Bilingualism predicts executive-function resilience after COVID-19 in aging

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Abstract

Bilingualism has been associated with enhanced executive functions (EFs), particularly attentional control, and may confer protection against cognitive decline in older age. At the same time, the COVID-19 pandemic has emerged as a factor negatively affecting EF in older adults. Bilingualism might offer resilience against these COVID-related cognitive declines, especially in late adulthood, by bolstering cognitive reserve. The present study collected data from 312 community-dwelling individuals spanning the adult lifespan (aged 18-80) to address two goals. Goal 1 was to identify a latent structure linking bilingualism and EF across the adult lifespan, using a continuous multivariate approach to help resolve controversies in the literature. Goal 2 was to determine whether bilingualism can protect against post-COVID EF decline in the most vulnerable older age group. We used partial least squares correlation (PLSC) analysis to extract latent relationships between multiple bilingual experience measures (and relevant covariates) and a battery of EF task outcomes. Results revealed that individuals with greater bilingual experience (earlier L2 age of acquisition and greater L2 proficiency) showed a multivariate association with executive-function measures, with the most consistent behavioral expression observed in task-switching performance. Earlier L2 AoA was most robustly associated with better non-verbal task-switching performance amongst older adults reporting a history of COVID, even when modeling COVID burden continuously (i.e., number of infections and recency of last infection). These findings demonstrate that bilingual experience contributes to resilience in attentional control under flexible task-switching demands in older adults even in the context of COVID-19.

Keywords: bilingualism; executive functions; cognitive reserve; aging; COVID-19; partial least squares

Significance Statement

Millions caught COVID-19; some report lingering “brain fog.” We asked whether lifelong bilingual experience relates to resilience in executive function, particularly with aging. Across 312 adults aged 18–80, multivariate analyses identified a latent pattern linking earlier second-language acquisition and greater proficiency to stronger executive function across tasks. In older adults, regression models showed that the relationship between COVID-19 history and task-switching performance depended on second-language age of acquisition: COVID-related differences in switch cost were larger among later L2 acquirers but minimal among earlier L2 acquirers. These findings provide moderation-based evidence consistent with cognitive-reserve models of aging and suggest that bilingual experience may relate to resilience in attentional control under flexible task-switching demands following illness.

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Converging evidence indicates that lifelong bilingualism can positively influence domain-general attentional control processes expressed across tasks throughout the lifespan (Adesope et al., 2010; Bialystok, 2017; Grundy, 2020; Grundy & Timmer, 2017; Ware et al., 2020). Bilingual individuals, on average, have shown better performance on tasks that place demands on attentional control, such as ignoring irrelevant information (Bialystok et al., 2004; Costa et al., 2008, 2009; Wimmer & Marx, 2014), switching between tasks (Prior & MacWhinney, 2010; Ward, & Awani, 2024; Wiseheart et al., 2013), and updating working memory (Jiao et al., 2019; Macnamara & Conway, 2014), although these effects tend to be modest in size. In fact, meta-analyses report a small but reliable positive effect of bilingualism on performance in tasks that recruit attentional control (e.g. Adesope et al., 2010; Donnelly et al., 2019; Grundy & Timmer, 2017; Gunnerud et al., 2020; Monnier et al., 2022; Ware et al., 2020), an effect size similar to that observed for other enriching activities like aerobic exercise on cognition (Colcombe & Kramer, 2003; Smith et al., 2010). Bilingualism has been discussed as a contributor to cognitive reserve, alongside factors such as education and occupational complexity (Cabeza et al., 2018; Stern, 2009; 2012; 2020), physical exercise (Colombe & Kramer, 2003; Smith et al., 2010), IQ (Kremen et al., 2022), and musical training (Hanna-Pladdy & MacKay 2011; Nogueira et al., 2022; Wolff et al. 2023). In contemporary frameworks, cognitive reserve is not defined as superior cognitive performance per se, but rather as reduced translation of a stressor or neuropathological burden into cognitive impairment (i.e., moderation of brain–behavior relationships; Stern et al., 2020; Kremen et al., 2022). In support of reserve-based interpretations, studies have found that bilinguals can experience neurodegenerative pathology yet maintain cognitive functioning longer than monolinguals. For example, bilingual older adults tend to manifest symptoms of dementia roughly 3–5 years later than monolinguals with equivalent neuropathology (Alladi et al., 2013; Bialystok et al., 2007; Craik et al., 2010; meta-analyses in Anderson et al., 2020; Brini et al., 2020; Chen et al., 2022; Paulavicius et al., 2020; Li & Coretta, 2025). Berkes et al. (2021) further showed that cognitive performance was better in bilinguals than monolinguals when the groups were matched on brain health using white matter integrity and on background variables using sex, age, and education. Bilingualism is also believed to contribute to functional connectivity changes across the lifespan (Anderson, 2023; Jafari et al., 2021). These structural and functional changes are consistent with the idea that bilingual experience may contribute to reserve-relevant mechanisms that buffer cognitive outcomes under increased burden (Bialystok, 2021; DeLuca et al., 2020; Grundy, Anderson, & Bialystok, 2017; Pliatsikas, 2020).

In the present study, we focus on attentional control as a core component of executive function. Under an attentional adaptation framework (Bialystok, 2017, 2024; Bialystok & Craik, 2022) effects of bilingual experience are not expected to manifest uniformly across all executive-function measures, but rather to emerge most clearly in tasks that directly recruit dynamic control allocation and flexible updating under competing demands.

Despite these positive findings, the literature on bilingualism and EF has been marked by considerable controversy. Many studies using between-group designs (monolinguals vs. bilinguals) have reported inconsistent results; some observing that bilinguals outperform monolinguals on EF tasks, and others finding no differences or even the reverse pattern of findings. Several reviews and meta-analyses endorse the presence of bilingualism-related changes to EF (e.g., Bialystok, 2017; Grundy, 2020; Van den Noort et al., 2019; Yurtsever et al., 2023), while other large-scale analyses have failed to detect reliable effects of bilingualism on

EF (Bao et al., 2024; Donnelly et al., 2019; Lehtonen et al., 2018). At least one population study of over 11,000 adults (but matched for confounds, only 7% of the total sample was used – N = 744; see also Luk et al., 2020, for commentary on the study) found no general cognitive benefit for bilinguals on a broad battery of EF tasks (Nichols et al., 2020). Some scholars have argued that positive findings may reflect publication bias or specific task choices rather than a broad cognitive effect (de Bruin et al., 2015; Paap & Greenberg, 2013). Given this debate, there is a need for approaches that can capture subtle effects of bilingualism on cognition that might be missed by traditional analyses (Gullifer & Titone, 2021; Luk & Bialystok, 2013; Surrain, & Luk, 2019; Yurtsever et al., 2023). One such approach is to examine multivariate, continuous relationships between bilingual experience and cognitive performance, rather than relying solely on extreme group comparisons or single-task outcomes (Deluca et al., 2019; Grundy, Pavlenko, & Bialystok, 2020; Privitera, Momenian, & Weekes, 2023; Yurtsever et al., 2025). By considering multiple dimensions of bilingualism (e.g., age of acquisition, proficiency, usage, exposure, balance, switching frequency) and multiple task-based measures that vary in attentional control demands simultaneously, we can identify latent structures that represent the shared variance between bilingualism and attentional control expressed across tasks (Anderson et al., 2021; Call, 2025; Li et al., 2021). This multivariate strategy may reveal consistent patterns of association even if any single task provides only a partial or weak behavioral expression of attentional control (Krishnan et al., 2011). The first goal of the present study, therefore, was to use a data-driven, continuous multivariate analysis to uncover the latent relationship between bilingual experience and attentional control as expressed across multiple tasks in a large sample of adults spanning early to late adulthood (Goal 1).

