Brain & Language 260 (2025) 105507

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

Bilingualism, sleep, and cognition: An integrative view and open research questions

F. Gallo [a,b,1,*], A. Myachykov [b,h,1], J. Abutalebi [a,b,d], V. DeLuca [a], J. Ellis [c], J. Rothman [a,e,f], L.R. Wheeldon [g]

[a] Uit The Arctic University of Norway, Tromsø, Norway
[b] Higher School of Economics, Moscow, Russian Federation
[c] Northumbria University, Newcastle-upon-Tyne, UK
[d] University Vita Salute San Raffaele, Milan, Italy
[e] Lancaster University, Lancaster, UK
[f] Nebrija Research Center in Cognition, Madrid, Spain
[g] Adger University, Kristiansand, Norway
[h] University of Macau, Taipa, Macau SAR, China

ARTICLE INFO

Keywords:
Bilingualism
Sleep
Reserve
Cognitive aging
Cognitive functions

ABSTRACT

Sleep and language are fundamental to human existence and have both been shown to substantially affect cognitive functioning including memory, attentional performance, and cognitive control. Surprisingly, there is little-to-no research that examines the shared impact of bilingualism and sleep on cognitive functions. In this paper, we provide a general overview of existing research on the interplay between bilingualism and sleep with a specific focus on executive functioning. First, we highlight their interconnections and the resulting implications for cognitive performance. Second, we emphasize the need to explore how bilingualism and sleep intersect at cognitive and neural levels, offering insights into potential ways of studying the interplay between sleep, language learning, and bilingual language use. Finally, we suggest that understanding these relationships could enhance our knowledge of reserve and its role in mitigating age-related cognitive decline.

1. Introduction

Sleep and language are central human experiences. We spend approximately one third of our lives sleeping and most of the rest communicating. Globally, a majority of us do the latter in more than one language, as over half the world's population today is bi/multilingual (De Houwer, 2021). For ease of exposition, we will use the term "bilingual(−ism)" throughout this paper as an umbrella term to refer to all forms of bi- and multilingualism, thus distinguishing between the state of knowing a single language versus more than one, without any assumption that all bi- and multilingualism are the same. While it might not seem immediately intuitive to bring sleep and bilingualism together, they display several theoretically and functionally important convergence points. To begin, both, significantly but differently, affect similar *behavioral* assays of cognition, including attention, inhibition, monitoring, learning and memory. Most importantly, higher degrees of bilingual engagement are associated with adaptations towards increased cognitive efficiency (Grundy, 2020), while impaired sleep is associated with strong adverse effects (Barclay et al., 2020; West, et al., 2024). Moreover, existing research shows that overlapping brain areas are implicated in, and affected by, sleep (Tai et al., 2022) and bilingual language control (Abutalebi & Green, 2007; DeLuca, Rothman, Bialystok, et al., 2019; Gallo et al., 2021). These striking observations motivate this paper and call for an empirical program that intersects research areas including bilingualism (i.e., the learning/usage of additional language(s)), sleep, and cognitive science.

Herein, we first offer an overview of the existing literature investigating the behavioral and neurophysiological aspects of language, sleep,

* Corresponding author at: Psycholinguistics of Language Representation (PoLaR) lab, Center for Language, Brain and Learning (C-LaBL), UiT, The Arctic University of Norway, Hansine Hansens veg 18, 9019 Tromsø, Norway.
E-mail address: federico.gallo@uit.no (F. Gallo).

[1] Both Federico Gallo and Andriy Myachykov act as first authors of this manuscript. The remaining of the authors' list is arranged alphabetically. Individual contribution statement is provided separately.

https://doi.org/10.1016/j.bandl.2024.105507
Received 30 April 2024; Received in revised form 27 November 2024; Accepted 28 November 2024
Available online 6 December 2024

and executive functioning. We then motivate conceptual and methodological reasons to explore the potential relationship between them. Given the contact points that bilingualism and sleep display at cognitive and neural levels, we then discuss how exploring the relationship between these two experiences could advance our knowledge of the role their common neurocognitive substrate serves in influencing cognitive performance. Such an exploration would elucidate the role sleep plays – and how it can be manipulated – for improved consolidation processes for language learning, use, and maintenance. Conversely, it could inform the development of language-mediated interventions towards specific executive function training with the best chance of mitigating the effects of impaired sleep. We will also argue that the failure to control for bilingualism profiles and/or sleep – in terms of its quality, quantity, and timing – could be adding noise that clouds the interpretation of findings in both fields. Finally, we will articulate new research questions that naturally arise from considering the connections between sleep, bilingualism, and executive functioning. Most importantly, doing so has the potential to contribute to our understanding of *reserve*, a crucial buffer that increases resilience to age-related cognitive impairment (Stern et al., 2020).

1.1. Reserve

As the notion of reserve is particularly important for the purposes of this paper, we need to first clarify several related definitions. Reserve refers to the brain's ability to maintain optimal cognitive function despite age-related changes or brain damage. Reserve is argued to derive from a combination of genetic factors and lifestyle activities that exercise cognitive systems and the brain networks underlying them (see Stern et al., 2020 for review). Reserve accrual is known to affect aging trajectories via both structural- and functional-related neural mechanisms, and therefore includes the concepts of *brain reserve* (BR) and *cognitive reserve* (CR). In brief (see Stern, 2009 for details), BR is a passive buffer that increases the critical threshold at which age-related structural brain deterioration triggers cognitive impairment. CR is instead an active protective mechanism, which mitigates age-related cognitive impairment through ameliorations in neural networks in terms of their levels of flexibility (the degree of intra- and inter-network functional connectivity), capacity (the maximum activation threshold an individual can reach), and efficiency (the minimum amount of neural activation required for successful cognitive performance). CR therefore generates additional neurocognitive resources to deploy for the compensation for age-related neural deterioration.

