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The unique role of bilingualism among cognitive reserve-enhancing factors

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Opinion

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Abstract

The umbrella term cognitive reserve-enhancing factors refers to those experiential and lifestyle factors (such as intellectual activities, regular physical exercise, healthy nutrition, educational attainment, etc.) that may help individuals to compensate for age-related neural deterioration, thus enabling them to maintain relatively stable cognitive functioning during senescence. In the last 10 years, mounting evidence has shown that speaking a second language is a powerful cognitive reserve contributor, which could mitigate the consequences of healthy aging and contribute to the delay of dementia onset. In this piece, we argue that bilingualism may play a unique role among the well-known cognitive reserve-enhancing factors, thus contributing to the achievement of successful aging in a distinctive fashion. After reviewing behavioral and neuroimaging evidence for bilingualism-induced protection against healthy and pathological cognitive aging, we discuss theoretical reasons and experimental findings supporting the view that bilingualism should be granted an individual spot among reserve-enhancing life experiences.

1. Introduction

We live in an aging world. Thanks to advances in health sciences and improving life conditions, average life expectancy is steadily increasing and projected to continue to grow in the forthcoming years (Kontis et al., 2017). Among numerous positive aspects, this achievement carries an often neglected downside. Indeed, with the number of senior individuals steadily increasing, so do the negative consequences of aging, such as cognitive impairment, dementia, and mild cognitive impairment (MCI), which are increasingly more widespread among the population. The World Health Organization reports that dementia rates are ramping up worldwide, with cases increasing from 49.92 million in 2015 to 58.66 million in 2020 (World Health Organization, 2019). With over 10 million new yearly cases worldwide, implying one new case every 3.2 seconds, it is foreseen that patients will almost double every 20 years, reaching 78 million in 2030 and 139 million in 2050. Dementia and age-related cognitive impairment can be among the trickiest medical conditions to deal with, since the development of pharmacological treatments is still at an embryonal stage (Dyer et al., 2018) and so is our understanding of their etiopathogenesis. Given the difficulties in TREATING such conditions, the scientific community is focusing on ways of PREVENTING, MITIGATING or, at least, DELAYING them. It is in this scenario that the theory of COGNITIVE RESERVE (CR), the dominant framework for prevention of age-related cognitive impairment, emerged (Stern, 2002). CR is generally defined as THE DISCREPANCY BETWEEN THE OBSERVED AND EXPECTED LEVEL OF COGNITIVE ABILITY, GIVEN THE OBSERVED LEVEL OF NEURAL INTEGRITY. Although CR may also emerge in young populations (Gallo et al., 2021) and/or in the aftermath of sporadic events that may cause brain damage, such as stroke (Alladi et al., 2016; Paplikar et al., 2018), it is a concept mostly discussed in the field of cognitive aging research. In this field, its most common definition is that of THE DISCREPANCY BETWEEN THE SEVERITY OF AGE-RELATED NEURAL DETERIORATION AND THE CORRESPONDING LEVEL OF COGNITIVE IMPAIRMENT (Stern et al., 2020). The development of CR has been shown to be prompted by several life experiences, including but not limited to physical exercise, healthy nutrition, frequent engagement with leisure activities, higher levels of education and occupational complexity (e.g., Goh & Park, 2009; Yaffe et al., 2009; Hötting & Röder, 2013; Vemuri et al., 2014; Hindle et al., 2017; Wang et al., 2017; Dause & Kirby, 2019; for a review, see Cheng, 2016). One such factor, gaining increasing popularity in the last decade, is bilingualism (for a review, see Gallo et al., 2020, 2022a). Widespread behavioral and neuroimaging evidence suggests a role of bilingualism in mitigating and delaying both pathological and healthy age-related cognitive decline.