A second line of inquiry motivating this study stems from recent evidence on the cognitive impacts of COVID-19. The COVID-19 pandemic has had significant neurological and cognitive consequences, especially for older adults. SARS-CoV-2 infection has been linked to declines in attention, memory, and executive abilities in older populations (Corbett et al., 2023; Douaud et al., 2022; Hampshire et al., 2021). For instance, large population-based longitudinal studies have observed that older adults who contracted COVID-19 often experience persistent deficits in working memory capacity (Corbett et al., 2023) and general cognitive function (Demmer et al., 2025; Liu et al., 2024) long after recovery. These findings raise concerns that COVID-19 may accelerate age-related cognitive decline, particularly in functions that rely heavily on attentional control and flexible task coordination that are crucial for independent living. However, individuals differ widely in their cognitive resilience to COVID-related insults; some recover cognitive function over time, while others show prolonged impairments. This variability suggests that protective factors or reserves might mitigate the cognitive impact of COVID-19 in some people.

Bilingualism could be one such protective factor. Given bilingualism's association with enhanced attentional control and cognitive reserve (Abutalebi et al., 2015; Bialystok, 2021; Gold et al., 2013; Stevens et al., 2023; Schweitzer et al., 2012; Voits et al., 2024), it is plausible that lifelong bilingual experience buffers against cognitive decline triggered by COVID-19, especially in older adults who are most vulnerable. In other words, older highly bilingual individuals might retain better executive functioning post-COVID than older monolinguals and less proficient bilinguals due to the cognitive reserve accumulated through managing two languages. Meta-analyses have shown that cognitive reserve is associated with positive cognitive outcomes in COVID patients (r_{sp} =.29), and among high reserve individuals, cognitive deficits are reduced by 33% compared to lower reserve individuals (Foreman et al., 2025). Although bilingualism is recognized as a likely cognitive reserve factor, no research to date has directly examined its role as a moderator of COVID-19's cognitive effects.

The second goal of this study (Goal 2) was therefore to explore whether bilingualism provides measurable protection for attentional control as expressed in non-verbal task performance in older adults with a history of COVID-19. We were particularly interested in older adults (60+ years), as this group is at highest risk for severe COVID-19 outcomes and age-related cognitive decline. We asked whether, within this older cohort, those with stronger bilingual backgrounds, who have greater cognitive reserve via this proxy experience, would perform better on executive tasks following COVID infection, even after accounting for other factors like education and general cognitive status.

In summary, the present study investigates two primary questions. First, we test whether a continuous multivariate framework (partial least squares correlation; PLSC) can identify a stable latent association between bilingual experience and attentional control across the adult lifespan, moving beyond traditional monolingual–bilingual group contrasts and univariate relationships. Second, we examine whether bilingual experience moderates COVID-related differences in executive functioning in older adults. This approach is novel in simultaneously modeling multiple bilingual dimensions and executive outcomes while leveraging COVID-19 exposure as a natural stressor to evaluate reserve-related hypotheses.

We had two primary hypotheses. First, we predicted that bilingual experience, operationalized multidimensionally and modeled using a continuous multivariate framework (PLSC), would show a reliable latent association with attentional control on non-verbal task performance across adulthood. Because bilingualism is heterogeneous, we did not specify a priori which bilingual dimensions would contribute most strongly to the latent structure. Second, we predicted that bilingual experience would moderate COVID-related differences in attentional control in older adults across tasks (i.e., differential susceptibility under COVID exposure), consistent with moderation-based definitions of cognitive reserve.

Methods

Participants

A total of 312 adults (age range 18–80 years) were recruited. Participants were community-dwelling individuals recruited via Prolific, an established and reliable online platform for high-quality data-collection (Peer et al., 2017; 2021), and studies were created and run on psytoolkit.org (Stoet, 2010; Stoet, 2017). Participants self-selected by enrolling via Prolific in response to a study advertisement indicating that participation was restricted to bilingual individuals and that the study involved a language-background questionnaire, an online-adapted MMSE screening, and four brief cognitive tasks assessing inhibition, task switching, attention, and memory. Eligibility therefore required self-reported bilingual language experience in addition to English proficiency and use of a computer with audio. The first wave of data collected aimed to extract a latent bilingualism-EF multivariate structure, but because most of these individuals were young adults, we selectively recruited individuals between 30-59 and 60+ years of age in the next wave so that the distribution would be more representative of participants across the adult lifespan. Final numbers included 84 younger adults (18-29 years of age), 124 middle-aged participants (30-59 years of age), and 104 older-aged participants (60+ years of age). All participants completed a background questionnaire and a series of cognitive tasks. Older and middle-aged participants additionally underwent a health and cognition screening, using an online-adapted version of the Mini-Mental State Examination (MMSE;

Folstein et al., 1975). Because testing was conducted remotely, the orientation-to-place items, multi-step motor command items, reading/writing items, and the pentagon-copying item were not included. The resulting version had a maximum score of 19 points. MMSE scores showed adequate variability ($M = 14.7$, $SD = 2.9$, range = 4–19), indicating that the measure was not restricted to ceiling values. As part of the background survey, participants reported their language history and usage, as well as any history of COVID-19 infection. For those reporting a positive COVID-19 history, we requested they report the number of times they had been diagnosed with COVID-19, the time (in months) since their most recent, as well as first, infection; for analysis, these were treated as continuous measures of COVID burden.

Several control variables were also included. Labor force status was coded categorically as: Unemployed, Homemaker/Caregiver, Retired, Employed/Self-employed, Student. Participant education was not collected in the initial survey wave. However, it was added later by re-contacting participants to obtain the highest level of education where possible. Education was coded categorically as: Less Than High School, High School, College/University, Graduate/Post-Graduate. Because education was introduced after initial data collection, this variable is missing for a subset of participants and was included as a Missing category in any analyses including this variable to avoid substantial data loss. Education data were missing for a substantial subset of participants because this measure was added after the initial survey wave. In the middle-aged and older analytic sample, missingness was not significantly associated with COVID status (χ^2 $p = .189$) or age group (χ^2 $p = .171$). Missingness was also not significantly associated with L2 proficiency, L2 exposure, L2 usage, or code-switching frequency ($ps > .076$), but it was associated with L2 AoA ($p = .0025$). For this reason, participant education was retained in the fully adjusted moderation model using a missing-category approach, and we also report a reduced model excluding participant education and labor-force status to verify that the COVID × L2 AoA moderation result was not dependent on this specification.