As a complex phenomenon, reserve relies upon several contributing factors. These include, but are not limited to, education level, occupational complexity, social engagement, leisure, and physical activity (Pinto & Tandel, 2016; Song et al., 2022). Crucially, as we will discuss below, sleep and bilingual experience are also among these factors. Poor sleep has been shown to negatively impact reserve accrual (Parker et al., 2021; Zimmerman et al., 2012) while bilingualism can have a positive impact (Bialystok, 2021; Calvo, et al., 2024; Gallo et al., 2022; Perani & Abutalebi, 2015; Rothman, 2024; Voits et al., 2023). Given this, exploring the bilingualism/sleep interaction can potentially inform a broad range of disciplines focusing on cognitive/brain trajectories in senescence, but also across the whole lifespan. Indeed, it is widely accepted that most natural phenomena develop gradually rather than emerge abruptly. Reserve is no exception: although its effects are most evident in older age, it is natural to assume that reserve accumulates throughout much of the lifespan, beginning in early life (Tucker & Stern, 2011). Despite this, most existing research investigates reserve only in aging populations, as if it manifests abruptly once cognitive decline begins. This misconception arises because reserve is primarily *observed* when neurocognitive resources decline following cognitive aging. However, this does not mean that the reserve accumulation does not start earlier in life. We suggest that the tendency to overlook the presence of reserve effects in youth is due to two primary factors.

Firstly, some of the best-known factors contributing to reserve, such as physical exercise or social engagement, vary in frequency during late life stages but are generally more consistent during youth. This reduced variability in younger individuals may obscure the detection of reserve accrual effects. In contrast, multilingualism varies widely in intensity and occurrence even in youth (Bialystok, 2016; Luk & Bialystok, 2013, among others), which may allow for the observation of reserve effects in young adults. Indeed, some of the few investigations reporting reserve effects in youth come from bilingualism research (Gallo et al., 2021, 2023). Secondly, young adults typically possess optimal neurocognitive resources, which can mask the effects of life experiences on reserve due to task insensitivity and ceiling effects in task performance. This explanation has been proposed as a possible reason for the inconsistent findings regarding bilingualism-induced cognitive effects in young adults in existing research (e.g., Kroll & Bialystok, 2013). If these issues influence the study of bilingualism—one of the most observable indicators of reserve in youth, for reasons just detailed above—they may equally affect other factors that contribute to the development of reserve. For these reasons, the considerations contained in this paper, including those about reserve, encompass individuals from youth to late life stages.

2. Sleep and cognition

Sleep is a central, regular, and natural human process, generally defined as a recurring state of reduced responsiveness and motor activity (Carskadon & Dement, 2005). Although externally sleep appears to be a relatively passive process, internally considerable activity occurs over approximately 90–100-minute cycles. Within each cycle, sleep is characterized by different stages (e.g., W – Wake; N1 – Stage 1; N2 – Stage 2; N3 – Stage 3; and REM – Rapid Eye Movement Sleep), based upon the frequency and amplitude of brain activity, eye movements, and levels of muscle tone, sampled every 30-seconds (an epoch). N1 is generally considered the gateway between wake and sleep whereas N2, which makes up the largest percentage of sleep (approx. 45–55 %), is the lightest stage of sleep and is characterized by two waveforms seen in brain activity. The first is a sleep spindle; a brief but rapid saw-toothing in brain activity and a k-complex; a brief high vertex wave, negative then positive, which then centralizes. Stage 3 is often referred to as Slow Wave Sleep (SWS) or deep sleep and is characterized by low frequency high amplitude brain activity. While SWS takes approximately 10–20 % of the night it predominates in the first third of the night. Finally, REM is the stage of sleep where there should be no muscle tension, with the individual in a state of paralysis. Brain activity can look similar to wakefulness but with the marked characteristic of irregular rapid eye movements and cardiac surges. Conversely to SWS, REM predominates in the last third of the night, taking between 18–23 % of total sleep.

The full purpose of individual sleep stages and their components is still poorly understood. Nevertheless, it is agreed that sleep plays a pivotal role in several aspects relating to human health, well-being, and performance, including physical and emotional regulation, brain detoxification, and augmentation of the immune system (Assefa et al., 2015; Gruber & Cassoff, 2014; Irwin, 2019; Zielinski et al., 2016). Importantly, sleep also plays a vital role in supporting and restoring optimal and efficient cognitive functioning (see for reviews Frank & Heller, 2019; Rechtschaffen, 1998; Satterfield & Killgore, 2019; Walker, 2009). Below, we will briefly review the existing evidence, elucidating the role of sleep in attention and memory with specific focus on how these processes contribute to language learning and linguistic functioning.

As noted earlier, a good night's sleep is vital for maintaining optimal cognitive performance, including sustained attention during the day. This is supported by numerous studies showing that sleep deprivation, sleep restriction, and sleep disorders are associated with impaired attentional focus maintenance, reduced alertness, inflated reaction times, and generally decreased cognitive abilities (Alhola & Polo-

Kantola, 2007; Barclay & Myachykov, 2017; Barclay et al., 2020; Lim & Dinges, 2008, 2010). Importantly, sleep deprivation and poor sleep affect attentional networks *selectively,* with the orienting and executive control networks showing the heaviest detrimental impact (Jugovac & Cavallero, 2012; Martella et al., 2011; Trujillo et al., 2009).

