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Linguistic distance dynamically modulates the effects of bilingualism on executive performance in aging

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Abstract

To better explain various neurocognitive consequences of bilingualism, recent investigations have adopted continuous measures of bilingual experience, as opposed to binary bi/monolingual distinctions. However, few studies have considered whether bilingualism's effects on cognition are modulated by the linguistic distance (LD) between L1 and L2, and none of the existing studies has examined cognitive consequences of LD in aging populations. Here, we investigated the modulatory role of LD on the relationship between bilingualism, executive performance, and cognitive reserve (CR) in a sample of senior bilinguals. Our results show a dynamic trajectory of LD effects, with more distant language pairs exerting maximum effects at initial stages of bilingual experience – and closer language pairs at advanced stages. Bilingualism-related CR effects emerged only in the individuals with closer language pairs, suggesting that the language control stage of bilingual experience may play a key role in CR accrual, as compared to the L2 learning stage.

1. Introduction

The concept of COGNITIVE RESERVE (CR; Stern et al., 2020) refers to structural and functional neural modifications resulting from life experiences and supporting the maintenance of optimal cognitive performance when faced with injury or age-related deterioration. Increasing evidence indicates that, among various lifestyle factors contributing to CR, bilingualism promotes successful aging (Bialystok, 2021). Moreover, recent evidence suggests that bilingualism may provide a unique contribution to CR development (Gallo et al., 2022b; Gallo & Abutalebi, 2023). The mechanism posited to underlie these effects is putatively rooted in bilingualism's impact on executive functioning. Since all known languages are believed to be simultaneously active in the bi/multilingual brain (Kroll et al., 2015), the bilingual speaker is typically faced with a constant necessity to manage crosslinguistic conflicts in order to prevent unwanted interferences from the language(s) not in use at the given moment. To achieve successful communication without interferences from competing linguistic codes, the bilingual speaker relies on the use of a so-called LANGUAGE CONTROL SYSTEM, which in turn is linked to the domain-general executive control system (Abutalebi & Green, 2016). Thus, bilingualism potentially provides ongoing training for the executive control system.

Cognitive consequences ensuing from this training encompass bilinguals' improved performance in a range of executive function tasks (for a review, see Bialystok, 2017). While several investigations have reported such executive enhancements, some attempts failed to confirm superior cognitive performance in bilinguals compared to monolinguals (e.g., Gathercole et al., 2014; Kalia et al., 2014; Paap et al., 2015). This variability has been typically attributed to the difficulty of assessing the numerous dimensions of individual bilingual experiences (Luk & Bialystok, 2013; Mishra, 2015; Surrain & Luk, 2019), which has led to a recent turn towards a more nuanced description of bilingual experimental samples (e.g., Del Maschio et al., 2020; DeLuca et al., 2019; Gallo et al., 2021a; Hervais-Adelman et al., 2018), as opposed to the more traditional mono- vs. bi/multilingual dichotomous distinction. While an increasing number of investigations have adopted a more scrupulous approach in delineating certain sub-aspects of bilingual experience (e.g., proficiency, age of acquisition, exposure, immersion) on a continuous spectrum, few investigations have considered the dimension of LINGUISTIC DISTANCE and its potential role in modulating neurocognitive consequences of bilingualism.

Linguistic or language distance (LD) is defined as the relative degree of similarity between two languages (Richards & Schmidt, 2002). In historical linguistics, languages that are derived from a common ancestral source are referred together as a language family. With respect to the level of kinship, these languages form subfamilies or branches inside the language family. The most-studied language family, the Indo-European family, has eight branches (although classifications vary) of languages that are still used to date. Although all Indo-European languages share certain phonological, lexical, morphological, and syntactic features, the similarities between languages within subfamilies/ branches is much higher. That level of similarity can be described as LD. Several approaches have been proposed to quantify LD, varying from the use of Levenshtein distance (Wichmann et al., 2010) to genetic proximity between languages (Longobardi et al., 2015). For instance, Swedish and English are both members of the Germanic branch with a common Proto-Germanic ancestor and therefore have a smaller LD between them. On the other hand, Italian arose from the Italic (Romance) subfamily, and thus LD between Italian and English is larger than that between English and Swedish.

Predictions regarding LD's impact on bilingual cognition are linked to the theoretical models of bilingual language control. Such models argue that, in order to avoid cross-linguistic interference, bilinguals do not only have to correctly select targets belonging to the language currently in use (Costa et al., 1999), but they also need to control for potential intrusions from any other known languages (Bates & MacWhinney, 1982; Green, 1986, 1998; Lee & Williams, 2001). It is well established that such intrusions are frequent when using a relatively 'weak' second language, e.g., at the early stages of second language acquisition. However, once a speaker achieves higher levels of L2 proficiency, overt intrusions become infrequent. A decrease in interference is to be expected to the extent the system underlying the use of L2 is differentiated from that of L1 (for further discussion on competition, see Hernandez et al., 2005).