To provide additional enrichment/socioeconomic-relevant controls that were available for a larger proportion of the sample, we also derived occupational enrichment variables from participants' self-reported occupation, including occupational class and occupational complexity scores. Occupational complexity has been associated with better later-life cognitive performance, including measures of executive function and global cognition, even after accounting for formal education and other demographic factors (Smart et al., 2014; Pool et al., 2016; Soh et al., 2023).

All participants provided informed consent, and the study was approved by the institutional review board at Iowa State University.

Bilingualism Measures

Bilingualism variables were assessed via self-report. Key measures included: (a) L2 Age of Acquisition (AoA) – the age at which the individual began learning their second language; (b) L2 Proficiency – self-rated proficiency in speaking the second language (on a scale, with 10 indicating native-like fluency); (c) L2 Usage – the average proportion of time the individual uses the L2 in everyday life (across speaking, listening, reading, writing contexts); (d) L2 Exposure – cumulative exposure to L2 (e.g., years of formal/informal immersion); (e) L1–L2 Balance – an index from 1 to 3 indicating how balanced the individual is between their first and second language (higher values meaning more balanced bilingualism); and (f) Language Switching Frequency – how often the person switches between languages in daily interactions (rated 1 = never to 5 = always). These measures capture distinct facets of bilingual experience, from early-life exposure to current use patterns. All bilingualism questions were drawn from the Language and Social Background Questionnaire (LSBQ; Anderson et al., 2018), a validated instrument for quantifying degree of bilingualism in diverse populations. Socioeconomic status was approximated by the highest education level of the participant's mother (coded on a 1–5 scale), as a control variable.

Executive Function Tasks

All executive function (EF) tasks were readily available from psytoolkit.org (Stoet, 2010; Stoet, 2017), a widely used and reliable online data-collection platform. EF outcomes were derived from a battery of cognitive tasks that varied in their demands on attentional control: task-switching performance, interference resolution, and working memory. For task-switching performance, participants performed a task-switching paradigm in which they alternated between two simple classification tasks on each trial (e.g., judging one of two attributes of a stimulus). Each trial was either a repeat of the same task as the previous trial or a switch to the other task rule, and performance typically declines on switch trials. We obtained task-switching performance metrics including mean accuracy and response time for repeat trials vs. switch trials, and specifically calculated the switch cost in accuracy (accuracy on repeat trials minus accuracy on switch trials) and the switch cost in reaction time (RT on switch trials minus RT on repeat trials) for each participant. Smaller switch cost values indicate better switching ability (i.e., less performance decrement when switching tasks). Participants were instructed about both task rules and practiced the switching procedure before completing the mixed-task block.

For *interference resolution*, we employed two classic measures: a Go/No-Go task and an Eriksen flanker task. In the Go/No-Go task, participants saw a series of stimuli and were required to respond (press a key) for frequent "Go" signals and withhold their response for infrequent "No-Go" signals. We used an implementation in which the words "Go", or "No-go" were presented on each trial. Participants had to press the spacebar within 2 seconds when "Go" appeared, and make no response when “No-go” appeared. This task was made challenging by having many more Go trials than No-Go trials (in a 4:1 ratio) to establish a prepotent tendency to respond. Performance was indexed by Go trial accuracy/RT and No-Go trial accuracy, where higher No-Go accuracy reflects better response inhibition. In the flanker task, participants saw an array of five arrows and had to identify the direction of the central (target) arrow by pressing the corresponding key (e.g., press “A” if the middle arrow pointed left, “L” if it pointed right). On congruent trials, all arrows pointed in the same direction, whereas on incongruent trials, the flanking arrows pointed opposite to the target. We recorded flanker effect scores in accuracy (congruent minus incongruent accuracy) and RT (incongruent minus congruent RT), where a smaller flanker effect indicates better interference control. There were an equal mix of congruent and incongruent trials presented randomly, following on-screen instructions and practice.

For *working memory*, participants completed a spatial Corsi block span task implemented on the computer. This task is analogous to the classic block-tapping test developed by Corsi (1972): a set of nine blank squares (blocks) is displayed, and on each trial a sequence of blocks lights up one by one in a random order; the participant must then click those blocks in the same order. Sequence lengths start short and gradually increase. If the participant correctly reproduces the sequence, the length increases on the next trial; if they make an error, they are given one more attempt at the same length, and if a second error occurs, the task terminates. The Corsi span score is defined as the longest sequence length the participant can accurately recall at least once. This score reflects visuo-spatial working memory capacity. Participants received visual feedback (e.g., a smiley face for a correct sequence) and verbal prompts (a recorded voice saying “go”) to aid timing in the task.

Analysis Overview

We employed partial least squares correlation (PLSC; Krishnan et al., 2011) analysis to identify latent relationships between the set of bilingualism-related predictors and the set of EF outcome variables. PLSC is a multivariate technique that finds linear combinations (latent components) of two sets of variables that are maximally correlated with each other. In our implementation, one set (predictors) included the bilingualism measures and relevant covariates (see below), and the other set (outcomes) included the EF task measures. PLSC yields one or more latent variables (LVs); each LV consists of a weighted pattern of predictors and a corresponding weighted pattern of outcomes, with an associated covariance (or correlation) between those weighted composites. The statistical significance of each LV is evaluated via permutation testing, and the reliability of individual variable contributions (saliences) to the LV is assessed via bootstrapping (providing confidence intervals for each weight). This approach allowed us to determine whether a reliable multivariate association exists between bilingual experience and EF performance, and to interpret which specific variables drive that association.

Goal 1 Analysis (Adult Lifespan PLSC)

We first conducted a PLSC on the full sample of 312 participants to address Goal 1. Importantly, bilingualism was not treated as a single composite score; instead, multiple dimensions of bilingual experience (AoA, proficiency, usage, exposure, balance, switching frequency) were entered simultaneously, allowing differential contributions to emerge within the latent structure rather than creating a composite bilingualism score. Two versions of this analysis were run: (1) a full-model PLSC including the bilingualism variables plus Age and SES as covariate predictors, and (2) a bilingual-only PLSC including only the six bilingualism variables (AoA, proficiency, usage, exposure, balance, switching frequency) as predictors. In both cases, the outcome set included the EF measures (Switch Cost – accuracy, Switch Cost – RT, Flanker

Effect – accuracy, Flanker Effect – RT, No-Go accuracy, Go accuracy/RT, and Corsi span). The inclusion of age and SES in the first model allowed us to test whether any bilingual-EF relationship is independent of basic demographic factors; the second model (reported in Supplementary Materials) served to verify that the latent patterns observed are indeed driven by bilingual variables and not an artifact of including covariates. We used 1,000 permutation tests to determine LV significance (i.e., whether the covariance explained by an LV is greater than random chance) and 1,000 bootstrap resamples to derive 95% confidence intervals for the salience of each variable on the LV. "Reliable" or "stable" contributors to an LV were defined as those with bootstrap confidence intervals not crossing zero.