Another important function of sleep is memory (re)organization and consolidation (Diekelmann & Born, 2010; Stickgold & Walker, 2007; Walker & Stickgold, 2004). This function is of a particular evolutionary importance as it supports and enhances learning processes, allowing the brain to reinforce and consolidate neural connections related to newly acquired knowledge and skills across the life-span (Kurdziel, et al., 2017). Indeed, it has been shown that the brain selectively organizes and stores memories acquired throughout the day during sleep, by either integrating or pruning memory traces (Mednick et al., 2003; Poe, 2017; Spencer et al., 2017). Optimally balanced rapid eye movement (REM) and slow-wave sleep (SWS) stages represent specific patterns of neural activity that cumulatively contribute to the consolidation of declarative and procedural memories, including those related to language learning (Simon et al., 2022; Yu, et al., 2024). Sleep is also implicated in the functioning of bi-hemispheric semantic networks (Monaghan, et al., 2017). At the same time, impaired sleep can lead to problems with forming and retaining memories. Supporting this, several studies have demonstrated that sleep deprivation substantially impairs hippocampus-dependent memory consolidation (Newbury et al., 2021; Sterpenich, et al., 2017; Yoo et al., 2007). The abnormal non-rapid REM patterns associated with schizophrenia also lead to impoverished memory consolidation (Manoach & Stickgold, 2019). While sleep is indeed essential for learning and memory (Born & Wilhelm, 2012), it is likely that the importance of sleep for memory is not uniform. Declarative memories may benefit from SWS and Stage 2 sleep, whereas procedural memories may benefit more from REM sleep (Born et al., 2006; Gais & Born, 2004). It has also been shown that sleep spindles may play a special role in selective consolidation of memories with motivational significance (Sdudte, et al., 2017). This suggests that distinct sleep processes and stages differentially affect distinct memory systems.

When it comes to sleep and reserve, the relationship is mutual: while several studies have suggested that good quality sleep promotes reserve and poor sleep quality and sleep disorders can have significant deleterious effects on it, other studies show that enhanced reserve improves sleep quality and may act as a protective factor against sleep disorders (Ourry et al., 2023; Zijlmans et al., 2023). As we have already reviewed above, sleep plays a crucial role in memory consolidation, where information acquired during waking hours is processed and transferred into long-term memory, and preserved memory consolidation could contribute to increased CR (van den Berg et al., 2022). Importantly, specific sleep disorders have been associated with increased risk of cognitive decline and neurodegenerative conditions, such as Alzheimer's dementia (AD) with recent studies showing that nREM sleep, and specifically SWS, may act as a protective CR factor in AD by providing resilience against the memory impairment caused by this age-related pathology (Ourry et al., 2021; Zavecz et al., 2023). One primary pathway proposed is the clearing of Beta Amyloid, via the glymphatic system, during SWS (Eugene & Masiak, 2015; Shokri-Kojori et al, 2018). Moreover, sleep is also essential for brain plasticity – the brain's ability to reorganize itself by forming new neural connections and maintaining functional and structural integrity (Dutil et al., 2018). In short, sleep might enhance neuroplasticity and lead to BR accrual. Conversely, poor sleep and sleep disorders, such as obstructive sleep apnoea or insomnia, have been associated with cognitive impairment and deterioration in attentional and cognitive control networks, as well as increased risk of neurodegenerative diseases (Bourgouin et al., 2019; Jones & Ikuta, 2022; Stoffers et al., 2014). Finally, sleep is involved in synaptogenesis and synaptic pruning, crucial for both brain development and plasticity. For example, in infants and young children, sleep promotes the formation of new neural connections and the refinement of synaptic pathways while in adults sleep supports brain plasticity via enabling the brain to adapt to new experiences, learn from them, and optimize cognitive functioning (Frank & Cantera, 2014; Tononi & Cirelli, 2014).

The brief overview above clearly demonstrates that sleep that is of good quality, sufficient duration and appropriately timed (i.e. good sleep) is important as a physiological regulator of homeostasis and general health. Moreover, it plays a crucial role in the maintenance of several cognitive functions. Indeed, advances in neuroimaging methodologies have enabled the examination of the dynamic impact of sleep on brain plasticity (Guzman-Marin & McGinty, 2006; Maquet et al., 2003). However, our understanding of the multifaceted impact of sleep may benefit from more holistic approaches to human cognition. Instead of examining individuated cognitive systems (e.g., attention and memory) in relation to their neuroanatomical counterpart networks, several new lines of research attempt to understand them dynamically, e.g., across the lifespan. This includes the investigation of how multiple cognitive, physiological, neurophysiological, and socioeconomic/demographic factors including language use in general, and bilingualism in particular, can work together to affect "higher order" or more complex phenomena.

3. Bilingualism and cognition

In the previous section we briefly discussed how sleep impacts cognitive functioning and, by proxy, the accrual of reserve. Similarly, research shows that language acquisition, processing, and use are intimately linked to domain-general cognitive systems including attention, memory, and cognitive control (e.g., Harris, 2006). Herein, however, we consider primarily how *bilingualism* may influence executive functioning (Bialystok et al., 2012) with a specific focus on aspects of language use that apply (uniquely or with significantly increased regularity) when bilingualism is present.

Most importantly compared to monolinguals, bilinguals have the option to switch between distinct languages, a process that requires management and exercises mental/brain mechanisms. All activities inherent to the management of more than one language, during both acquisition and use, entail executive control to some extent (Abutalebi & Green, 2007; Green & Abutalebi, 2013). If such control fails, such as in the case of brain lesions and/or age-related cognitive impairment, unwanted language switches and interference typically appear during conversation (Green & Abutalebi, 2008). Psycholinguistic evidence shows that for bilinguals all languages are constantly active regardless of contextual cues, need or relevance (e.g., Jared & Kroll, 2001; Kroll et al., 2008; Spivey & Marian, 1999). Bilinguals, therefore, face cross-linguistic competition every time they engage in language processing (e.g., Kaushanskaya & Marian, 2007; Kroll et al., 2014). The cognitive construct overseeing such conflict management has been labeled *language control* (Abutalebi & Green, 2007; Green & Abutalebi, 2013) and is underpinned by a neural network that largely overlaps with the domain-general executive network (Abutalebi & Green, 2016; Anderson et al., 2018).