As to the cognitive mechanisms involved, the inhibitory control model (Green, 1986) and its further expansions (Abutalebi & Green, 2007, 2016; Green & Abutalebi, 2013) propose that bilinguals use domain-general executive control mechanisms to efficiently juggle their languages and limit interference from non-target activations. This view is supported by widespread evidence indicating that bilinguals tend to outperform monolinguals in several executive tasks, e.g., the Flanker task (e.g., Costa et al., 2008). It is further corroborated by findings of an increase in cross-language intrusions accompanying aging-related decline in executive functioning (Gollan et al., 2011). The crucial theoretical tenet following from these accounts is that bilinguals who speak more proximal languages are expected to experience higher levels of cross-language interference (since the languages to be disentangled have a higher degree of similarity) and, as a consequence, the language control system should be taxed (and thus trained) to a higher extent, thus leading to a greater executive enhancement. Indeed, previous studies have found that a closer LD is associated with more efficient language processing in bilinguals. For example, Bialystok et al. (2003) showed that Spanish–English bilinguals (i.e., speaking two Indo-European languages) outperformed monolinguals on a phoneme segmentation task, whereas Chinese–English bilinguals (different language families) did not show a similar advantage. This pattern aligns well with findings reported by Barac and Bialystok (2012), where Spanish–English bilinguals demonstrated better metalinguistic performance than their Chinese–English peers, despite having similar second language (L2) exposure. Further confirming these results, Blom et al. (2020) reported that LD influences receptive vocabulary outcomes in L1-Dutch bilingual children, with better performance emerging in children speaking L2s closer to the native Dutch (Frisian, Limburgish) than more distant ones (Turkish, Afro-Asian, Slavic). Finally, closer language pairs have been shown to yield better performance in reading skills than dissimilar ones (Bialystok et al., 2005).

When it comes to non-linguistic tasks, however, the few available studies examining the impact of LD on bilingual cognitive performance have produced mixed results. On the one hand, some studies indeed indicate that closer language pairs entail increased effects upon executive functions. For instance, Morrison and Taler (2023) reported enhanced inhibition, switching and processing speed in English–French bilingual young adults compared to Arabic–English peers, which supports the hypothesis of closer LD enhancing executive functioning to a greater extent. This pattern of results is consistent with the work of Ljungberg et al. (2020), who reported significantly better episodic memory recall performance for Swedish–English bilinguals (smaller LD) as compared to Swedish–Finnish (greater LD) and to monolingual groups. On the other hand, other studies have reported null or opposite results. For example, Linck et al. (2008, Study 2) used the Simon task as an inhibitory control measure and found no effects of script similarity when testing differences between Spanish–English (smaller LD) and Japanese–English (larger LD) bilinguals matched for age, L1 proficiency, and age of L2 acquisition. Similarly, Coderre and van Heuven (2014) found no difference in Simon task performances between German–English, Polish–English, and Arabic–English bilinguals. Furthermore, Sörman et al. (2019) examined three measures of inhibition in adults aged 50-75 and found no effect of LD in their sample, which included two sub-groups of Swedish–English (lower LD) and Swedish–Finnish (higher LD) bilinguals.

Given these mixed findings, the extent to which LD modulates bilingualism's cognitive consequences remains unclear. Thus, the study reported here aimed at advancing our knowledge of LD's role in modulating bilingualism-induced effects on cognition. We tested two (partially) alternative hypotheses, one of which has received particularly little consideration to date. Namely, we propose that closer and more distant LDs may index two different stages where the cognitive effort imposed by bilingualism is maximized. With more distant LD pairs, the maximum effort is required during the LEARNING stage. Learning dissimilar phonemes, lemmas, and grammar (e.g., Italian and Japanese) requires more effort than learning an L2 with characteristics similar to one's L1 (e.g., Italian and Spanish). With closer LD pairs, while the learning phase is less cognitively effortful, the LANGUAGE CONTROL needs are substantially higher. Indeed, as mentioned above, selection between very similar alternatives is known to require greater cognitive resources (Furman & Wang, 2008). For instance, it has been shown that an increasing degree of similarity between alternatives has a detrimental effect on selection performance, leading to increased interference in lexical selection (e.g., Fieder et al., 2019; Rose et al., 2019) and in visual search (e.g., Feria, 2012; Verghese, 2001) paradigms. This framework offers an optimal test-bed that allows advancing our understanding of the relative contribution of the two phases of bilingual experience, learning and language control, as well as the modulatory effect of LD on bilingualism-induced cognitive changes.

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Indeed, it allows testing between two theoretically possible alternatives:

i) L2 LEARNING as such is the main mechanism underlying bilingualism's general cognitive benefits. Higher cognitive effects emerging in the executive performance of bilinguals with more distant language pairs, as opposed to closer ones, would support this hypothesis.
ii) Bilingualism's main contribution to cognition stems from the LANGUAGE CONTROL processes, most involved at later stages of bilingual experience when using two languages concurrently. Bilingualism-induced cognitive effects emerging more prominently for closer language pairs than for more distant ones would support this account.

Finally, it is also possible that both mechanisms provide partial contributions to cognition. In this case, speakers with closer and more distant language pairs would experience bilingualism-induced cognitive consequences at different stages of the bilingual experience.

Disentangling the contributions of these two stages of bilingual experience – L2 learning and language control – could also improve our knowledge of bilingualism's role in promoting CR accrual. While some investigations of the modulatory role of LD on bilingualism's cognitive effects have been conducted in young age groups, only one report to date has addressed the issue in older age (Sörman et al., 2019). Unfortunately, this study found no bilingualism-induced executive benefits whatsoever, thus making it impossible to test these effects in relationship with bilingualism's effect as a CR contributor.

In order to disentangle between the two (partially) alternative hypotheses described above and better understand bilingualism's role as a CR contributor, we conducted a study investigating the modulatory role of LD in the relationship between subcomponents of bilingual experience (measured continuously using a number of variables; see e.g., Del Maschio et al., 2020; DeLuca et al., 2019; Gallo et al., 2021a, and Methods and Materials below) and executive performance as indexed by a Flanker task (the standard benchmark for evaluating inhibitory control; Fan et al., 2002), in a sample of older bilingual adults.