Goal 2 Analyses (Bilingualism & COVID-19 in Older Adults)

To address Goal 2, we carried out two sets of analyses focusing on middle-aged and older adults and the impact of COVID-19:

Goal 2a – Effects of bilingualism, age, and COVID status on EF.

We ran a PLS similar to Goal 1 by examining L2 predictor variables on EF outcomes. We again included SES and Age in the model as predictors, but also included MMSE, and whether the participant had a history with contracting Covid (1 = yes) or not (0 = no) as additional predictors.

In addition, to directly test attenuation (i.e., whether bilingual experience moderated COVID-related EF differences), we conducted regression-based moderation analyses focusing on the two EF outcomes that loaded reliably in Goal 1 (switch-cost accuracy and Corsi span). In these models, COVID status, L2 AoA, and their interaction (COVID × L2 AoA) were entered as predictors. Fully adjusted models included Age, mother's education (SES), MMSE, labor force status (categorical), and participant education (categorical; missing retained as a separate category due to follow-up collection). Reduced models excluding labor force status and participant education were also run to retain the larger available sample. All continuous predictors (L2 AoA, Age, mother's education (SES), and MMSE) were mean-centered prior to computing interaction terms. Categorical predictors (labor force status and participant education) were dummy-coded. Regression models were estimated using ordinary least squares with HC3 robust standard errors. To further evaluate the robustness of this effect, we conducted a sensitivity analysis excluding MMSE from the model.

Goal 2b - Continuous PLSC within COVID-positive participants.

We next focused on the subset of participants who had contracted COVID-19 to test within-group sensitivity to different Covid experience variables. We ran a PLSC where the predictor set included the bilingualism variables plus Age, SES, and baseline MMSE score, as well as three COVID-19 burden measures (number of COVID infections, and months since the most recent, as well as first, infection). The outcome set again included the EF measures. Permutation testing and bootstrapping were applied as before. This analysis allowed us to determine whether the bilingual effect in EF remains detectable in those with COVID, even when accounting for the severity and timing of illness and baseline cognitive health. For completeness, we also conducted a parallel PLSC on the COVID-positive subgroup using only the bilingual predictors (excluding age, SES, MMSE), which is reported as a supplementary figure to verify that including covariates did not obscure any bilingual effects. Prior to analysis, all continuous variables were z-scored.

Results

For transparency and reproducibility, all data are available on Figshare.com at the following link: https://doi.org/10.6084/m9.figshare.27226458. Figure 1 demonstrates the relationship between the bilingualism variables collected and analyzed in the present study. Importantly, all VIFs for L2 variables were less than 1.8, suggesting that multiple collinearity was not a concern.

[Figure 1 about here]

Goal 1: Latent Bilingualism–EF Relationship Across the Lifespan

The PLSC on the full sample revealed a significant latent variable (LV1) linking bilingual experience to EF outcomes (permutation $p < 0.001$). This LV1 accounted for a sizable portion of cross-block covariance (83.5%; Figure 2A) and was reliable by permutation test. Figure 2B illustrates the pattern of weights for this LV1 on both the bilingual predictor variables and the EF outcome measures. On the predictor side, the strongest contributors were L2 Age of Acquisition (with a negative weight) and L2 Proficiency (with a positive weight). Age also contributed reliably to LV1, with a strong negative loading. SES and other bilingual variables did not load reliably. Notably, L2 exposure did not load reliably on the latent variable, indicating that cumulative duration of bilingual engagement did not account for the observed bilingualism–EF association in this dataset. On the outcome side, the most pronounced contributors were Task-Switching Cost (Accuracy, and to a lesser extent, RT) and Corsi Span, which both had robust weights (the 95% CI of their saliences did not include zero). Other EF measures (flanker and go/no-go outcomes) did not show reliable contributions on LV1. In other words, the positive bilingualism-EF latent factor we identified was most evident for task-switching and working memory capacity paradigms, in which greater L2 proficiency and earlier L2 AoA led to smaller switch costs and greater working memory span contributions to the latent structure.

[Figure 2 about here]

To ensure that our findings were not an artifact of controlling for age and SES, we compared the above results to the supplementary bilingual-only PLSC (excluding Age and SES). The bilingual-only analysis (Supplementary Figure S1) likewise yielded a significant LV1 with a very similar pattern: earlier L2 AoA and greater proficiency were linked to smaller switch costs in accuracy (repeat minus switch accuracy; lower values indicate better switching performance) (same direction for RT, but 95% CIs now crossing zero) and greater working memory capacity. The congruence between the models indicates that the bilingual-EF latent structure is not driven by age or socioeconomic differences. In other words, whether or not we statistically control for age and SES, a similar bilingualism-related EF factor emerges. This adds confidence that our LV reflects a genuine association between bilingual experience and executive function. These reliable predictors and outcomes (L2 proficiency, L2 AoA, switch-cost accuracy, working memory span) were therefore carried forward as key outcomes of interest in subsequent analyses focused on COVID effects. Although Corsi span loaded reliably on the latent dimension in Goal 1, subsequent moderation analyses indicated that bilingual-related attenuation under COVID exposure was specific to task-switching performance. This pattern suggests that not all measures contributing to shared multivariate variance are equally sensitive to adaptive control mechanisms under increased demand.

In summary, Goal 1 results revealed a stable latent dimension in which bilingualism (particularly early L2 AoA and greater L2 proficiency) correlates with executive-function outcomes, with the most consistent and reliable expression in task-switching performance. This finding addresses the field’s controversy by demonstrating that when EFs are considered in aggregate and bilingual experience is treated continuously, a reliable multivariate association can be detected. Notably, the association appears graded, such that greater or earlier bilingual engagement was associated with more efficient executive performance across the reliably loading measures. This pattern helps reconcile prior mixed results by highlighting that the effects of bilingualism on EF, while modest, are reliable when multiple EF domains and a broad spectrum of bilingual experiences are analyzed together.

Goal 2: Bilingualism and COVID-19 Effects in Older Adults

Table 1 presents participant characteristics for the analyses used in goal 2.

