.g., Esposito et al., 1999; Townsend et al., 2006) and motor tasks (e.g., Calautti et al., 2001; Heuninckx et al., 2010) found that older adults showed greater brain activation (and often the recruitment of additional brain areas) when performing the same task as younger adults. To account for these distinct neural activation patterns in the ageing brain, two major hypotheses were initially put forward: the compensation and dedifferentiation hypotheses.

*The compensation hypothesis* suggests that the additional recruitment of brain areas or greater activation will occur to counteract age-related decline in brain function (Cabeza et al., 2002; Reuter-Lorenz and Cappell, 2008). Using positron emission tomography (PET) during a memory task, Cabeza and colleagues (2002) found that high-performing older adults recruited the bilateral prefrontal cortex (PFC), whereas low-performing older adults showed lateralised PFC activity. Based on this finding, the authors proposed the hemispheric asymmetry reduction in older adults (HAROLD) model, which posits that additional recruitment of bilateral regions assists in the task performance of older adults. Extending from the HAROLD model, the compensation-related utilisation of neural circuits hypothesis (CRUNCH) postulates that more challenging tasks prompt compensation through recruiting additional brain regions and cortical networks, particularly those in the PFC (Reuter-Lorenz and Cappell, 2008).

In contrast, the neural *dedifferentiation hypothesis* argues that the additional activations observed in older adults are due to deficits in the selective recruitment of task-specific neural mechanisms (Grady, 2002; Koen and Rugg, 2019). Several studies suggest that the additional recruitment of brain regions reflects inefficiencies in utilising neural resources in the ageing brain instead of compensatory mechanisms, because task performance was comparable between younger and older adults (for a review, see Zarahn et al., 2007). Indeed, greater cortical activations have been linked to poorer performance in older adults (Stevens et al., 2008). Similar results occur in studies of older adults' increased brain activity in the PFC during memory encoding (de Chastelaine et al., 2011) and retrieval (Persson et al., 2011), both of which were correlated with poorer memory performance. Similarly, older adults with slower and more variable reaction times in a set of visual tasks also show higher activity than younger adults in a distributed set of regions, including the PFC and parietal cortex (Scarmeas and Stern, 2003).

Although the evidence for the compensation and dedifferentiation hypotheses seems contradictory, there is a potential reconciliation in the scaffolding theory of ageing and cognition (STAC, see Park and Reuter-Lorenz, 2009), subsequently revised to STAC-r (Reuter-Lorenz and Park, 2014). The STAC hypothesis extends the compensation hypothesis by suggesting that increased frontal activation with age is a marker of an adaptive brain that engages in compensatory scaffolding in response to the challenges posed by declining neural structures and functions. This view does not necessarily contradict the dedifferentiation hypothesis since it assumes that compensatory mechanisms are utilised to a capacity limit, while also accounting for performance decline beyond the limit (Zanto and Gazzaley, 2017). Therefore, the STAC proposes that the recruitment of additional brain regions is beneficial for tasks with relatively low demands, whereas further activation would not elicit performance benefits under high task demands that surpass the limit of compensatory mechanisms.

Even though these hypotheses have advanced our understanding of age-related changes in brain activation, they are primarily limited to explaining *regional activations* specific to older adults. More recent evidence from neuroimaging studies suggests that there are changes to large-scale brain *networks* with advancing age (Li et al., 2015), highlighting the importance of a network perspective for understanding the ageing brain. This perspective argues that the decline in cognitive function in older adults corresponds with lower global efficiency and higher local clustering in cortical networks (e.g., Cao et al., 2014; Schlee et al., 2012; Song et al., 2014; Zhu et al., 2012). Hinault et al. (2020) found that the coherence of white matter microstructural connectivity within the inferior fronto-occipital network subserves functional connectivity within the network, which promotes arithmetic performance in older adults. This finding indicates that the interplay between structural and functional networks drives the cognitive functioning of older adults. Research using non-invasive brain stimulation (NiBS) has also provided empirical support for the network perspective of healthy ageing. For instance, the direct manipulation of network connectivity via NiBS resulted in improvements in working memory performance (Reinhart and Nguyen, 2019). Their findings also underscore the capacity for neuroplastic changes in the healthy ageing process. Indeed, neuroplastic changes via cognitive training and/or NiBS can partially remediate age-related alterations in brain structure and function (e.g., Fujiyama et al., 2017; Park and Bischof, 2013; Reinhart and Nguyen, 2019). As noted earlier, the finding that hippocampal neurogenesis occurs in older adults (and even AD patients) provides a significant opportunity to study the formation of new memories in newly developed neurons, which may potentially lead to novel treatments for neurodegenerative diseases (Tobin et al., 2019).