2. Materials and Methods

2.1. Participants

We recruited 64 cognitively healthy bilingual adults (30 males; mean age = 64.7, SD ± 4.7) via social media and the Prolific research recruitment platform (www.prolific.com). Selection criteria for the study included speaking an L2, being at least 60 years old, and having no psychiatric or neurological impairments.[1] Initial screening led to the discarding of one participant with an active Major Depression diagnosis. A second check consisted in presenting participants with an adapted online version of the Mini-Mental State Examination (MMSE; Cockrell & Folstein, 2002), to exclude the presence of undiagnosed age-related cognitive impairment in the sample. No participants were discarded at this stage. Our original aim was to test participants with L2 English, to ensure the possibility of measuring L2 proficiency objectively using the same standardized tools. However, due to Prolific's specific routines for recruiting experimental populations, our sample of 63 senior bilinguals also included 27 individuals who spoke English as L1 with various L2s. Since our design did not include an objective L2 proficiency measure for these L1 English speakers, our final sample for statistical analyses only included the 36 participants who spoke various L1s and English as an L2 (19 males; mean age = 63.9, SD ± 3.2). Nonetheless, we were able to use the full 63-participants sample for structural equation modeling (SEM) estimation, since this analysis focused solely on CR profiles, and not on the language background (see section 2.4.2 below). Data was collected via the Psytoolkit software (Stoet, 2010, 2016) and the Qualtrics platform (Qualtrics, Provo, UT). The study was approved by the local research ethics committee, and all participants provided informed consent prior to their participation in the study.

2.2. Sociodemographics and language background assessment

All participants underwent an online questionnaire assessing several dimensions of their sociodemographic profiles, including age, sex, marital status, frequency of physical exercise and various leisure activities, lifelong occupational complexity, perceived positive support from their close circle, highest educational attainment, size of their social network, and eventual presence of any financial difficulties in the household during upbringing. All these factors are known to affect cognitive performance and maintenance of neurocognitive efficiency during aging – by contributing to CR accrual (see e.g., Cheng, 2016). In addition to the general sociodemographic assessment, we also assessed several dimensions of participants' language background, including the languages they spoke, exposure to and subjective proficiency in L2, and number of years since they acquired it. Furthermore, to obtain an objective measure of their L2 English proficiency, participants were asked to complete the online Cambridge Test for Adult Learners (http://www.cambridgeenglish.org/test-your-english/general-english/). LD for individual language pairs was obtained using the eLinguistics genetic proximity software (http://www.elinguistics.net/). This tool, based on Swadesh Lists (Serva & Petroni, 2008; Swadesh, 1952), calculates genetic proximity between languages based on evolutionary trees using a database of 220 different languages and returns a continuous number as a result. The higher the number, the more distant the two languages are. L1s in our sample included Spanish, Hungarian, Polish, Italian, German, Portuguese, French, Swedish, Greek, Arabic, Dutch, and Estonian. The mean LD was 51.9 (SD 16.8). The lowest LD was with L1 Swedish (26.7); the highest was L1 Hungarian (87.9).

Finally, we presented participants with a subset of the Raven's Standard Progressive Matrices for adults (Court & Raven, 1992) to assess their level of general intelligence, another factor known to affect cognitive performance in senescence (e.g., Puccioni & Vallesi, 2012).

2.3. Cognitive performance assessment

All participants underwent a Flanker task (Fan et al., 2002), a benchmark task for evaluating inhibitory executive control performance. This ability is argued to be influenced by bilingualism, since it is routinely required in bilingual language control (Costa et al., 2008; Green & Abutalebi, 2013). Thus, the Flanker task has been widely adopted in investigations of bilingual cognition (e.g., Costa et al., 2008; Dash et al., 2019; Luk et al., 2010; Del Maschio et al., 2018; Gallo et al., 2021a, 2022b). In this task, participants are required to indicate the direction of a central target arrow, flanked by two additional arrows per side, as accurately and fast as possible. The task includes three conditions: a congruent

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condition, where flankers and target point in the same direction (←←←←←); an incongruent condition, where the flankers point to the opposite direction to the target (←←→←←); a neutral condition, where the target is flanked by dashes and not arrows (– – → – –). Since incongruent trials require inhibitory control to suppress the irrelevant interference from flankers, they typically entail longer reaction times (RTs) than congruent and neutral trials. Following the original procedure of the Flanker task within the ANT setup described by Fan et al. (2002), we presented trials in a pseudo-randomized order, in two runs of 96 trials each (32 trials per each condition). Response timeout was set to 1700 ms.

2.4. Statistical analyses

Mean performance accuracy in the Flanker task was 91.4% (SD = 20.2%) for the congruent condition, 87% (SD = 17.9%) for the incongruent condition and 94.1% (SD = 11.2%) for the neutral condition. Before performing statistical analyses, we trimmed the Flanker RT data by adopting a mild *a priori* outlier removal procedure recommended as standard when using linear mixed modeling with RT data (Baayen & Milin, 2010). Neutral trials, incorrect trials, responses given after the response timeout, and false starts (i.e., RT < 100ms) were discarded, as were outlier trials with RTs deviating beyond 3 SDs from the individual mean.