Table 1 – *Participant characteristics for middle-aged and older participants stratified by COVID status. Values are means with standard deviations in parentheses. Switch-cost accuracy is computed as Repeat − Switch (lower values indicate better performance). Ns reflect the analytic subgroup available for each COVID-status x age-group comparison shown in the table; model-specific Ns are reported separately in the corresponding Results sections.*

Variable	Middle-aged COVID+	Middle-aged COVID−	Older COVID+	Older COVID−
N	44	53	33	61
Age	40.55 (8.41)	39.11 (7.65)	66.67 (3.97)	66.51 (6.09)
L2 AoA	7.73 (6.16)	7.00 (7.63)	12.64 (14.27)	12.05 (12.91)
L2 Proficiency	3.36 (1.04)	3.61 (0.97)	4.02 (1.25)	4.05 (1.16)
MMSE	15.16 (2.89)	14.40 (2.55)	13.88 (3.36)	15.20 (2.88)
Switch-cost accuracy	0.08 (0.11)	0.08 (0.11)	0.12 (0.15)	0.12 (0.12)
Corsi span	4.02 (2.72)	1.98 (2.39)	2.25 (2.52)	1.80 (2.30)

Goal 2a – Effects of bilingualism, age, and COVID-19 status on EF. We first followed the same approach that we followed in Goal 1 and put all predictors and all outcomes in the analysis, which yielded a significant LV1 (p = 0.02). However, all bootstrapped confidence intervals for all the predictor and outcome variables crossed zero, making the interpretations per variable unreliable (see Supplementary Figure S2). To increase sensitivity and circumvent this, we ran *two separate sets of analyses*:

1) *First*, we ran a PLSC as before but restricted it to the reliable L2 experiences and outcome variables identified in Goal 1, which included: L2 AoA, L2 Proficiency, Switch Cost ACC, and Corsi scores. We also included Age, SES, and MMSE as additional predictors, as in Goal 1, to rule these out as primary contributors to any outcomes associated with L2 AoA or L2 proficiency. Figure 3 shows the outcome of this analysis. The significant LV1 (p = 0.003) demonstrated that younger adults, greater MMSE scores, and earlier L2 AoA all reliably predicted better working memory Corsi scores and smaller switch cost accuracy scores, in line with expectations. Counter to expectations, a history with Covid in this model was positively predictive of better switch cost accuracy and greater working memory scores.

Although COVID-19 status showed a positive weight on this LV, PLSC weights alone do not test moderation or attenuation of COVID-related EF differences. Therefore, to directly evaluate whether bilingual experience attenuates COVID-related EF differences, we conducted regression-based moderation analyses.

2) The *second* sensitivity check ran four independent PLS analyses according to group (History with Covid, No history with Covid) and age (middle-age: 30-59 years old, older age: 60 years +). Age-stratified analyses were conducted as a sensitivity check to examine whether the bilingualism–EF latent structure was detectable within theoretically meaningful developmental bands, given prior evidence that bilingual effects may be more pronounced in later adulthood. These subgroup analyses are descriptive and complement, rather than replace, the interaction-based moderation models. The results of these

analyses are illustrated in Supplementary Figure S3. Older adults with a history of COVID-19 showed the only significant bilingual-EF latent factor, indicating the strongest association between bilingualism and EF performance was in this group. In contrast, older adults with no COVID history and the middle-aged groups (with or without COVID) showed no reliable association (note that middle-aged participants overall performed at a high level on EF tasks regardless of bilingualism, which might have reduced variance to observe any effect). Put simply, the subgroup PLS analyses suggest that the bilingualism–EF latent pattern was most detectable in older adults with a history of COVID-19, whereas the other subgroups did not show a reliable LV under the same specification. Because subgroup PLS analyses are descriptive, we treat these findings as supportive visualization and rely on the regression-based COVID × bilingualism interaction models for inferential tests of moderation (Goal 2b). These results are consistent with a cognitive-reserve interpretation in which greater bilingual experience is associated with smaller COVID-related differences in executive switching performance among older adults.

[Figure 3 about here]

Goal 2b – Regression-Based Moderation Analyses.

Switch-Cost Accuracy: In a fully adjusted linear regression model including Age, SES, MMSE, labor force status, and participant education (coded categorically with missing retained), the COVID x L2 AoA interaction was significant (N = 158; b = 0.00722, SE = 0.00171, $p = 2.45 \times 10^{-5}$). The main effect of COVID was not significant ($p = 0.459$). This interaction indicates that the relationship between COVID status and switch-cost performance depended on L2 age of acquisition. Participants who acquired their second language later showed larger switch costs when COVID-positive, whereas those who acquired their second language earlier showed little to no COVID-related difference in switching performance (Figure 4).

[Figure 4 about here]

To confirm that this effect was not dependent on the reduced sample required for employment controls, we tested a model including Age, SES, and MMSE but excluding labor force and education variables ($N = 191$). The COVID × L2 AoA interaction remained significant ($b = 0.00539$, $SE = 0.00209$, $p = .0099$). To further evaluate the robustness of this effect, we conducted a sensitivity analysis excluding MMSE from the model. The COVID × L2 AoA interaction remained significant ($b = 0.0059$, $SE = 0.0018$, $p = 0.001$), indicating that the moderation effect does not depend on the inclusion of MMSE as a covariate. These robustness checks are particularly important given that participant education included missing-category coding; however, the consistency of results across models indicates that the observed moderation effect is not driven by these aspects of the data structure.

Corsi Span: In contrast, in the fully adjusted model ($N = 158$), the COVID × L2 AoA interaction was not significant for Corsi span ($b = -0.0481$, $SE = 0.0354$, $p = 0.174$). A significant main effect of COVID status was observed ($b = 1.30$, $SE = 0.44$, $p = 0.003$), indicating higher Corsi scores among individuals reporting COVID history, and this effect was not moderated by bilingual experience.

This divergence between task-switching and Corsi span outcomes is consistent with an adaptation-based account of control systems. Task-switching directly indexes dynamic control allocation under changing demands (Botvinick & Cohen, 2014; Monsell, 2003; Shenhav et al., 2013), whereas Corsi span reflects capacity limits that are not contingent on moment-to-moment control reconfiguration (Engle, 2002; Kane & Engle, 2002; Unsworth & Engle, 2007). Under this framework, bilingual experience is expected to most strongly influence tasks that recruit adaptive control processes, particularly under increased demand or stressor exposure, rather than producing uniform effects across all executive-function measures, consistent with the well-established task impurity problem in executive-function measures (Friedman & Miyake, 2017; Miyake et al., 2000). The absence of a corresponding moderation effect for Corsi span therefore does not contradict a reserve-based interpretation, but instead highlights the specificity of the effect to control processes most sensitive to experience-dependent adaptation.

Goal 2c – PLSC within COVID-positive participants.

Figure 5 shows the continuous analysis within the 84 individuals who had contracted COVID-19. We performed a PLSC to directly assess the multivariate relationship between bilingualism and EF in this subset. This analysis included Age, SES, and MMSE as covariates, and COVID-19 burden measures (number of infections and time since most recent infection) among the predictors. The PLSC yielded a significant LV1 ($p = 0.002$ by permutation), which was largely consistent with the pattern from Goal 1. On this LV, earlier L2 AoA again emerged as a strong predictor (negative weight) and was associated with better EF outcomes – notably a smaller task-switching accuracy cost (negative weight) and higher working memory span (positive weight). The contribution of L2 proficiency may have been overshadowed by L2 AoA in this subgroup analysis (likely because many COVID-positive older adults generally had uniformly high L2 proficiency, whereas their L2 AoA varied more). Crucially, this LV remained significant even with Age, SES, and MMSE in the model, suggesting that the bilingualism-related boost cannot be explained by younger COVID patients or by healthier individuals selectively being bilingual. MMSE itself showed a positive weight in the predicted direction (better MMSE = smaller switch costs and greater working memory spans), but this factor was not reliable given that the confidence interval overlapped with zero.