1.1 Bilingualism and pathological aging

Bilingualism has been consistently shown to positively affect pathological aging, both via delay and mitigation of symptoms, and in both population and neuroimaging studies. For instance, several retrospective investigations have found a delaying effect of bilingualism on the onset of symptoms associated with Alzheimer's Disease (AD). A landmark work conducted in Canada by Bialystok et al. (2007) showed a striking 4-year delay in AD onset for bilinguals with various first languages (L1s) and English as a second language (L2), as compared to monolingual peers. This study paved the way for many more following investigations which confirmed and expanded such results. A follow-up study from the same group (Craik et al., 2010) confirmed the same time gap between bilinguals' and monolinguals' symptoms onset. Another subsequent study (Alladi et al., 2013) expanded the original findings by demonstrating a comparable effect for non-immigrant, native, bilinguals from India, speaking different Indian dialects as an L1 and Hindi or English as an L2. These findings were further replicated in different cultural settings, including a cohort of bilinguals based in Belgium, with different L1s and Dutch/French as an L2 (Woumans et al., 2015), Cantonese/Mandarin bilinguals from China (Zheng et al., 2018) and bilingual US residents with various L1s and English as an L2 (Mendez et al., 2019). Bilingualism has also been shown to delay the onset of (i) MCI, by as long as 7.4 years (Bialystok et al., 2014a; Ramakrishnan et al., 2017); (ii) amnestic MCI (Ossher et al., 2013); (iii) primary progressive aphasia (de Leon et al., 2020) and (iv) Parkinson's Disease (Saidi, 2019). The delaying effect of bilingualism on dementia onset has been also confirmed by different meta-analyses (Anderson et al., 2020; Brini et al., 2020; Paulavicius et al., 2020), which consistently point towards a 4/5-year delay among bilinguals, as compared to monolingual peers. Further confirming these findings, although from a different perspective, is a recent study by Berkes et al. (2020). A comparison between MCI-to-dementia conversion rates of bilingual and monolingual patients revealed that bilinguals tended to convert faster. This finding, possibly counterintuitively, is in line with predictions of the CR framework: individuals with higher CR are expected to counteract age-related cognitive deficits for longer, resulting in a faster deterioration when the CR "warehouse" is depleted (see Valenzuela, 2019 for a more detailed explanation).

Besides delaying effects, initial evidence seems to also suggest a role of bilingualism in lowering MCI and dementia incidence. For instance, Perquin et al. (2013) found an inverse relationship between MCI incidence and number of languages spoken, while Wilson et al. (2015) reported lower MCI incidence for bilinguals over a 6-year span. Finally, a study by Klein et al. (2016) highlighted a negative relationship between the degree of multilingualism and dementia incidence in 93 countries. To conclude this brief review of population studies, and spanning beyond effects on dementia, some recent evidence also suggests that bilingualism may lead to better recovery outcomes for multiple sclerosis (Aveledo et al., 2020; Soltani et al., 2018), as well as stroke patients (Alladi et al., 2016; Paplikar et al., 2018). Stroke is characterized by an acute onset, rather than progressive neurodegeneration. Nonetheless, since cardiovascular health is known as a risk factor for faster and more severe age-related cognitive impairment, the finding that bilingualism leads to better post-stroke cognitive outcomes might suggest that bilingualism could mitigate the impact of cardiovascular issues on the cognitive aging trajectory, although further research is required to confirm this assumption.

In addition to population studies, the literature also presents neuroimaging evidence that supports claims of beneficial consequences of bilingualism for pathological aging. The first investigation of this kind, by Schweizer et al. (2012), compared the extent of brain atrophy between bilingual and monolingual AD patients matched for disease severity. For comparable severity of AD symptomatology, bilinguals' medial temporal pole (a neural structural suffering early consequences of AD) displayed higher levels of atrophy, indicating a higher capacity for compensation of AD-related neural deterioration among bilingual patients. Similarly, PET studies reported more severe glucose hypometabolism in bilingual AD (Perani et al., 2017; Sala et al., 2021) and MCI (Kowoll et al., 2016) patients, as compared to monolinguals matched for symptoms severity. Finally, senior bilinguals have been reported to exhibit reduced levels of t-tau protein (a biomarker of AD) in the cerebrospinal fluid, as compared to monolingual peers (Estanga et al., 2017). These results seem to suggest that bilingualism leads to improved resilience against age-related cognitive decline, potentially by mitigating the impact of neural deterioration on cognitive ability (in accordance with the CR definition reported above).