2.4.1. Linguistic distance and effects of bilingualism on executive performance

Our first analyses aimed at testing whether LD would modulate previously reported bilingualism-induced effects on executive performance. To this end, we started by investigating the effect of L2 proficiency, L2 exposure, and the number of years since L2 acquisition (henceforth, L2 years) on Flanker task RTs. L2 exposure data had to be discarded due to insufficient variability across the sample. Linear mixed regressions showed a significant beneficial effect of bilingualism on Flanker RTs using both L2 proficiency ($\beta = -8.988$; $p < 0.001$) and L2 years ($\beta = -2.77$; $p < 0.001$). For increasing levels of bilingual experience (both along L2 proficiency and L2 years dimensions), Flanker RTs decreased – signaling an improvement in executive performance. Figure 1 illustrates that this relationship was driven by the effect observed in incongruent trials while no relationship between bilingual experience and performance emerged for congruent trials – in line with the hypothesis that bilingualism selectively affects executive inhibitory control. This result allowed us to proceed with further analyses to test whether varying LD would influence bilingualism's effects on executive performance. To do this, we ran two linear mixed regressions – one for L2 proficiency and one for L2 years – with Flanker RTs as the dependent variable. The model structure included a three-way interaction between LD, trial type and L2 proficiency or L2 years. The trial type (congruent vs. incongruent) interaction term was added to ensure that we tested bilingualism's effect differentially for congruent and incongruent trials. Models' covariates included age, sex, and general intelligence, and random effects included random intercepts for participants and random slopes for trials. Here, and throughout the entire analysis pipeline, we adopted a single-trial repeated measures approach using linear mixed modeling (see e.g., Baayen et al., 2008). This allowed us to increase the amount of individual data points from 2 (one average per condition) to 128 (one data point per each trial).

2.4.2. Linguistic distance and the three-way relationship between bilingualism, cognitive reserve and executive performance

We also aimed at testing whether LD influences previously reported modulatory effects of bilingualism on CR. We used generalized Structural Equation Modeling (gSEM) to derive an individual latent measure of CR that comprised the contributions of different traditional CR proxies. The model (reported in Figure 2) combined contributions from occupational complexity, marital status, physical exercise, perceived positive support, maximal educational attainment, frequency of leisure activities, size of social network, and financial hardships during upbringing. The model structure choice was motivated by the aim to derive a comprehensive index of CR. In fact, all the factors inserted in the model have been shown to affect cognitive aging trajectories by promoting CR accrual (e.g., Dekhtyar et al., 2019; see also e.g.,

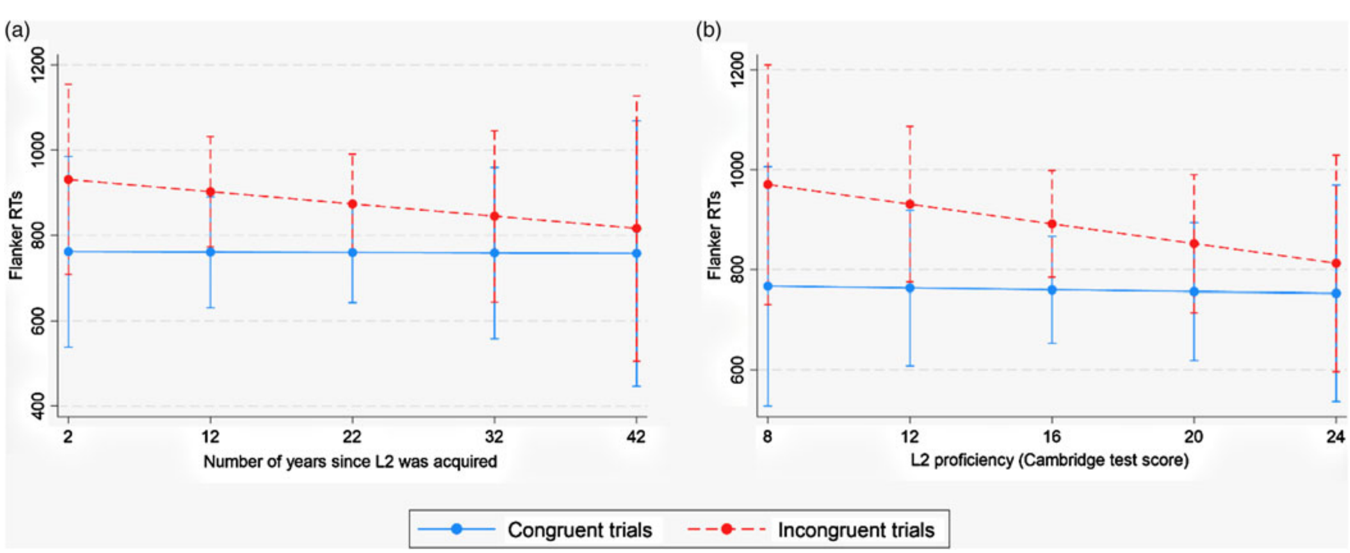

Figure 1. Graphical representation of the effects of L2 years (a) and L2 proficiency (b) on Flanker performance (RTs, in ms). The effects are differential for the two task conditions (incongruent vs congruent).