[Figure 5 about here]

Perhaps somewhat counterintuitively, the number of COVID infections a person had was negatively associated with switch cost accuracy and working memory span outcomes on this LV, indicating that participants reporting multiple COVID infections tended to have *smaller* switch costs (i.e., better switching performance) and *greater* working memory scores than those who had fewer infections. The time since most recent infection (and time since first COVID infection, since most only had COVID once) had a near-zero weight, suggesting that recency of infection did not strongly relate to EF performance after accounting for other factors. In contrast, age in this analysis continued to show a substantial negative weight on the LV, underscoring that age-related variance in EF was still present even among the COVID-positive subset.

To double-check the above results, we ran a supplementary PLSC on the COVID-positive subgroup using only bilingual predictors (omitting Age, SES, MMSE). The pattern of that analysis (see Supplementary Figure S4) echoed what we found: earlier L2 AoA was linked to smaller switch costs and higher memory scores among those who have had COVID. The similarity of results with and without covariates strengthens the conclusion that the bilingual effects are robust within the COVID-positive group.

In summary, Goal 2 results indicate that the bilingualism x COVID interaction for switch-cost accuracy was most evident in older adults. Regression-based moderation analyses demonstrated that the COVID x L2 AoA interaction was specific to EF switching tasks and remained significant after controlling for age, SES, MMSE, labor-force status, and participant education. Earlier L2 AoA, in particular, was associated with smaller switch-cost differences by COVID status, whereas no moderation was observed for Corsi span. We also found that, contrary to expectation, those who had experienced multiple COVID infections showed no greater EF impairment; they even exhibited slightly better switching and higher working memory performance than those with fewer infections (see also Supplementary Figure S5 for bivariate correlations). This counterintuitive finding likely reflects uncontrolled differences in infection severity, testing access, vaccination status, and selection factors rather than a beneficial effect of repeated infection. Because we did not directly measure infection severity, these patterns should be interpreted cautiously. We elaborate on these points below.

Discussion

The present study yielded two main findings. First, across a large sample of adults spanning early adulthood to old age, we identified a significant latent structure linking bilingualism to executive functions (EF). This latent bilingualism-EF factor was characterized by earlier second-language age of acquisition (L2 AoA) and higher L2 proficiency being associated with better attentional control on tasks used to measure switching and working memory. Crucially, this relationship held even after controlling for age and socioeconomic differences, indicating it is not an artifact of demographic confounds. Second, we found evidence that bilingualism may serve a protective role for cognition in older adults, even after considering

COVID-19 infection history. Earlier L2 AoA was associated with smaller switching costs for those with a self-reported history of COVID-19. The same was not true for those who did not have a self-reported history with COVID. Importantly, this moderation finding complements, rather than contradicts, the general bilingualism–EF association identified in Goal 1. Whereas Goal 1 established a continuous multivariate association between bilingual experience and executive functioning across adulthood, Goal 2 demonstrates that this association becomes most detectable under conditions of elevated cognitive vulnerability (i.e., COVID exposure in older adults), consistent with moderation-based models of cognitive reserve. We discuss each of these points and their implications in turn.

Bilingualism and EF across the lifespan

Our finding of a robust bilingual–EF latent factor provides an important piece of evidence in the long-running debate about whether bilingualism produces cognitive change. By using a multivariate approach (PLSC) that aggregates signal across multiple EF measures, we were able to detect a clear association between bilingual experience and EF, despite the effect being modest in any single measure. This result aligns with prior meta-analytic conclusions that bilingual benefits, while real, are typically small in magnitude (Adesope et al., 2010; Donnelly et al., 2019; Grundy & Timmer, 2017; Ware et al., 2020). It also resonates with theoretical perspectives suggesting that bilingual effects might manifest more strongly at the level of general cognitive processes (like attentional control) rather than in specific narrow tasks (Bialystok, 2017, 2024; Bialystok & Craik, 2022; Chung-Fat-Yim et al., 2017, 2022, 2023; Grundy et al., 2020; Grundy & Chung-Fat-Yim, 2023; Phelps & Bozic, 2025). In our data, bilingualism's effects were evident at the multivariate level for both task-switching and working memory outcomes, but moderation under COVID exposure was specific to task-switching performance, consistent with the view that not all measures contributing to shared executive-function variance are equally sensitive to adaptive control processes under increased demand. Task-switching and working memory both contribute to demanding cognitive performance, but task-switching in particular taps the coordination of multiple control processes. Conditions involving the coordination of multiple control processes, as in task-switching, are those under which group differences between bilinguals and monolinguals have been hypothesized to emerge more reliably (Bialystok, 2017, 2024; Costa et al., 2009; Ware et al., 2020). In contrast, simpler EF measures (like the flanker interference score) did not show a reliable bilingual effect here, consistent with many prior studies that find no group differences on basic inhibitory control tasks (Donnelly et al., 2019; Paap & Greenberg, 2013).

Our findings underscore the importance of considering qualitative differences in bilingual experience: factors like *when* the second language was acquired, the context of acquisition (e.g. simultaneous vs. sequential bilingualism), and lifelong usage patterns may modulate which cognitive domains are affected (Luk et al., 2011; DeLuca et al., 2019; Yurtsever et al., 2023, 2025). Recent studies directly support this idea: different bilingual experiences predict different executive function outcomes. For example, Yurtsever et al. (2025) found that second-language AoA and switching frequency between languages each uniquely predicted performance on specific EF tasks (in their case, mouse-tracking versions of the flanker and Stroop), and that these relations depended on the attentional demands of the task. Such evidence highlights that bilingualism is not a static variable but a complex set of experiences that can interact with task context. Likewise, a recent quantitative analysis of child bilinguals reported that bilingual groups outperformed monolinguals on EF tasks far more often than chance; but also emphasized considerable heterogeneity across studies, suggesting that effect sizes depend on specific participant and task characteristics (Yurtsever, Anderson, & Grundy, 2023). Our multivariate approach captured a *latent* bilingual effect on EF by pooling across multiple measures, which likely increased sensitivity to detect the consistent signal among the noise of task-specific variance. In line with this, we observed what appears to be a dose-response pattern: participants with more intensive or longstanding bilingual engagement (earlier L2 onset, higher proficiency) showed progressively better EF performance. This pattern strengthens the argument for a genuine bilingualism-related effect on cognition, suggesting that the cognitive boosts of bilingualism accrue gradually over time and intensity.