Due to the overlap between the cognitive mechanisms and neural topography implicated in bilingual language control and domain-general executive functioning, routine language control training is argued to affect executive functioning both at the cognitive and at the neural levels (e.g., Bialystok, 2017; Kroll et al., 2015). This has been empirically shown in executive performance in both young and elderly populations. For example, bilingualism has been repeatedly linked to adaptive performance in a variety of executive tasks including Flanker, Stroop, and Simon tasks (for a review, see Bialystok, 2017; Grundy, 2020). Cognitive consequences of bilingualism have also been shown to expand beyond executive functioning: bilingualism-related performance enhancements have emerged in tasks involving memory recall (Ljungberg et al., 2013; Wodniecka et al., 2010), episodic memory (Schroeder & Marian, 2012; Voits et al., 2022), semantic memory (Arce Rentería et al., 2019), working memory (Bialystok et al., 2014) and general intelligence (Bak et al., 2014).

While widespread evidence is available for effects of bilingualism on cognition, the literature also presents instances in which bilingual-induced executive behavioral effects fail to emerge, in particular in young adult populations (e.g., Paap, 2022; Paap et al., 2015). This has sparked a debate related to the genuine validity or generalizability of bilingualism effects on executive processing (e.g., Grundy, 2020; Lehtonen et al., 2018; Leivada et al., 2021; Paap, 2022). Valian (2015) proposed a straightforward explanation for such inconsistencies. She suggested that since young adults experience other cognitively enriching activities besides bilingualism, it might be harder to observe bilingual effects behaviorally in this population, due to ceiling levels of performance. This would also explain why non-replication levels are considerably lower when investigating children or older adults – populations less likely to perform at peak levels of cognition. Similarly, Kroll & Bialystok (2013) suggest that, due to young adults' optimal neurocognitive efficiency (Hartshorne & Germine, 2015), bilingualism's neurocognitive consequences may be harder to observe in youth due to task insensitivity and ceiling effects.

In light of the issues inherent in behavioral testing, it is important to highlight that extensive work reports bilingualism-related consequences at the neural level. Neuroplastic changes in areas associated with bilingual language control and executive functioning have been observed both in young and senior bilingual populations (see Bialystok, 2021; Li et al., 2014; Taylor et al., 2022 for reviews). Volumetric changes in gray matter (GM) of young bilingual adults have been reported in the inferior parietal lobule, anterior cingulate cortex, cerebellum, prefrontal cortex, Heschl's gyri, putamen, caudate nucleus, thalamus, hippocampus and globus pallidus (see Pliatsikas, 2019, for review). These results have been replicated for aging bilinguals in the inferior parietal lobule, anterior cingulate cortex and prefrontal cortex, and also reported in the temporal pole, orbitofrontal cortex and hippocampus, areas specifically targeted by age-related deterioration (see Voits et al., 2020, for review). Bilingualism-induced neuroplastic changes also emerge in the form of increased white matter (WM) integrity in tracts connecting regions of the language control and executive functions networks, such as the inferior and superior longitudinal fasciculi and the inferior fronto-occipital fasciculi (see Pliatsikas, 2019, for review).

As with sleep, the effects of bilingualism on cognitive performance and neural anatomy contribute to the gradual accrual of reserve (Bialystok, 2021; Gallo et al., 2022; Gallo & Abutalebi, 2023; Grant et al., 2014). Multiple studies have reported bilingualism-induced cognitive and neurostructural benefits during healthy aging (see Bialystok, 2021, for a review). Bilingualism-related benefits also mitigate the impact of age-related pathology e.g., recent *meta*-analyses consistently report that bilingualism delays dementia symptom onset by 5–7 years (Anderson et al., 2020; Brini et al., 2020; Paulavicius et al., 2020). The contribution of bilingualism to the accumulation of reserve follows from the fact that routine bilingual language control is posited to result in neural adaptations at the structural and at the functional levels (Bialystok, 2017). Following our rendition of reserve, imaging studies have reported that bilingualism preserves the efficiency of the executive network during senescence: to achieve comparable levels of performance, executive tasks appear to require lower or differential neural activations for senior bilinguals as compared to age-matched monolinguals (Abutalebi et al., 2015; Ansaldo et al., 2015; Gold, Kim, et al., 2013; Rodríguez-Pujadas et al., 2014). Similarly, it has been shown that bilingualism leads to the improved maintenance of network flexibility in aging, with bilingual older adults displaying superior resting-state (De Frutos-Lucas et al., 2020; Grady et al., 2015; Luk et al., 2011) and task-related connectivity (Ansaldo et al., 2015; Luk et al., 2010) in the executive network. Widespread evidence also indicates that bilingualism leads to the development of anti-aging compensatory mechanisms, with several papers reporting higher levels of neural deterioration in bilingual seniors, as compared to monolingual peers matched for cognitive status or disease severity. This indicates that bilingual seniors are better equipped to compensate for age-related neural deterioration and stave-off the resulting cognitive impairment. The same result emerges both in healthy (Berkes et al., 2021; Gold, Johnson, et al., 2013) and pathological (Costumero et al., 2020; Kowoll et al., 2016; Perani et al., 2017; Sala et al., 2022; Schweizer et al., 2012) cognitive aging, and with different neuroimaging techniques including DTI, PET, CT, and MRI. Studies also show that bilingualism modulates the relationship between neurostructural integrity and related cognitive outcomes, confirming that senior bilinguals are able to compensate for age-related neural tissue loss and maintain cognitive efficiency (Abutalebi et al., 2015; Arce Rentería et al., 2019; Del Maschio et al., 2018).