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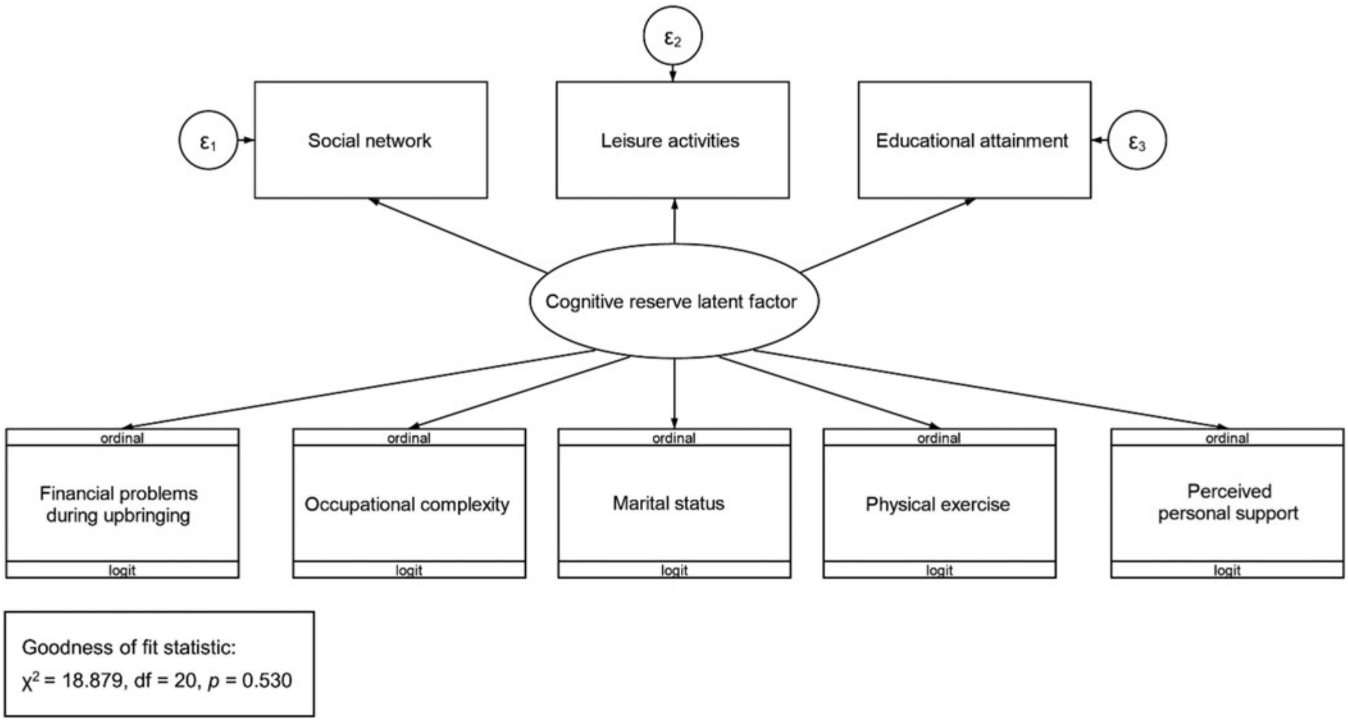

Figure 2. Graphical representation and goodness of fit of the generalized structural equation model (gSEM) used to derive the cognitive reserve latent factor.

Cheng, 2016; Stern et al., 2020 for reviews). This view is also supported by the presence of these factors in some of the most diffused questionnaires assessing individual CR levels (e.g., Cognitive Reserve Scale, León et al., 2014; Cognitive Reserve Index questionnaire, Nucci et al., 2012).

For categorical factors, an ordinal logit family link was used. For continuous factors, a linear family link was used. The model fit the data well ($\chi2$ of fitted vs. saturated model test = 18.879, df = 20, $p = 0.530$). From this gSEM we predicted an individual, continuous, latent measure of CR.

Once we derived the latent CR measure, we tested the modulatory effect of bilingualism on CR's effects on Flanker performance. Bilingualism's contribution to CR was strong enough to modulate the beneficial effect of other CR proxies (combined as one latent variable) on executive performance. For high levels of L2 proficiency (but not for L2 years), the traditional CR proxies exerted no effect on executive performance, while a beneficial effect of bilingualism was still detectable (see Figure 3). Building on this result, our final analysis tested whether LD played a role in further modulating this relationship between bilingualism, CR and executive performance in senescence. To do this, we estimated a linear mixed regression with Flanker RTs as the dependent variable, a four-way interaction between L2 proficiency, traditional CR proxies, trial type and LD as the main predictor, covariates for age, sex, and general intelligence as well as random intercepts for participants and random slopes for trials.

3. Results

3.1. Modulation of bilingualism's effects on executive performance by linguistic distance

Linear mixed regressions showed a significant beneficial effect of bilingualism (both as L2 Proficiency and L2 years) on Flanker performance (see section 2.4.1 and Figure 1 above). Our first modulation analyses revealed a significant three-way interaction between L2 years, trial type, and LD ($\beta = 0.49$; $p < 0.001$), indicating that LD modulated this beneficial effect of bilingualism on executive performance. A similar result emerged for the three-way interaction between L2 proficiency, trial type, and LD ($\beta = 1.253$; $p < 0.001$): LD dynamically modulated the beneficial effect of both variables on Flanker performance, differentially for congruent and incongruent trials (see Figure 4). More distant LD predicted better executive performance (i.e., lower RTs) with fewer years from L2 acquisition and when proficiency was low. As L2 years and L2 proficiency increased, performance of individuals with more distant LD gradually worsened. Conversely, closer LD entailed improving performance when L2 years and L2 proficiency increased.