Amidst evidence supporting a contribution of bilingualism to successful aging, it is necessary to point out that some investigations have failed to corroborate such findings, both in the context of healthy (Crane et al., 2010; Kousaie & Phillips, 2012; Mukadam et al., 2017) and pathological (Lawton et al., 2015; Mukadam et al., 2017; Sanders et al., 2012; Yeung et al., 2014; Zahodne et al., 2014) aging. Inconsistencies among findings on the neuroprotective role of bilingualism have been attributed to a series of factors, including inter-study variation in experimental designs, sampling procedures and definitions of bilingualism. An in-depth analysis of the potential reasons behind inconsistent results in the field is beyond the scope of this brief opinion piece, but we refer the reader to Del Maschio et al., 2021 for a comprehensive discussion on the issue.

1.2 Bilingualism and healthy aging

Evidence – both from behavioral and neuroimaging investigations – in favor of a beneficial contribution of bilingualism during healthy aging appears even more substantial.

At the behavioral level, bilingual older adults have been reported to outperform monolingual peers in an array of tasks, to date. While mainly emerging for executive functions (EF) tasks (e.g., Bialystok et al., 2004; Abutalebi et al., 2014; Del Maschio et al., 2018; Incera & McLennan, 2018; López Zunini et al., 2019; see below for discussion on the relationship between bilingualism and EF), these effects have also been reported for tasks assessing memory recall (Ljungberg et al., 2013; Wodniecka et al., 2010), working memory (Bialystok et al., 2014b), semantic memory (Arce Rentería et al., 2019) and general intelligence (Bak et al., 2014).

At the neuroimaging level, several investigations have shown that bilinguals maintain higher neurostructural integrity than monolinguals during aging. Bilingualism-induced neuroplasticity, emerging as modifications in gray- and white matter density in the brain, has mainly (but not exclusively) been reported for structures of the so-called language control network (Abutalebi & Green, 2016; see below for further discussion). As per the gray matter, senior bilinguals display neuroplastic changes, in the form of greater density than monolingual peers, in the inferior parietal lobule (Abutalebi et al., 2015a; Del Maschio et al., 2018), the anterior cingulate cortex (Abutalebi et al., 2015b; Del Maschio

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et al., 2018), the prefrontal cortex (Del Maschio et al., 2018), the temporal pole (Abutalebi et al., 2014; Olsen et al., 2015), and the orbitofrontal cortex (Abutalebi et al., 2014). Regarding the white matter instead, bilingualism-induced mitigation of aging effects, in the form of enhanced tissue preservation for senior bilinguals as compared to monolinguals, has been observed in the superior longitudinal fasciculus (Anderson et al., 2018; Luk et al., 2011), the frontal-lobe white matter tracts (Olsen et al., 2015) and the right inferior fronto-occipital and uncinate fasciculi (Luk et al., 2011). These results assume particular relevance as some of these regions are known to be strongly implicated in the process of brain aging. For instance, the temporal pole and the orbitofrontal cortex are known to be among the earliest cortical areas to be targeted by non-pathological age-related atrophy (Kalpouzos et al., 2009). Similarly, gray matter volume loss in the inferior parietal lobule is linked to MCI (Apostolova et al., 2007) and early stages of AD (McDonald et al., 2009). Finally, pre-frontal and frontal white matter circuitries have been reported to be heavily affected by age-related disruption (Gunning-Dixon et al., 2009; Pfefferbaum et al., 2005). In line with these results, senior bilinguals also show better preservation of functional efficiency as compared to monolingual age peers. For instance, Gold et al., (2013) reported lower task-related switch costs for senior bilinguals in the left dorso- and ventro-lateral prefrontal cortices and the anterior cingulate cortex. Moreover, both functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) studies showed increased resting state functional connectivity in several occipitoparietal clusters (De Frutos-Lucas et al., 2020), as well as in the Prefrontal EF network and Default Mode Network (DMN; Grady et al., 2015) of bilingual older adults, when compared to monolingual peers. Resting-state connectivity of functional networks represents interregional coherence of spontaneous neural activity fluctuations during rest, and it can be regarded as a "signature" of an individual's level of intraneural communication (Fox et al., 2005). The functional networks that are analysed with this technique are associated with higher-order cognitive functions. The DMN, for instance, is known to be associated with episodic memory, which is also vulnerable to AD pathology. Patterns of spontaneous network activity represent a "history" of local and long-range functional pairing between brain regions, which reflects simultaneous engagement in regularly-performed tasks – like, for example, bilingual language control (Bice et al., 2020; see below for further discussion).