4. Convergence between sleep, bilingualism, and cognition

The research reviewed above shows important overlaps between sleep and bilingualism at the behavioral, neural and cognitive levels. Therefore, it is reasonable to hypothesize that sleep and bilingualism should reveal several significant points of convergence at both theoretical and functional levels. Below, we will highlight the synergy between sleep and bilingualism focusing on the parallel structures between the two. Before we do that, however, it is important to note that there are two (time) dimensions of bilingualism that are of primary concern for the present discussion: (i) the learning of an additional language itself or the emergent period of becoming bilingual separately from (ii) the effects of multiple language usage after communicative competence has been acquired. The distinction between (i) and (ii) is important because each engages increased cognitive resources and, while there is overlap in how this plays out, they crucially manifest with distinct effects (see Rothman, 2024 for discussion).

The first important convergence point between bilingualism and sleep is the involvement of sleep in language learning. Existing research offers compelling evidence supporting the role of sleep in vocabulary learning of both pseudowords (Dumay & Gaskell, 2007) and foreign language words (Schreiner & Rasch, 2015). Several studies have also demonstrated that sleep facilitates phonological (Earle et al., 2017; Earle & Myers, 2015) and grammatical (Batterink & Paller, 2017; Mirković & Gaskell, 2016) learning. These and similar studies clearly indicate that sleep effectively aids language learning, including rule consolidation (Palma & Titone, 2021). Given that distinct memory systems are argued to be differentially implicated for various domains of language, e.g., lexis versus grammar, (Paradis, 1994), it is reasonable to assume that sleep asymmetrically affects the acquisition and use of distinct domains, i.e., phonological, lexical, and grammatical. That said, we know very little about how these distinct components of language in general are affected by differences in the quality, quantity, and timing of sleep, including in the pathophysiology of sleep disorders. What is clear, however, is that sleep affects consolidation processes, a crucial component affecting the rate of, and ultimate success in, language learning of any type. It follows that sleep should play at least an equal, if not more weighted role in additional language learning because the processes inherent to consolidation in a newly learned language are essentially the same as those in learning one's first language. To consider but one example, these same processes are arguably more complex in the learning of an additional language (i.e., in emerging bilingualism) given the cognitive resources needed to control intrusions (transfer or cross linguistic influence) from previous language experience. Therefore, one could hypothesize an even more deterministic role of sleep in additional language learning. Given the dearth of specific research, this and other related questions remain to be answered.

The second important convergence point between sleep and bilingualism is the fact that both experiences impact partially overlapping brain structures and functions. A good starting point to address the interplay between bilingualism and sleep at the brain level are subcortical structures such as the basal ganglia and the thalamus. Specifically, the Caudate Nucleus (CN) has been shown to be involved in language development (Tan, et al., 2021) as well as bilingual language control and language switching (Abutalebi et al., 2013; Zou et al, 2012). Importantly, lesions of the left CN are often associated with pathological language switching in bilinguals (Abutalebi et al., 2000) or with other dysfunctions of language control in bilinguals (Green & Abutalebi, 2008) highlighting its role in bilingual language processing. Moreover, several studies demonstrate that bilingualism leads to neuroplastic changes in this area with findings indicating that increased language proficiency and usage are associated with structural changes in this subcortical region (Sulpizio et al., 2020; Yee, et al., 2023). These neuroplastic adaptations are calibrated to specific aspects of bilingual experience including degree of engagement with conversational contexts, language proficiency, and duration of bilingual experience (Abutalebi & Green, 2016; DeLuca et al., 2024; DeLuca, Rothman, & Pliatsikas, 2019; Gallo et al., 2023; Korenar et al., 2023). At the same time, the CN has been shown to play an important role in other cognitive functions including sleep. For example, volumetric deterioration in the CN has been shown to be associated with shorter sleep duration (Jones & Ikuta, 2022), less REM (Bourgouin et al., 2019), poorer self-reported sleep quality (Jiang et al., 2023), a potential vulnerability for the development of insomnia (Emamian et al., 2021; Stoffers et al., 2014; Van Someren, 2021), and day-time sleepiness (Feng, et al., 2024) as well as with specific executive deficits. Finally, the CN has been implicated in memory consolidation, problem solving, and skill acquisition during sleep – cognitive processes that underlie language acquisition, selection, and communication (van den Berg et al., 2022). Further supporting our argument is the observation that the CN plays a key role in executive functioning, one of the main cognitive abilities affected by both poor sleep and bilingualism. Supporting a simultaneous and complimentary involvement of CN in language, sleep, and cognitive control, a recent metanalysis (Bulut & Hagoort, 2024) shows the involvement of the CN, along with the thalamus, in sleep regulation and language use. Importantly, some recent studies also show a complex "cooperation" network between the thalamus, speech, motor, and sleep regions suggesting if not a causal, then at least an important codependence relationship between the functions performed by the network, including sleep regulation and multilingual language use (Li, et al., 2023). Future studies must therefore help us to unpack the nature (and directionality) of the potential relationship between *sleep* and *bilingualism* in neurocognitive and neurobiological terms and within a broader network of subcortical and cortical circuits. Therefore, it should be noted that we do not view the CN as the only brain structure linking bilingualism and sleep, but rather motivate it as a good starting point for dedicated and purposely designed research.