3.2. Modulation of relationship between bilingualism, cognitive reserve, and executive performance by linguistic distance

Linear mixed regressions revealed that bilingualism's contribution to CR spanned beyond the beneficial effect of other CR proxies on executive performance (see section 2.4.2 and Figure 3 above). In our second modulation analysis stage, we tested whether varying LD modulated this effect. The analysis showed a significant four-way interaction between L2 proficiency, trial type, traditional CR proxies, and LD ($\beta = -10.508$; $p < 0.001$). To interpret this four-way interaction via graphical plotting, we transformed linguistic distance in a binary variable via a median split. To ensure the robustness of our result prior to interaction plotting, we tested the same model with the new binary measure of LD instead of the continuous one. This four-way interaction was also significant ($\beta = -330.056$; $p < 0.001$). Figure 5 indicates that the modulatory effect of bilingualism on other CR proxies emerged for the closer

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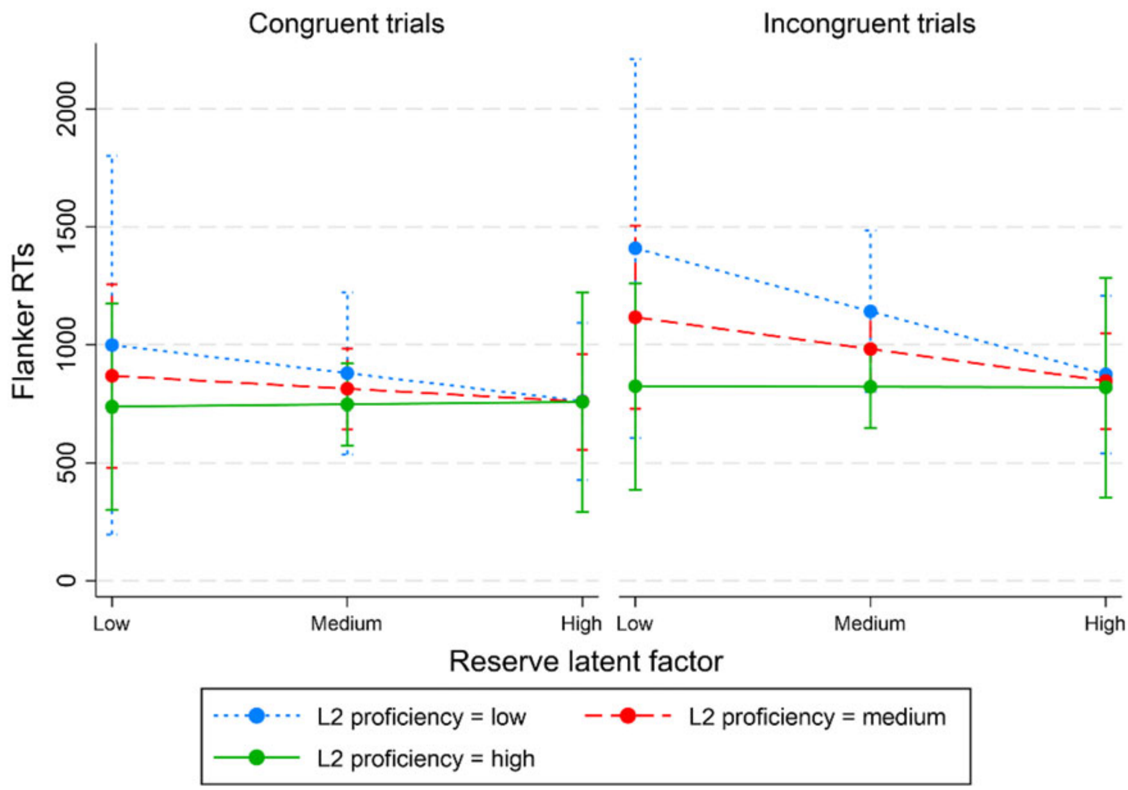

Figure 3. Graphical representation of the modulating effect of L2 proficiency on the relationship between cognitive reserve latent factor and Flanker performance (RTs, in ms). For plotting purposes, the three levels of cognitive reserve latent factor and L2 proficiency, i.e., low, medium and high, represent 1σ below the mean value, mean value, and 1σ above the mean value, respectively.

language pairs, but not for the more distant ones. In closer language pairs, increasing levels of L2 proficiency gradually reduced the beneficial impact of traditional CR proxies on Flanker performance. Concurrently, increasing levels of L2 proficiency kept predicting increasing levels of executive performance (i.e., progressively smaller Flanker RTs).

4. Discussion

Here, we tested whether LD modulates the well-known effects of bilingualism on executive performance during senescence. To do this, we assessed the Flanker performance of a group of senior bilinguals with differing L1s and English as an L2. Since LD