Grady et al.'s (2015) results are particularly relevant since the EF network, responsible for controlling attention, inhibiting distraction and shifting between goals, is known to play a central role in the cognitive aging trajectory (Reuter-Lorenz et al., 2021). The modulation of DMN's activity, known to increase during rest and decrease during task performance, is also important for EF: greater task-related de-activation and stronger internal functional connectivity in the DMN have been linked to better performance on executive tasks (Dang et al., 2013).

Finally, in line with results from dementia patients (see previous section), bilingualism has been shown to mitigate the relationship between gray matter loss and cognitive decline also in healthy aging (Del Maschio et al., 2018), again in complete overlap with the definition of CR, i.e., the discrepancy between the severity of age-related neural deterioration and the corresponding level of cognitive impairment (Stern et al., 2020). Evidence corroborating this finding comes also from a recent study by Berkes et al. (2021) in which, for levels of white matter integrity comparable to those of monolinguals, bilingual seniors displayed better clinical and cognitive outcomes, indicating greater ability to compensate for age-related neural deterioration.

As emerging from investigations reviewed above, a considerable amount of evidence seems to support the status of bilingualism as a factor prompting CR development. But does bilingualism play a unique role among such factors? We discuss this in the following section.

2. Is bilingualism unique among cognitive reserve factors?

In this section, we argue that bilingualism should occupy a unique position among reserve-enhancing factors, for several – independent yet interlinked – reasons. We illustrate such reasons in what follows.

First of all, differently from most other CR factors, managing two or more languages is an OMNIPRESENT activity in bilinguals' daily life, throughout the lifespan. Widespread evidence shows that both language representations are constantly activated in the bilingual brain, irrespectively of contextual need or conscious intent (Green & Abutalebi, 2013; Kroll et al., 2008; Spivey & Marian, 1999). To successfully juggle their two languages, bilinguals rely on a cognitive ability named language control. The cognitive mechanisms and neural resources used for language control are thought to overlap at least partially with those of domain-general EF, which leads to a reinforcement of bilinguals' EF both at the behavioral and neural levels (Abutalebi & Green, 2007). Within the multi-componential construct of EF (Diamond, 2013), for many years bilingualism research attributed a primary role for language control to inhibitory control (e.g., Blumenfeld & Marian, 2011; Liu et al., 2016; Misra et al., 2012). Inhibitory control is a cognitive ability that allows individuals to avoid natural, habitual, or dominant behavioral responses to stimuli, in favor of selecting the correct response to complete their goals (Diamond, 2013). The term subsumes abilities such as response inhibition or interference suppression. The hypothesis of a primary role of inhibitory control for bilingual language control stems from the observation that bilinguals rarely show intrusions from the non-target language. Thus, researchers saw in inhibitory control a logical mechanism for avoiding interference from the non-selected language during language processing. However, this theoretical view fails to explain inconsistencies emerging from the literature on cognitive consequences of bilingualism (see Bialystok, 2017 for a comprehensive review). Thus, a new theoretical framework has been recently proposed by Bialystok et al. (Bialystok, 2017; Bialystok & Craik, 2022) that identifies the key causal mechanism for observed bilingual benefits in attentional control, a cognitive ability supervising both goal maintenance and conflict resolution. The explanation is that bilinguals' controlled attention is taxed by the interference between competing concepts and structures in L1 and L2, resulting in a constant training that increases the flexibility and efficiency of attentional control. Importantly, according to this view the mechanism underlying bilingualism-induced benefits is not to be found in enhanced attentional RESOURCES, but rather in enhanced EFFICIENCY in utilizing those resources. This account is in turn linked with a shift from EF models attributing a more central role to inhibition (e.g., Miyake et al., 2000; Miyake & Friedman, 2012) to ones revolving around attentional control (e.g., Engle & Kane, 2004; but see Bialystok & Craik, 2022 for a more detailed explanation). Given the key role played by EF in cognitive aging (for a review see Reuter-Lorenz et al., 2021), the CONSTANT attentional training provided by bilingualism, which in turn would increase EF efficiency, would result in benefits during senescence.