An important theoretical implication of the present findings concerns the distinction between cumulative exposure and developmental timing as mechanisms underlying bilingualism–EF associations. In our data, L2 age of acquisition (AoA) emerged as a robust predictor, whereas cumulative exposure measures did not load reliably in the multivariate analyses. If duration of bilingual engagement were the primary mechanism, one would expect exposure-based measures to show comparable or stronger associations than AoA. The absence of such a pattern instead is more consistent with a developmental timing account, in which early bilingual experience shapes neural and cognitive systems during sensitive periods in ways that later experience does not fully replicate. This interpretation is consistent with neuroimaging evidence demonstrating that the neural organization of a second language is highly sensitive to the timing of acquisition and its interaction with neurodevelopmental or neurological factors (DeLuca et al., 2019; Stasenko et al., 2025).

It is worth noting that some bilingual factors we measured did not show much influence in this study. For example, language switching frequency (how often one code-switches) did not relate strongly to EF performance here. This might be because code-switching, while linguistically interesting, may not impose additional cognitive load if done naturally within bilingual conversation; balanced code-switchers might treat it as a seamless process. L2 usage (daily use proportion) did not emerge as a notable predictor in our analysis, which might be due to most of our bilingual participants being relatively active users of both languages (the range was somewhat restricted). Alternatively, it could suggest that how long and how well one has been bilingual (captured by L2 AoA and proficiency), in our sample, are more critical than how often one uses L2 on a given day for these particular EF tasks. These results encourage a more fine-grained theory of bilingual cognitive effects; specific bilingual experiences likely map onto specific cognitive outcomes (Green & Abutalebi, 2013, 2023). For example, early bilingual immersion might primarily benefit task-switching performance, while continued high proficiency might help keep working memory robust. Understanding these mappings can help clarify why different studies sometimes find different cognitive outcomes associated with bilingualism—they may be tapping into different facets of bilingual experience (Yurtsever et al., 2023, 2025; Grundy, 2020).

From a lifespan perspective, our results also shed light on when bilingual effects are most likely to manifest. The bilingualism–EF association appeared descriptively smaller in middle adulthood and more pronounced in older age (especially among those with COVID exposure); however, formal age x bilingualism interaction tests in the full sample were not significant, and these developmental patterns should therefore be interpreted cautiously. This pattern is consistent with a reserve-based account in which bilingual experience contributes to resilience mechanisms whose behavioral expression may be more detectable under conditions of elevated vulnerability. Importantly, the absence of a strong association earlier in adulthood does not imply that underlying mechanisms are inactive; rather, executive tasks can be supported by multiple solution pathways that may mask small effects in correlational data. In line with this reasoning, many studies have found larger bilingual effects in older adults than in younger adults (Bialystok et al., 2004; Bialystok et al., 2014). Our inclusion of middle-aged adults helps fill a gap in the literature and indicates that bilingual benefits might be a form of resilience that "kicks in" as cognitive aging accelerates (Bialystok et al., 2012). Future research should continue to examine bilingual effects in mid-life and track how they emerge over the lifespan, as well as investigate whether interventions in mid-life (e.g., second-language training) can confer later-life benefits.

Bilingual cognitive reserve in the context of COVID-19

In older adults, the association between COVID-19 history and executive functioning depended on L2 AoA. Larger switch costs for COVID-positive than COVID-negative participants were observed only among late L2 learners, not early L2 learners. This interaction remained significant after controlling for age, socioeconomic status, baseline cognition (MMSE), labor force status, and participant education, indicating that it was not attributable to demographic or general cognitive differences.

L2 AoA emerged as the most robust bilingual predictor in these analyses. Early L2 acquisition indexes bilingual experience occurring during development and therefore captures engagement within sensitive periods for neural and cognitive system organization. This type of early, long-term exposure aligns most closely with cognitive reserve frameworks, which emphasize how life experience influences vulnerability to later stressors. In contrast, measures of current language use or language switching reflect present-day habits that may fluctuate over time and were not reliable predictors in our multivariate analyses. Accordingly, the observed moderation pattern appears to be driven primarily by developmental timing rather than ongoing language behavior. Although cumulative exposure may still contribute to bilingual outcomes in other contexts, it was not a reliable predictor in the present analyses, and therefore does not provide a primary explanation for the observed effects.

Early L2 AoA was the most robust bilingual predictor, but AoA can reflect heterogeneous developmental contexts, including heritage-language acquisition and potential shifts in language dominance. While the LSBQ captures AoA, context of learning, and language use across life stages, it does not include explicit measures of language dominance or dominance change over time. Accordingly, we cannot definitively classify heritage status or formally model dominance-switching trajectories in the present dataset. Future work should directly assess heritage context and dominance change to determine whether these features further qualify AoA-related effects.

How might bilingualism protect the brain against COVID-related cognitive decline? COVID-19 is known to affect the brain through multiple pathways, including direct viral invasion (in severe cases), inflammation, cerebrovascular damage, and systemic effects on organs including the brain (Ellul et al., 2020; Gupta et al., 2020; Iadecola, Anrather, & Kamel, 2020; Spence et al., 2020). These can result in both acute delirium and longer-term cognitive deficits, often in attention, processing speed, and executive functions (Hampshire et al., 2021). Cognitive reserve theory (Stern, 2009; Stern et al., 2020) posits that individuals with more enriched cognitive life experiences (like higher education, intellectually challenging occupations, or bilingualism) have more efficient or flexible brain networks that can better compensate for injuries or pathology. In the context of COVID-19, we propose that bilingual older adults had a “head start” in terms of neural efficiency or redundancy in executive networks (developed over years of bilingual language control). Therefore, even if COVID-19 caused neural insults (e.g., white matter lesions/hyperintensities, or inflammation in frontal regions), bilingual individuals could better maintain function by recruiting alternate networks or using their networks more efficiently.

Our findings support this interpretation, and the pattern echoes what has been observed in research on bilingualism and dementia. Bilingual patients, despite displaying brain decline, manifest cognitive symptoms later or less severely than monolinguals (Alladi et al., 2013; Bialystok et al., 2007; meta-analyses in: Anderson et al., 2020; Brini et al., 2020; Chen et al., 2022; Paulavicius et al., 2020). Here, COVID-19 can be seen as an acute analog: although effects were specific to task-switching performance and based on cross-sectional data, the moderation pattern is consistent with the possibility that greater bilingual experience may buffer switching-related costs associated with COVID exposure. It is important to emphasize that our data are cross-sectional; we did not track individuals pre- and post-COVID. However, the differences we observe (bilingual vs. not) in the post-COVID older group are suggestive. Because the design is cross-sectional, moderation effects should not be interpreted as demonstrating causal protection. To bolster causality, future longitudinal studies should examine cognitive trajectories in older adults who get COVID, comparing different levels of bilingualism from baseline to post-illness. If greater bilingualism leads to less decline or faster recovery, that would provide strong evidence for a protective effect of second-language experience against cognitive decline. Our results lay the groundwork by highlighting this possibility.