To be sure, various forms of poor sleep and sleep disorders seem to be associated with the volume and thickness of other brain regions that are at the same time known to be implicated in- and affected by bilingual language control. For instance, REM sleep behavior disorder (RBD) has been linked to decreased gray matter volumes (GMVs) in the anterior cingulate cortex, inferior parietal lobule, and hippocampus (see e.g., Campabadal et al., 2021, for a review), regions shown to display affected GMVs in bilingual populations (see e.g., Abutalebi et al., 2012; Voits et al. 2022, 2024; Tao et al., 2021, for reviews). Longitudinal studies further assert a link between sleep, bilingualism and aging trajectories at the neural level. For example, it has been shown that idiopathic RBD converts within 10 years to neurodegenerative syndromes in 33 % to 75 % of cases, with Parkinson's Disease the most common resulting pathology (e.g., Iranzo et al., 2014). Conversely, bilingualism is argued to mitigate and delay age-related neuropathology, including Parkinson's Disease (see Voits et al., 2020, for a review). Similarly, sleep deprivation has been associated with reduced GMVs in the inferior parietal lobule (Dai et al., 2018), whereas bilingualism has been shown to positively affect GMVs in this region in children (Della Rosa et al., 2013), young (Del Maschio et al., 2018; DeLuca et al., 2024; Mechelli et al., 2004) and older (Abutalebi et al., 2015; Del Maschio et al., 2018) adults. The inferior parietal lobule is also known to be a key structure for cognitive aging, targeted early and severely by age-related brain deterioration (e.g., Apostolova et al., 2007), once again pointing to a possible tripartite relationship between bilingualism, sleep and aging. Obstructive Sleep Apnea has also been linked to structural (Huang et al., 2019; Shi et al., 2017) and functional (Yeung, 2019) impairments in the anterior cingulate cortex. The same region is argued to be among the main brain areas affected by bilingualism, with extensive research showing bilingualism-related enhancements in functional efficiency (e.g., Abutalebi et al., 2012) and structural integrity (e.g., Del Maschio et al., 2018). Taken together, there is clearly no shortage of overlapping points within the neural networks related to sleep and bilingualism making it reasonable to hypothesize a moderating relationship between the quality of these experiences.

Finally, existing research using EEG shows important and often overlooked similarities between bilingualism and sleep at the neurophysiological level – with both affecting similar frequency bands in the brain's electrical activity. Before discussing overlapping points, it is important to note that the measurement of oscillatory dynamics can be done both at rest and in response to task stimuli. Task-free or resting-state EEG (rs-EEG) can be taken as a measure of the brain's readiness to deploy neurocognitive resources towards handling specific demands (Anderson & Perone, 2018). Assuming a similar relationship exists between rs-EEG and task-related EEG as does for rs- and task-based fMRI (e.g., default mode network, see Raichele & Snyder 2007), it is reasonable to hypothesize a correlation between patterns of rs-EEG power and that of on-task power. A few studies have examined the connection between the two and have almost exclusively linked rs-EEG to ERP, (see e.g., Lee et al., 2011). To our knowledge, no work to date has linked rs-EEG oscillatory dynamics with on task oscillatory activity.

There are several contact points within the relevant sleep- and bilingualism literatures examining oscillatory dynamics with EEG, which are relevant for both additional language learning and bilingual language control. First, low-frequency delta activity, most prominent during SWS sleep, has also been shown to play a key role in restorative processes and memory consolidation (Diekelmann & Born, 2010; Tononi & Cirelli, 2006). The same delta activity can be modulated by language learning and processing, especially during tasks that require deep cognitive engagement – both in monolinguals and in bilinguals (e.g., Harmony, 2013; Rossi, et al., 2023). Furthermore, theta waves, closely associated with light sleep (i.e. N1 and N2) and episodic memory processing (e.g., Cantero & Atienza, 2005; Ferrara, et al., 2013; Klimesch, 2003) are also linked to working memory and cognitive control in bilinguals (see for rs-EEG examples Pereira Soares, et al., 2024; Voits, et al., 2024; for task-based examples Carter et al., 2023; Pereira Soares et al, 2022). Alpha waves related to relaxation and N1 (Jacobs & Friedman, 2004; Malhotra & Avidan, 2013), also reflect attentional processes in bilinguals, where they may indicate the readiness for suppression of one language in favor of another (Bice et al., 2020). In wakefulness, beta waves have been connected to processes underlying working memory (Proskovec et al., 2019), decreasing during sleep but sometimes increasing during REM sleep due to cognitive processing during dreaming (Zhang & Wamsley, 2019). The same beta oscillations are crucial for language production and comprehension, with variations depending on the language used and task complexity (Prystauka & Lewis, 2019; Wiess & Mueller, 2012). Finally, gamma frequency, though rarely evident during most sleep stages, has been linked to high-level cognitive functions, such as vivid dreaming during REM sleep (Voss et al., 2009; Cantero, et al., 2004). In bilingualism, gamma activity is associated with complex language processing and the integration of information and structure building (Rossi, et al., 2023). It is important to note that REM sleep is characterized by theta, beta, and gamma activity (low-voltage, mixed frequency activity), which are also implicated during wakefulness. These examples further show how sleep and bilingualism jointly influence brain electrophysiological activity via distinct brain oscillatory signatures. As such, the evidence briefly reviewed above points to an overlapping neural substrate (rs- and task related oscillatory dynamics) implicated in- and affected by both bilingualism and sleep, with also a potential link to cognitive aging trajectories. The fact that bilingualism and sleep intersect both at the behavioral and neural levels leads to the establishment of the third convergence point – the two dynamically impact the accrual and the quality of reserve.

The third and last convergence point is that both experiences are known to affect reserve accrual. In the case of sleep, deep sleep stages such as SWS facilitate memory consolidation, a process in which information acquired during the day is transferred to long-term memory, directly contributing to enhanced reserve (e.g., van den Berg et al., 2022). Similarly, the constant language monitoring required by bilingualism engages the executive control network responsible for attentional control, inhibition, and cognitive flexibility, further bolstering reserve (e.g., Bialystok, 2021; Grant et al., 2014).

Both sleep and bilingualism have also been shown to affect the incidence and/or trajectory of neurodegenerative conditions such as AD. Chronic sleep disorders, such as insomnia or sleep apnea, have been linked to an increased risk of cognitive decline and dementia, potentially due to the disruption of restorative processes during sleep, such as the clearance of neurotoxic waste products from the brain (e.g., Eugene & Masiak, 2015; Jones & Ikuta, 2022). Symmetrically, bilingualism has been shown to delay the onset of dementia symptoms, with bilingual seniors often displaying a higher tolerance for neural deterioration compared to monolinguals, thereby delaying the clinical expression of cognitive impairments (e.g., Anderson et al., 2020; Brini et al., 2020). This suggests that both adequate sleep and bilingualism help build a form of cognitive resilience that allows the brain to better withstand age-related pathology.