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This OMNIPRESENCE of the "training" mechanisms leading to neuroprotective effects is the first reason that makes bilingualism stand out as compared to other CR factors – like, for instance, physical exercise (Hötting & Röder, 2013), which intrinsically have a limited temporal extension.

A second reason for attributing a unique role to bilingualism among CR factors is that it is a large-scale phenomenon: with the majority of the World's population currently estimated to be bilingual (De Houwer, 2021), it can be considered among the most WIDESPREAD CR factors, globally. Also, bilingualism is arguably more EQUITABLE than the majority of other CR-enhancing factors. For instance, attaining a higher level of education often requires certain financial means. Similarly, attitudes towards a healthy diet, physical exercise and health in general are known to be heavily influenced by socioeconomic status (e.g., Wardle & Steptoe, 2003), with minorities often disproportionally suffering from health-related issues. Bilingualism is different. High levels of language diversity are often found in economically challenged areas of the world. Similarly, in monolingual dominant societies, bilingualism is usually more diffused among migrant minorities, which often overlap with the most socioeconomically challenged fringes of society. The relationship between bilingualism and education is a particularly interesting one. In some instances, i.e., formal L2 learning contexts, the two factors may be seen as intrinsically related: for individuals with low education, who may be illiterate or have low literacy levels, learning an L2 formally may be challenging. Thus, it might seem that in some cases bilingualism is restricted to certain strata of the population. However, instances exist in which education and bilingualism are not related, as in the case of early bilinguals, who acquire both languages from early life stages, or immigrants. Both can acquire an L2 through immersion and not necessarily through formal learning. To date, the results have been inconsistent when directly testing the relationship between education and bilingualism in fostering successful aging. For example, a study by Gollan et al. (2011) found that bilingualism delayed AD onset in low-, but not high-education bilinguals. Conversely, an abovementioned study by Ramakrishnan et al. (2017) found a delaying effect of bilingualism on MCI, but no effect of education. Another study by Alladi et al. (2013) found a delay of dementia onset for both low- and highly educated bilinguals, but the effect was stronger for individuals with low education, suggesting that bilingualism's and education's contributions to successful aging share at least some variance. However, studies that have directly tested bilingualism's benefits for aging BEYOND education's contribution (Gallo et al., 2022b), or controlled for education effects (see e.g., Anderson et al., 2020 for a meta-analysis), corroborate the finding that bilingualism may independently affect trajectories of age-related cognitive decline.

Returning to its unique characteristics among CR factors, bilingualism stands out for its greater APPLICABILITY in the real-world context as compared with, for instance, other types of cognitive training. Acquiring a new language offers the opportunity to open novel channels of communication, explore new travel routes, and overcome cross-cultural barriers. Additionally, it could INDIRECTLY contribute to CR development by affecting other CR factors. Although this might not be a unique characteristic PER SE, we believe it is worth mentioning an ulterior perk of language learning: language has an intrinsic SOCIAL dimension. Thus, for example, learning a new language could contribute to expand individuals' social networks or create the opportunity for new leisure activities, factors that are known to support CR development as a result of the cognitive demands imposed by social engagement on attention, reasoning, language, EF and processing speed (Seeman et al., 2011).

A further difference with respect to other CR-promoting factors is our (at least partial) knowledge of the mechanism underlying bilingualism's beneficial effects on aging. As mentioned above, the neurocognitive route for such effects is to be found in the relationship between bilingual language control and EF, mediated by enhancements in attentional control (Bialystok & Craik, 2022). The constant training provided by bilingualism has been repeatedly shown to affect executive neurocognitive trajectories (e.g., Bialystok et al., 2008; DeLuca et al., 2019; Gallo et al., 2021, *inter alia*), which in turn would favor successful aging due to the central role played by EF during senescence (Reuter-Lorenz et al., 2021). An interesting account of the trajectory of bilingualism-induced neuroplastic changes is offered by the Dynamic Restructuring Model (DRM; Pliatsikas, 2020). The DRM models the time course of neurostructural and neurofunctional changes related with various stages of bilingual experience development. It posits that, initially, the novel cognitive burden imposed by language control causes the brain to undergo structural changes in the white and gray matter substrates via SYNAPTOGENESIS (i.e., the generation of new synaptic connections). With progressive experiential engagement, the learning trajectory triggers an increase of functional efficiency of the regions and networks involved in bilingual language control, enabling the individual to accommodate the extra cognitive effort via functional reorganization. At this stage, the surplus synaptic connections undergo a PRUNING process, eventually reverting back to pre-bilingualism levels. In this pruning phase, in alignment with existing theories of synaptic reorganization (e.g., Lövdén et al., 2013, *inter alia*), only the most efficient synaptic connections are maintained, while others are eliminated. It is believed that this process of synaptic reorganization, with (i) novel connection being formed, (ii) selected connections being reinforced, (iii) surplus, non-efficient connections being pruned and (iv) efficient connections being maintained and prioritized, lies at the base of the neuroprotective effect observed in bilinguals during senescence. Indeed, augmented efficiency, capacity and flexibility of brain networks are the main causal mechanisms posited for CR effects (Stern, 2009).