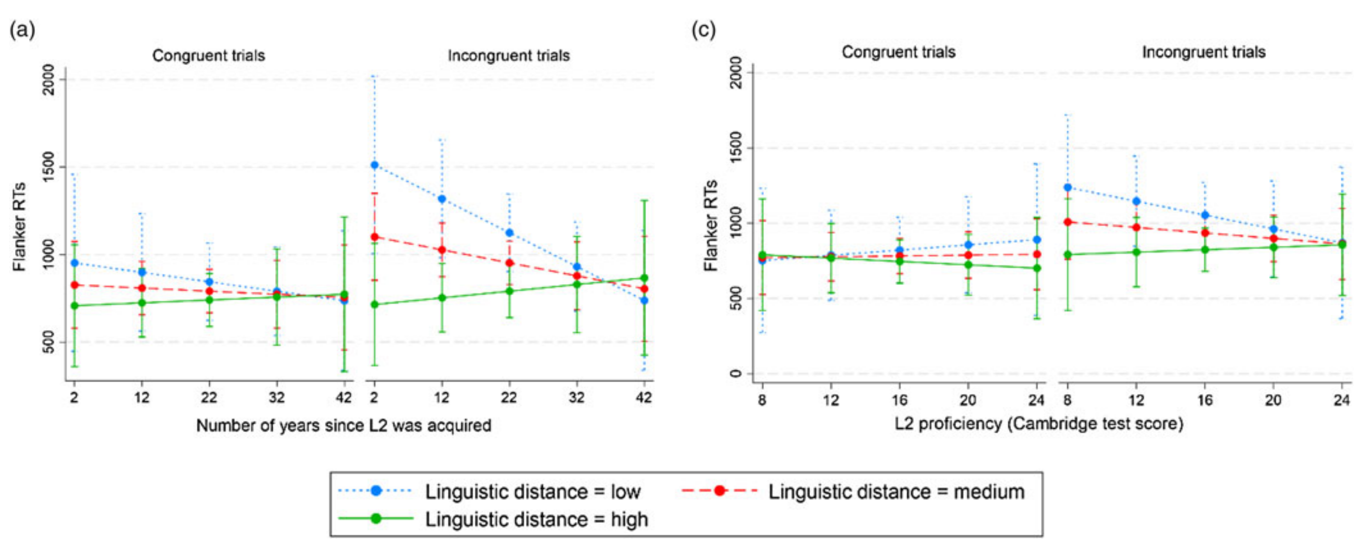

Figure 4. Interaction plot for the L2 years*task condition*linguistic distance (a) and L2 proficiency*task condition*linguistic distance (b) interactions predicting Flanker RTs (in ms). The plot shows the modulatory effect of linguistic distance on the contributions of the two bilingual experience factors to Flanker performance. For plotting purposes, the three levels of linguistic distance, i.e., low, medium and high, represent 1σ below the mean value, mean value, and 1σ above the mean value, respectively.

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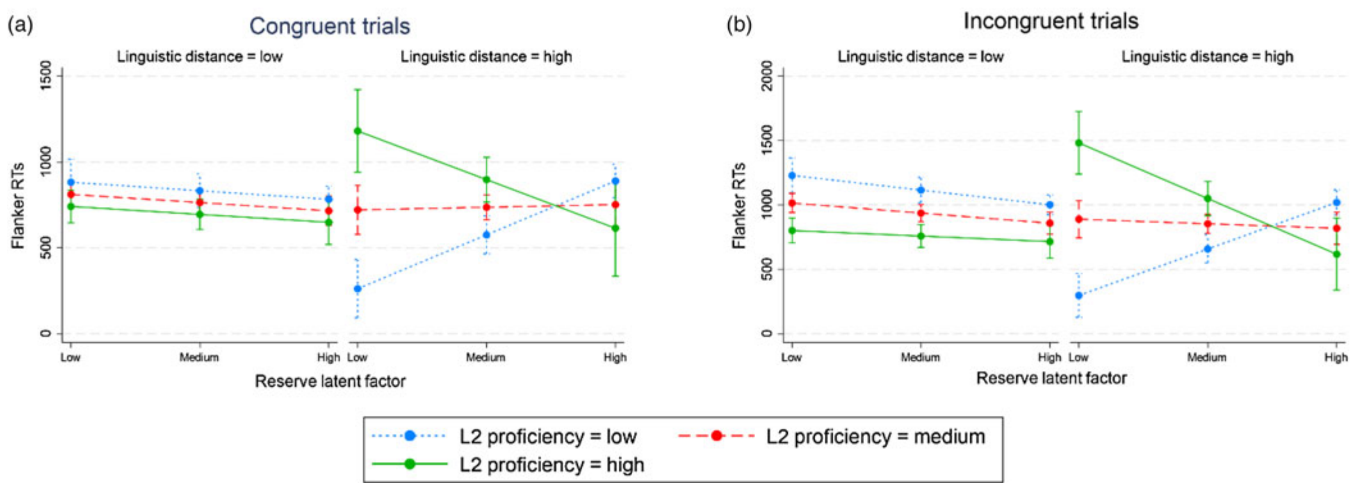

Figure 5. Interaction plot for the L2 years*cognitive reserve latent factor*linguistic distance interaction for congruent (a) and and incongruent (b) task condition, predicting Flanker RTs (in ms). The plot shows the modulatory effect of linguistic distance on the relationship between bilingualism and other cognitive reserve proxies and its effect on Flanker performance. For plotting purposes, the three levels of L2 proficiency and cognitive reserve latent factor, i.e., low, medium and high, represent 1σ below the mean value, mean value, and 1σ above the mean value, respectively. The two levels of linguistic distance were obtained with a median split.

varied substantially across the different language pairs in our sample, we were able to test its modulatory effect on bilingualism-induced effects on executive performance and CR accrual.

We also aimed to test two (partially) alternative hypotheses. First, higher LD (i.e., more distant language pairs) should maximize bilingualism's contribution to executive performance and CR development. This would indicate a preponderant contribution of the *L2* LEARNING phase, where the cognitive effort (and thus training) is maximal when L1 and L2 are distant. Second, lower LD (i.e., closer language pairs) should maximize bilingualism-induced executive and CR effects. This would indicate a preponderant contribution of the LANGUAGE CONTROL phase, where cognitive effort (and thus training) is maximal with closer L1 and L2 and the higher resulting crosslinguistic interference.