Defining cognitive decline and identifying interventions that may prevent or ameliorate such decline have benefited from the approaches reviewed above. However, it is now time to work towards a more global, systemic approach that identifies stepwise and personalised neuropsychological interventions to minimise the risk of decline progressing into impairment and clinical manifestations, such as MCI and dementia. An emerging trend in ageing research is the shift from relying solely on chronological age to evaluating an individual's "biological age", considering factors such as genetics, environment, lifestyle, overall health, and various lifetime influences (Franke and Gaser, 2019). The approach is invaluable in identifying individualised health characteristics and risk patterns associated with age-related diseases. This shift toward assessing "biological age" allows for personalised interventions based on an individual's specific health profile. Our ability to predict individual risks for age-related diseases has significantly improved thanks to novel biomarkers such as DNA methylation, genetic damage accumulation, telomere length, physical fitness, and allostatic load (Franke et al., 2020). These biomarkers offer valuable insights into designing more effective treatment strategies. In light of this trend, there is a growing body of literature dedicated to assessing "brain age" in cognitive neuroscience. Neuroimaging and neurophysiological techniques have been used to develop biomarkers that accurately reflect an individual's ageing process and assess the risk of cognitive dysfunction. For instance, using a measure termed multiscale entropy (MSE) that reflects the functional role of complexity in physiological signals, McIntosh et al., (2014) highlighted how variability in brain network dynamics changes with advancing age and MSE has been proposed as a biomarker for evaluating an individual's brain health status (Shen et al., 2021). Reports of the loss of complexity in the pathological ageing brain, observed in both animal (Araya-Arriagada et al., 2022) and human (Hsu et al., 2020) studies, further underscore the utility of MSE. Other neurophysiological assessments provide additional layers of insight, such as the evaluation of coordinated synchronised neural activity (neural avalanches; Varley et al., 2020), analysis of asynchronous EEG/MEG activity (aperiodic or 'scale-free' broadband activity adhering to 1/f power distribution; Voytek et al., 2015), the examination of long-range temporal correlations to distinguish pathological brain activities (Montez et al., 2009), and short-lasting periods of synchronised activity in large-scale brain networks termed microstates (Michel and Koenig, 2018). Although each marker corresponds to different levels of neural inference, they are likely interconnected and may estimate overlapping aspects of the underlying signal at various scales (Martínez-Cañada et al., 2023). This holistic approach not only enhances our understanding of the ageing process but also holds the promise of identifying robust biomarkers for healthy ageing, ultimately contributing to the development of personalised strategies for managing age-related conditions.

### 1.7. Unifying theoretical approaches to cognitive ageing

There are various theoretical accounts of age-related cognitive decline that we briefly noted including cognitive reserve, dedifferentiation, and scaffolding. The recently introduced Systems Biological Approach on cognitive ageing (Ebaid and Crewther, 2020) is promising in its inclusion of such factors as age-related sensory decline, cardiovascular problems, immune system response to stress, as well as hormonal and cellular changes (mitochondria). However, it fails to include other biological contributions (e.g., genetics, gut microbiome), and environmental factors and their neuropsychological outcomes (e.g., agricultural pesticides, war, or COVID-19 pandemic impact on older adults' cognitive functions).

The Tripartite Contextual Approach (Diehl and Wahl, 2020) provides a more comprehensive approach to cognitive ageing. This theoretical model includes the lifespan/developmental context (e.g., experiences and biography, genetics), the social/physical/technological context, and the historical/cultural context (e.g., pandemics, wars, medical advances, cultural movements). Accordingly, the aforementioned factors define the context of the developmental and biopsychosocial process of cognitive ageing (Diehl and Wahl, 2020).

The Tripartite Contextual Approach provides a comprehensive and well-defined explanation of the effects of person, society at large, and historical/cultural context of ageing including cognitive function (Neupert and Bellingtier, 2022; Neupert and Zhu, 2020). However, the relative contribution of each of these “Tripartite Contexts” and their interaction requires further explanation. In this regard, biological age seems to be more relevant than chronological age, especially as medical, psychological, societal, industrial, and financial advances have significantly increased the average human lifespan. For example, the designers of an algorithm for the calculation of Bio-Age (biological age) argue that using inflammation, oxidative stress, and vascular health markers to predict cognitive decline could be more accurate than other methods (DeCarlo et al., 2014). However, future research is necessary to determine the accuracy and validity of Bio-Age methods, as not all cognitive functions are similarly assessed (nor do they decline at a similar rate), and not all dementias present with similar cognitive deficits. Further, treating cognitive decline as a linear process is a major shortcoming of most hypothetical approaches.

The non-linearity and variability of cognitive decline might be better addressed through brain age prediction, which is estimated using machine learning models applied to neuroimaging data (Niu et al., 2020). By identifying clusters of imaging features with distinct developmental trajectories, multidimensional brain age prediction can potentially account for inter- and intra-variability in brain development trajectories (Niu et al., 2022). However, research has also found that health-related factors other than brain age influence cognitive trajectories (Wrigglesworth et al., 2022). As highlighted by the Tripartite Contextual Approach and the concept of cognitive reserve, cognitive decline extends beyond biological markers. The integration of “psychosocial markers” such as social connectedness (Roth, 2022) can potentially contribute to a more comprehensive assessment of cognitive decline. Here again, we emphasise the need to apply a broad, multi-disciplinary lens to aid understanding healthy ageing.