The knowledge of bilingualism's action route on aging allows also to compare its contribution with those of other CR proxies in a QUANTITATIVE manner, directly testing the assumption that bilingualism may play a unique role among CR-enhancing factors. Following this observation, Gallo and coworkers (Gallo et al., 2022b) attempted to extrapolate bilingualism's unique contribution to CR development. Participants underwent a comprehensive language background questionnaire, as well as a questionnaire assessing their sociodemographic information and their profiles with respect to several life experiences and activities traditionally associated with CR development – namely, occupational complexity, maximal educational attainment, social network size, frequency of leisure activities and physical exercise. The authors used structural equation modeling to extract a latent factor combining the contribution of all traditional CR proxies, except bilingualism. Subsequently, they used linear mixed modeling to test whether bilingual experience mitigated the contribution of these traditional CR proxies to executive performance in their sample of senior individuals. Increasing levels of bilingual experience progressively mitigated the positive contribution of these factors, to the point that, at high levels of L2 proficiency, bilingualism was the only factor to exert a positive effect on executive performance.

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These findings suggest that bilingualism may play a unique role in favoring the maintenance of optimal cognitive performance during senescence, spanning beyond the contribution of other traditional CR proxies.

3. Conclusion

Having discussed reasons supporting the claim that bilingualism may play a unique role in contributing to CR, we would like to conclude by briefly highlighting the concrete socio-economic relevance of pursuing policies that favor its growth and diffusion. With ever-increasing average life expectancy and, consequently, dementia incidence, and given the unavailability of effective pharmacological treatments, prevention and mitigation of cognitive aging via lifestyle choices might constitute, at present, the best available option. Mitigating the global impact of dementia could mean a remarkable relief for health expenditures worldwide. Indeed, when reviewing the costs of dementia, the figures appear astounding: in 2016, the global expense linked with dementia was estimated to near a trillion dollars (Xu et al., 2017). In the US alone, dementia care requires more than 300 billion dollars yearly (Wong, 2020). Beyond economic implications, one has to consider the significant amelioration of quality of life that improving the rate of successful aging could grant. Millions of elderly individuals worldwide, alongside their families and caregivers, could considerably improve the quality of their lives, finally benefitting from the advances of healthcare in full fashion.

To reach these goals, it is important to individuate current gaps and possible future directions of this interesting field of research. For instance, to better unveil the mechanisms underlying bilingualism-induced benefits for aging, it is of crucial importance to increase the number of longitudinal and test-retest investigations, which allow to soundly establish causal effects and reduce possible confounds. Also, studies comparing different factors underlying cognitive reserve – such as bilingualism vs physical activity or bilingualism vs cognitive stimulation etc. – would be useful to single out the power of each contributor to cognitive reserve.

Of equal importance are investigations at the MICROSCOPIC level of neurotransmitter/molecular mechanisms underlying bilingualism-induced successful aging. For this purpose, we invite researchers to employ techniques such as in vivo Magnetic Resonance Spectroscopy (MRS), i.e., a non-invasive analytical technique that allows to investigate metabolic changes in the human brain (such as changes in the concentration of neurotransmitters resulting from life experiences). Both types of investigation, longitudinal and microscopic-focused, require a great deal of interdisciplinarity as well as conspicuous funding. Thus, to further explore a promising research avenue that could greatly benefit both individuals and public institutions, it is crucial to spread the awareness about bilingualism and aging research among the general audience as well as policy makers and grant-awarding agencies.

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