In addition, both good quality sleep and bilingualism promote structural and functional neuroplasticity, the brain's ability to reorganize and form new neural connections, which is essential for maintaining functional and structural integrity and accumulating reserve. Both sleep (e.g., Dutil et al., 2018) and bilingualism (e.g., Taylor et al., 2022) support structural changes in the brain via synaptogenesis and synaptic pruning, leading to enhanced maintenance of neural networks in older age. Both have also been linked to functional brain modifications. Bilingualism has been shown to improve neural efficiency, particularly in the executive control network. Imaging studies reveal that bilingual seniors require less neural activation to achieve the same level of cognitive performance as their monolingual peers, indicating that bilingualism preserves neural efficiency as people age (e.g., Abutalebi et al., 2015; Ansaldo et al., 2015). This parallels findings in sleep research, where the preservation of memory consolidation during sleep has been associated with greater cognitive reserve and improved brain efficiency in older adults (e.g., Ourry et al., 2021).

In sum, the mutual benefits of sleep and bilingualism for cognitive reserve are evident in their shared ability to enhance cognitive capabilities, support neuroplasticity and preserve neural efficiency in the aging brain. Both factors are crucial for building resilience against cognitive decline and neurodegenerative diseases, contributing to a richer and more adaptive reserve that sustains cognitive health well into old age.

5. Research directions and open questions

Our argumentation above leads to some starting points for a research program examining bilingual language learning and/or bilingualism-induced neurocognitive adaptations that fold in sleep (or vice versa). The goal of this final section is to articulate these starting points and several novel research questions that naturally emerge from them, as well as their field-specific and cross-disciplinary implications. We have argued that neurobiological adaptations related to additional language learning and use are mediated by sleep. Unfortunately, to our knowledge, no research on this topic currently exists. We suggest that a program to fill this gap can emerge from combining the insights from the cognitive neuroscience literature of sleep, and that of bilingualism, by focusing on the several loci where the two overlap, as reviewed above.

Consider first the effects of multiple language use. Here, the task is to investigate whether the interface of sleep and life-long bilingual experience relates to cognitive and neurobiological adaptations. As outlined above, we have strong theoretical reasons to suggest that sleep and sleep disorders, such as insomnia, may differentially affect cognitive functioning in individuals with different bilingual profiles. More experienced bilinguals would be expected to better withstand the generally negative effect of poor sleep on executive functioning. Our very recent study offers a first-pass confirmation of this general hypothesis (Terekhina, et al., under review). Importantly, the data revealed that the beneficial effect of bilingualism on executive functioning, measured via a standard flanker-task setup, increased as a function of decreasing levels of sleep quality as measured via the Pittsburgh Sleep Quality Index (PSQI) and increasing levels of insomnia symptoms as measured via the Insomnia Severity Index (ISI). In other words, there was a stronger facilitating effect of second language proficiency on executive functioning in poor sleepers and individuals with insomnia. This pattern suggests that (1) bilingualism can mitigate the detrimental effects of poor sleep on cognitive performance and (2) that poor sleep, a factor detrimental for efficient cognitive performance, allows bilingualism's cognitive consequences to be more readily observed, in line with the hypotheses suggested by Valian (2015) and Kroll and Bialystok (2013) discussed above. When it comes to the neural underpinnings of this interplay, the first step would be to take continuous measures of bilingualism and sleep and examine their moderated effects on outcomes in the corresponding brain substrates (e.g., function, structural plasticity, etc.) and subsequently examine the relationship to executive function (e.g., attentional control). It is important to note that we do not necessarily view the relationship between sleep, bilingualism, and cognition as causal. What we argue for is a mediated relationship, which emerges as a byproduct of the fact that bilingualism and sleep affect the same cognitive functions that, over time, contribute to the accrual of reserve. At the same time, sleep is crucial for a cognitive mechanism essential for bilingualism and language learning – namely, information consolidation.

Second, when it comes to memory consolidation and learning, bilingualism and sleep should play a crucial role during both additional language learning and bilingual language use. As mentioned above, the role of sleep in the consolidation of language learning is well documented. However, much remains to be discovered about the effects of different sleep stages and sleep quality on specific aspects of the learning of language categories (phonological, morpho-lexical, syntactic), how the sleep consolidation of "declarative" and "procedural" learning relates to language processing, and the contextual effects of language learning and use on the sleep-related consolidation of linguistic knowledge. Other open questions relate to the role of sleep in the consolidation of (bilingual) language use, rather than learning. While there is little relevant research on the role of sleep in the updating of language use, some recent studies suggest that sleep may condition the consolidation of context-specific lexical information. For example, Gaskell, et al., (2019) explored how contextual priming of one of a homophones meanings (e.g., "fence" as a barrier or a sword sport) is influenced by sleep. They showed that being exposed to homophones in a particular context improves the retrieval of the context appropriate meaning, and that this effect becomes more stable after sleep. Mak et al. (2023) demonstrated similar sleep consolidation effects for non-homophonic interpretations of word meaning (e.g., bathtub-slip vs. bathtub-relax), and argued that episodic memory and sleep contribute to the maintenance of context-specific lexical information. Both of these studies demonstrate the role of sleep in the consolidation of contextual associations that influence subsequent language processing. These findings raise important questions about the role of sleep in the consolidation of language use in bilinguals. Critically, how much of what is consolidated is language specific, and what are the consequences of language-specific consolidation on language control? For example, to what extent does sleep consolidate language-specific word-to-concept links and how does this consolidation affect inhibitory control requirements during language switching, a process proposed to underpin the accrual of reserve (Gallo et al., 2022; Gallo & Abutalebi, 2023).