## 2. Summary and future directions

Cognitive decline is a heterogeneous, non-linear experience, particularly in terms of the rate, trajectory, and characteristics of decline experienced by older adults (Hedden and Gabrieli, 2004). Intra-individual variables which influence an individual’s cognitive reserve profile, such as educational, experiential, social and lifestyle factors can all seemingly alter neurocognitive health with increasing age. Recognition of the growing and projected healthcare burden associated with an increasing incidence in dementias such as AD in many populations around the world has also spurred research into interventions designed to directly modulate cognition in later life, such as cognitive training. Nevertheless, although we have begun to characterise risk and resilience factors specific to cognitive decline, viable preventive mechanisms remain elusive. Psychology as a discipline is at the forefront of cognition and ageing research. Recently, technological advances including the use of machine learning for the analyses of large datasets, have equipped modern scientists with better understanding of cognitive impairment (McKenzie et al., 2022; Wang et al., 2022), as well as the role of modifiable risk factors. As such, psychology is well-placed to provide guidelines for clinical practice, train the next generation of scientists/clinicians, and contribute to policy making and real-world translational research through a more comprehensive and multifactorial approach.

We have identified two broad challenges for the field. First, it is necessary to improve the reliability and replicability of findings. As we outlined, particularly in research on cognitive training, there are several notable gaps in the available evidence for neuropsychological rehabilitation strategies focused on slowing cognitive decline. Also, individual differences represent a challenge to reliability and replicability – although there are advances in tailoring psychological interventions (e.g., acceptance and commitment therapy) to ageing populations, it is important to continue to recognise that older adults are a unique and growing population, particularly in regard to cognitive functioning.

Second, more interdisciplinary collaboration is necessary, including neuroscientists, bio-physiologists, geneticists, epidemiologists, social scientists, and machine learning analysts. Each discipline brings a unique and valuable perspective to studying and promoting healthy cognitive ageing. Such collaborations provide an ideal opportunity to improve our understanding of the moderating and modulating factors that can change ageing trajectories, as well as more comprehensively evaluating the efficacy of intervention strategies (Diehl and Wahl, 2020). Further, encouraging a multi-disciplinary approach also incorporates important information on the downstream, ‘bigger picture’ elements of cognitive ageing, such as health economics and the promotion of age-friendly communities. Embracing these challenges will ensure that researchers and policy makers are well-equipped to optimise and improve the quality of life and overall health span of older adults around the world.

We close by identifying some limitations and future directions that we should consider as a field. First, it is important to promote a comprehensive lifespan approach to the study of normative (cognitive decline due to normal ageing) and non-normative cognitive function (e.g., dementia and neurodevelopmental conditions at higher risk of dementia). Furthermore, other less-examined demographic variables should be considered including cultural, geographical, and ethnicity factors (Babulal et al., 2019; Sachdev et al., 2015) in both research and clinical settings for assessment, intervention, and data interpretation.

Second, mega-analysis (utilising large scale multiple databases) can provide critical information that the field is currently lacking due to small or biased sample sizes. Although such studies are currently limited in their capacities, they come with some pathways to minimise the impact of different study methods used in designing the study, data collection, and data analysis methods. One such method is data harmonisation (Shishegar et al., 2021).

Third, issues of heterogeneity underscore the relevance of precision (personalised) medicine approaches, which incorporate genetic, environmental, and lifestyle factors in accounting for individual differences (Ashley, 2016). Having biological, lifestyle, and family history to the study of cognitive decline and dementia over time will provide details that can be used to tailor the type, duration, and intensity of the intervention to minimise the risk or delay the progression of dementia. Additional background could include details collected by social media tools, apps, and technological devices, although this must be balanced with privacy concerns.

Fifth, we reiterate that better quality of life and ability to function through maintaining cognitive abilities is one of the major pillars of the Decade of Healthy Ageing. Some psychological interventions such as mindfulness (for individuals with minimal cognitive impairment) may increase the ability to function, possibly through improved executive function, while therapeutic music interventions (for individuals with greater cognitive impairment) improve the quality of life and the trajectory of dementia-related decline. Therefore, interventions that are not directly aimed at cognitive ageing per se (e.g., diet and lifestyle interventions) may have beneficial side effects that represent possible future applications.

Finally, consistent with the available literature discussed here, it is likely that ageing and dementia will remain major issues for several decades. As such, interest in healthy cognitive ageing for older adults will only increase, although here we also note the numerical publication peak in 2019 (Fig. 1; see also Footnote 1). In fact, this figure only underscores the need to advocate for the advancement of research and the training of upcoming generations of researchers and clinicians, equipping them with the skills to proficiently conduct assessments and interventions in the field of cognitive ageing, employing a comprehensive array of available tools and methods.

## Declaration of Competing Interest

None

## Data availability

No data was used for the research described in the article.

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