An unexpected result from the COVID subgroup analysis was that having more than one COVID-19 infection was not associated with worse executive performance; in fact, those with multiple infections had slightly smaller switch costs than those with a single infection. We urge caution in interpreting this finding. It does not imply that getting COVID multiple times is beneficial for the brain; rather, it likely reflects characteristics of our sample. One factor is infection severity: a single COVID infection that is severe (requiring hospitalization, causing significant hypoxia, etc.) could do more lasting cognitive damage than two or three infections that are mild or asymptomatic (Liu et al., 2024). It is possible that many of our “multi-infection” participants had mostly mild cases or were better protected (e.g., vaccinated, healthy individuals), whereas some “single-infection” participants might have had a very severe bout that caused notable cognitive deficits. It is also possible that this pattern reflects an underlying difference in access to COVID-19 test kits, and potentially, awareness of the disease. Individuals with greater wherewithal to access kits, and who get regularly tested, would be alerted to minor bouts of COVID which may not have been clinically significant, whereas those who did not test regularly would only have become aware of contacting the disease if it was very severe.

The number of infections might inversely correlate with severity in an unexpected way. If someone survives multiple infections unscathed, none of those infections may have been as severe as the single worst infection in someone else. Another factor is the age distribution: in our data, the middle-aged individuals were slightly more likely to have had multiple COVID infections (perhaps due to higher exposure through work/social life) than the oldest participants. Even though the difference was not statistically significant (*t*-test $p = 0.11$), the effect size (Cohen’s d = 0.35) suggests a modest trend amongst limited variability in our sample: middle-aged adults reported somewhat more infections than older adults. Because the middle-aged adults also generally perform better on EF tasks than the oldest participants, this could create a spurious correlation where more infections (middle-aged individuals) correspond to better EF.

From a cognitive-reserve perspective, one could even speculate that individuals with more cognitive reserve (from bilingualism or other factors) might be more likely to resume normal activities sooner and thus risk re-infection, whereas those who suffered cognitive impairment after one infection might withdraw and avoid further exposure. If that were true, it would mean cognitive reserve could indirectly associate with more infections (due to behavior) but also with maintained cognition, which again could produce the pattern we saw. This is speculative, but it underscores that the relationship between COVID burden and cognition is complex and mediated by many variables (health status, behavior, timing of infections relative to vaccinations, etc.).

Because testing was conducted online, participation (particularly among older adults) may have selected for individuals with greater computer familiarity, stamina, and access to technological and socioeconomic resources. The online recruitment strategy likely selected for cognitively intact, technologically proficient older adults, potentially limiting generalizability to more vulnerable populations. These characteristics could covary with factors relevant to COVID exposure, recovery, and cognitive health, and therefore may limit generalizability. Replication using in-person or hybrid sampling, and/or direct assessment of digital literacy and social-resource variables, will be important for evaluating the robustness of the present findings.

Conclusion

In conclusion, our study offers new evidence that bilingualism is associated with better attentional control under flexible task-switching demands, particularly in the context of aging and health stressors. Using a multivariate approach, we found a reliable bilingual-EF link spanning multiple task contexts that vary in attentional control demands, driven by extensive bilingual experience and reflected mainly in complex EF tasks. Moreover, we demonstrated that this link was consistent with moderation-based models of cognitive reserve in older adults: lifelong bilingualism predicted stronger task-switching performance as an index of domain-general attentional control in those who had endured COVID-19, suggesting a protective effect on the aging brain. While the magnitude of the effect of bilingualism on EF on behavioral tasks is small and not consistent across all tasks, it is nonetheless detectable and potentially important, with the present findings indicating that effects are most readily expressed in tasks that place high demands on attentional control such as the task-switching paradigm used here, especially when considering long-term brain health and resilience. Our results help reconcile disparate findings in the literature by showing that when EF is evaluated in a holistic manner, bilingual experience does predict EF outcomes. Specifically, we provide evidence that different aspects of bilingual experience (e.g., early vs. later start) selectively impact different components of EF, with the present moderation results most clearly expressed in task-switching performance as a behavioral index of attentional control, reinforcing the need for more nuanced characterizations of bilingualism in research. We also highlight a novel intersection between bilingualism and infectious disease: cognitive reserve from bilingualism may help buffer the neurocognitive impacts of illnesses like COVID-19 in vulnerable populations. This finding has practical implications, including encouraging bilingualism (or other reserve-building activities) throughout the lifespan as a simple, non-pharmaceutical way to promote cognitive resilience in the face of neurodegenerative or vascular challenges. Of course, more work is needed to fully understand causal mechanisms and to explore how the effects of bilingualism on EF evolve over time. We hope that future studies build on this multivariate, experience-based approach to further unravel the multifaceted ways in which bilingual minds navigate cognitive aging and decline.

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Figure Captions

Figure 1 – Heatmap of Pearson correlations between L2 variables in the present study

Figure 2 – Partial least squares correlation (PLSC) results for the first latent variable (LV1) linking bilingual experience predictors (+ SES + Age) to EF outcomes in the full sample. A) Scree plot: LV1 accounts for 83.5% of cross-block covariance; higher LVs are negligible[1]. B) LV1 saliences with bootstrap 95% CIs. Reliable bilingual predictors: earlier L2 AoA (negative) and L2 proficiency (positive). Unreliable: L2 Usage, L2 Exposure, Language Switching Frequency and SES (CIs overlap zero). Reliable EF outcomes: smaller switch-cost (ACC & RT; negative weight) and higher Corsi span (positive). Bars with CIs crossing zero are not interpreted. C) Participant LV1 scores from the two blocks are moderately correlated (r = 0.50), shown for context. D) Zero-order Pearson correlations (predictors x outcomes) provided for orientation only; inferences are based on PLSC permutations/bootstrapping. E) Permutation test: LV1 singular value is significant ($p < .001$).

Figure 3 – Executive function performance for tasks used to measure task-switching and working memory (red bars) using a multivariate PLS with Age, MMSE, COVID-19 history (1 = yes, 0 = no), SES, L2 AoA, and L2 Proficiency as predictors (blue bars). Error bars reflect 95% bootstrapped confidence intervals.

[1] Even though LV4 showed a significant permutation test, all predictors and outcomes had confidence intervals that included 0, thus, no information could reliably be interpreted.

Figure 4 – Moderation of COVID-related switch-cost differences by L2 age of acquisition (AoA). Predicted switch-cost accuracy as a function of L2 AoA for participants with and without a history of COVID-19. Estimates are derived from the fully adjusted regression model including Age, SES, MMSE, labor force status, and participant education as covariates. Shaded regions represent 95% confidence intervals.

Figure 5 – PLSC analysis among participants with a history of COVID-19 (N = 84; complete cases = 77). Predictors include bilingualism variables, Age, SES, MMSE, and COVID burden measures. Switch-cost accuracy is computed as repeat minus switch accuracy; lower values indicate smaller switch costs (better performance). Corsi span reflects higher values for better performance. Opposite loading directions therefore reflect metric coding rather than contradictory effects.