Our results revealed a dynamic influence of LD to bilingualism-induced executive changes and indicated differential peak contributions of two stages of bilingual experience – namely, LEARNING and LANGUAGE CONTROL – to cognition. Indeed, while bilinguals with closer language pairs displayed surging beneficial effects with increasing time from L2 acquisition and L2 proficiency, the opposite pattern emerged for bilinguals with more distant language pairs. The latter individuals displayed a decreasing trend in executive performance as time passed from L2 acquisition and L2 proficiency grew. With regards to individuals with lower LD, our results indicate that, with accruing bilingual experience, the more challenging language control activity will continue to train the executive neurocognitive substrate of closer LD-bilinguals, thus showing ever-growing benefits as the experience builds up. As per individuals with higher LD, our result suggests that, as time passes from the cognitively challenging learning phase, the benefits start to decline. In this sense, while L2 years is an exact measure of time passed since L2 was acquired, L2 proficiency could also be seen as a time-related proxy – although spurious – of the progression of bilingual experience. This interpretation is reinforced by the fact that the effects discussed here, although emerging both for L2 years and L2 proficiency, appear more clear-cut in the former case (see Figure 4). In sum, our data reveal a dynamic contribution of LD to bilingualism-induced executive benefits. More distant pairs have more relevance in the beginning of bilingual experience, probably as they are more taxing in the learning phase. As time passes, the contribution of closer language pairs, more taxing in the language control stage, becomes central.

This finding also encourages considerations of whether the cognitive mechanisms engaged during the learning phase overlap with those engaged during the language control stage. Importantly, this putative overlap might itself be dependent on the degree of LD. It is possible that, for more distant LD pairs, control and inhibitory mechanisms might be at play only during advanced stages of bilingual experience while they might be less involved at the initial learning phase, with attentional control playing a more central role. For closer LD pairs, instead, control and inhibition mechanisms may need to be engaged already at the initial learning stages due to higher similarity between the two languages while at the same time engaging attention due to new language learning.

Addressing the other main aim of our investigation, we tested whether varying LD influences bilingualism's contribution to CR. Our results showed that for closer language pairs, but not for distant ones, variations in bilingual experience modulated the cognitive effects of other traditional CR proxies. Indeed, only for speakers with closer LD, at high levels of bilingual experience the effect of CR proxies on executive performance disappeared, while that of bilingualism remained. This indicates that for closer language pairs bilingualism's contribution to CR accrual was independent and spanned beyond other CR factors. The fact that this result only emerged for closer LD suggests that the training provided by bilingual language control, rather than L2 learning, is crucial to CR accrual. This finding is well in line with existing literature. Recent studies suggest that "crystallized" life experiences, such as education (or L2 learning, in our case), would influence cognitive aging by affecting peak cognitive levels earlier in life, rather than the slope of trajectories of age-related cognitive decline (Berggren et al., 2018; Gallo et al., 2021a; Lövdén et al., 2020; Seblova et al., 2020). "Lifelong" factors – in our case, the constant challenge of the highly demanding language control in the lives of bilinguals with closer language

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pairs – would instead maintain their CR-inducing effects across the whole lifespan, beginning in young adulthood (Gallo et al., 2021b) or even earlier and continuing into senescence (Gallo et al., 2022a).

The fact that closer language pairs entail stronger consequences for cognition is conceptually well grounded. Language pairs with lower LD are predicted to exert a higher cognitive burden by several general models of bilingual language control (Abutalebi & Green, 2007, 2016; Costa et al., 1999; Green, 1986, 1998; Green & Abutalebi, 2013; Lee & Williams, 2001). Such models predict that, in order to avoid intrusions by the non-target language, bilinguals use mechanisms of interference suppression, response inhibition and selection, and conflict monitoring, which are overseen by the language control system. Controlling interference between similar alternatives is known to require greater cognitive resources (Furman & Wang, 2008). Indeed, increasing degrees of similarity between alternatives have been reported to exert a detrimental effect on selection performance, leading to an increased interference in, e.g., lexical selection (e.g., Fieder et al., 2019; Rose et al., 2019) or visual search (e.g., Feria, 2012; Verghese, 2001) tasks. As a result, language control is expected to be more demanding for bilinguals with lower LD language pairs, who must disentangle between similar targets in L1 and L2. As reviewed in the Introduction, since the cognitive mechanisms deployed by the language control system are shared with domain-general executive control, bilingualism has been argued to affect executive functioning by means of the sustained cognitive training (Bialystok, 2017). In the case of bilinguals with closer language pairs, the language control system is taxed to a higher degree, and thus greater executive modulations could be achieved. The results of our investigation lend strong support to this mechanistic framework.

5. Conclusion

The present results offer a first step towards elucidating important contributions of language distance to bilingualism-induced cognitive benefits during aging and reveal a dynamic trajectory of LD-related effects. Our findings may also have significant practical implications. Indeed, cognitive aging and its health-related and economic consequences constitute a critical issue for modern-day aging societies. As the incidence of age-related pathologies grows steadily (World Health Organization, 2019), so do the economic repercussions for healthcare systems (Xu et al., 2017), with research on pharmacological interventions still far from reaching satisfactory outcomes (Dyer et al., 2018). Thus, identifying lifestyle factors that can potentially mitigate age-related cognitive decline is of utmost importance. With mounting evidence that bilingualism can be one such factor, future research is needed to focus on the specific features that can maximize its beneficial impact. As the present research suggests, LD between bilinguals' language pairs could be an important feature in this respect, although substantial further research is still required to verify and expand the present findings and elucidate their practical significance.

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Data Availability Statement. The data and analysis scripts that support the findings of this study are available from the authors upon reasonable request.

Note

[1] The present investigation uses the sample previously described in Gallo et al. (2022).

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