In order to determine the factors that underpin the role of sleep in language learning and control, interdisciplinary research is required. This research should combine carefully controlled language learning and consolidation manipulations with detailed sleep and bilingual experience data and/or interventions that manipulate sleep during a period of controlled language learning. As reviewed above, combining these methodologies with measurements of on-task oscillatory activity could extend our understanding of the role of different sleep stages in these processes. In addition, this research requires an individual differences approach to determine how the consolidation of language usage and language control are modulated by both sleep quality (across different stages) and aspects of bilingual experience. Finally, research will need to test the life-course progression of such mechanisms to test whether they undergo qualitative or only quantitative changes when the cognitive aging trajectory begins.

Third, when it comes to cognitive performance and reserve, bilingualism makes a generally positive contribution via facilitating attentional processes and executive control, as well as strengthening the corresponding neural resources, while poor sleep does the opposite- via insufficient recovery and exhausting the corresponding resources. These processes, taking place at different life stages, may eventually result in the accumulation or depletion of reserve. At earlier life stages, poor sleep will thus impair neurocognitive resources, while bilingualism may reinforce them. Logically, during later life stages, this predicts that an individual with a history of chronic sleep difficulties will be disadvantaged in terms of the amount of reserve they are able to accumulate. However, the same individual with rich bilingual experience should be able to mitigate the negative effects of accumulated poor sleep. In other words, bilingualism may function as a compensatory mechanism. This view suggests several avenues for both behavioral and neuroimaging studies. One such avenue follows from the study by Terekhina et al. (under review) discussed above. Namely, future research will need to examine how individual aspects of sleep, including the distribution and power of each sleep stage in both clinical and subclinical sleep disorders lead to the registration of the most general effect reported in Terekhina, et al. Conversely, there is a need to investigate whether specific parameters and components of bilingual experience (e.g., use scope, context, proficiency, age of acquisition, etc.) have equally strong compensatory effects for younger adults' neurocognition and seniors' reserve mechanisms. Future studies will also need to take direct measures of sleep and sleep dysfunction e.g., using polysomnography as a direct, online window into sleep. Another approach would involve the direct manipulation of sleep – e.g., employing existing sleep restriction and deprivation protocols. Finally, as noted above, it remains to be seen what the relative contribution of good quality sleep to reserve is and the extent to which that is modulated by bilingual experience.

Our final note is that it is important to keep in mind the directionality of influence when attempting to carve out the initial hypothesis space between sleep and bilingualism. Overall, while extensive engagement in bilingualism is linked to enhanced cognitive efficiency, impaired sleep leads to notable cognitive deficits. Therefore, the resulting intuition to be tested, is that each should modulate each other's impact on cognitive functioning. Although this novel idea regarding the interplay between sleep and bilingualism requires a great deal of empirical groundwork, it is reasonable to expect that, under the right conditions, the generally positive impact of bilingualism on cognitive functioning can compensate for the generally negative cognitive effects stemming from poor sleep. Similarly, while the effects of sleep on memory consolidation and learning are well documented, relatively little is known about the impact of sleep on how bilingual language usage finetunes cognitive functioning. Such fine-tuning should incur, as the research we have reviewed indicates, the shared involvement of specific brain regions in both sleep regulation and bilingual language control. This argument underscores the importance of a broader empirical investigation at the intersection of bilingual language learning and usage, sleep, and cognitive science.

6. Conclusions

The goal of the present paper was to map out the rationale for a novel, cross-disciplinary research program combining expertise from the cognitive neuroscience study of sleep, on the one hand, and that of bilingualism, on the other. To contextualize this, we began by reviewing literature regarding the effects of sleep on cognitive performance and its implications for brain structure and function. We then reviewed the same landscape with a focus on effects of bilingual experience. As we demonstrated, it is not simply the case that both sleep and bilingualism correlate with cognitive and/or brain adaptations. Crucially, there are significant overlaps in the specific cognitive functions, brain regions and networks in which adaptations are shown, and these adaptations often go in opposing directions. These observations support the utility of combining sleep and bilingualism in a single research program. The reviewed overlap in cognitive functioning and implicated neural networks strengthens the hypothesis that sleep and bilingual adaptations partially relate to shared underlying mechanisms at multiple levels. This, in turn, suggests that they could have a mitigating relationship for affecting the mind/brain in the real world, with serious implications for both theory and empirical work that have previously flown under the radar. Moreover, investigating sleep and bilingualism in a single research program will help to illuminate each more completely within their respective domains, as well as open new avenues for capitalizing on their relationship on both theoretical and practical levels. For example, the program of research we propose above will test our hypothesis that an individual's status of bilingualism and sleep are variables that need to be unconfounded. This will also help to explain the nature of individual differences observed in both disciplines. On the practical side, this new research will provide the necessary building blocks for harnessing knowledge about sleep quality towards better language interventions in older age or simply for improved language learning at any age.

7. Author notes

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Sklodowska-Curie grant agreement No 101106069 to FG. VD, JA and JR were supported by the Center for Language, Brain and Learning (C-LaBL), UiT the Arctic University of Norway. The article was prepared in the framework of a research grant funded by the Ministry of Science and Higher Education of the Russian Federation (grant ID: 075-15-2022-325) to AM.

CRediT authorship contribution statement

F. Gallo: Writing – review & editing, Writing – original draft, Conceptualization. **A. Myachykov:** Writing – review & editing, Writing – original draft, Conceptualization. **J. Abutalebi:** Writing – review & editing, Writing – original draft, Conceptualization. **V. DeLuca:** Writing – review & editing, Writing – original draft, Conceptualization. **J. Ellis:** Writing – review & editing, Writing – original draft, Conceptualization. **J. Rothman:** Writing – review & editing, Writing – original draft, Conceptualization. **L.R. Wheeldon:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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