

Older Bilinguals Reverse Language Dominance Less than Younger Bilinguals: Evidence for the
Inhibitory Deficit Hypothesis

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The authors thank Rosa Montoya and Mayra Murillo for assistance with data collection. We have no known conflict of interest to disclose. Alena Stasenko was funded by a NRSA fellowship from the National Institute on Aging (F31 AG058379-02). Dan Kleinman was supported by funding from NIH grants DC013864 and HD086168, and by collaborations between Haskins Laboratories, AIM Academy, and The Windward School. Tamar Gollan was supported by grants from the National Institute on Deafness and Other Communication Disorders (011492), National Science Foundation BCS1923065, and by a P50 (AG05131) and a P30 (AG062429) from the National Institute of Aging to the University of California. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NIH or NSF. Some of the research presented here was previously presented at the Center for Research in Language talk series at UCSD and at the Multicultural Alzheimer's Prevention Program Rounds at MGH.

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Abstract

Inhibitory control is thought to play a key role in how bilinguals switch languages and to decline in aging. We tested these hypotheses by examining age group differences in the reversed language dominance effect—a signature of inhibition of the dominant language that leads bilinguals to name pictures more slowly in the dominant than the nondominant language in mixed-language testing blocks. Twenty-five older and 48 younger Spanish-English bilinguals completed a cued language switching task. To test if inhibition is applied at the whole-language or lexical level, we first presented one set of pictures repeatedly, then introduced a second list halfway through the experiment. Younger bilinguals exhibited significantly greater reversed language dominance effects than older bilinguals (who exhibited nonsignificant language dominance effects). In younger bilinguals, dominance reversal transferred to, and was even larger in, the second list (compared to the first). The latter result may suggest that inhibition is partially offset by repetition in ways that are not yet fully understood. More generally, these results support the hypotheses that aging impairs inhibitory control of the dominant language, which young bilinguals rely on to switch languages. Additionally, inhibition is applied primarily at the whole-language level, and speculatively, this form of language control may be analogous to nonlinguistic *proactive control*.

Keywords: bilingualism, aging, language switching, proactive control, reversed language dominance

Reduced Inhibition of the Dominant Language in Aging Bilinguals:

Testing the Inhibitory Deficit Hypothesis

Switching languages is beneficial for bilinguals, but it also introduces processing costs. A language switching task provides a unique opportunity to study a relatively naturalistic form of switching behaviors in aging. Bilinguals avoid switching languages when they need to but switch between languages easily and often when they want to. If normal aging changes either of these abilities—by reducing whatever allows bilinguals to avoid switching or increasing whatever motivates an initiation to switch—we might expect to see dramatic changes in switching behavior in aging bilinguals. However, like many age-related changes, the picture that emerges is one of subtle differences, sometimes with declines but at other times with improvements in performance relative to younger bilinguals. The present study exploits a unique signature of bilingual language control—the reversed language dominance effect—to better understand language control and how it may change in aging.

A prominent theory of bilingual language processing is the Inhibitory Control Model, or *ICM* (Green, 1998). On this view, bilinguals manage competition between languages by inhibiting whichever language is not currently in use, both at the lexical level, and via an independent global inhibitory control mechanism at the whole-language level. Supporting the *ICM*, the dominant language often exhibits greater switching costs. That is, in language-switching tasks, bilinguals name pictures or digits in one language or another based on a cue (e.g., a red cue for one language and a blue cue for the other). Response times are slower when bilinguals are cued to switch versus not switch between languages, exhibiting *switch costs*—that surprisingly, are often larger when bilinguals switch back into their dominant language than when switching into their nondominant language. This counterintuitive *switch cost asymmetry* is

often cited as evidence for inhibitory control (but see Bobb & Wodniecka, 2013): To produce words in the nondominant language, the more dominant language must be inhibited, meaning that, when returning to the dominant language, bilinguals must overcome this inhibition, leading them to exhibit greater switch costs (e.g., Meuter & Allport, 1999; for review see Declerck & Philipp, 2015; Khateb et al., 2017).

Another even more powerful signature of sustained inhibition in bilingual language processing—and the focus of the present study—is found in fully *reversed language dominance* effects. When there is no requirement to switch languages, bilinguals typically respond faster in their dominant language (i.e., in single-language blocks; for review see Hanulová, et al., 2011; Runnqvist et al., 2011). In contrast, in mixed-language blocks bilinguals sometimes respond more slowly in their dominant than in the nondominant language (Christoffels, Firk et al., 2007; Christoffels, Ganushchak, et al., 2016; Costa & Santesteban, 2004; Costa et al., 2006; Gollan & Ferreira, 2009; Heikoop et al., 2016; Kleinman & Gollan, 2018; Peeters & Dijkstra, 2018; Verhoef, et al., 2009, 2010). This counterintuitive finding of reversed language dominance effects is most often explained by assuming that bilinguals apply global inhibition to the dominant language to facilitate production of both languages in the same testing block (Christoffels et al., 2007; 2016; Gollan & Ferreira, 2009; Heikoop et al., 2016; for review see Bobb & Wodniecka, 2013 and Declerck, 2020). Although reversed dominance may serve as strong evidence of inhibition (e.g., Declerck et al., 2020; Kleinman & Gollan, 2018), it is not always found, and it is not fully understood what conditions lead it to emerge (Declerck, 2020 for review). Reversed dominance is also thought to be a marker of *proactive language control* (or *sustained language control*)—a process recruited during anticipation of non-target language interference *before* it occurs (Declerck, 2020). This preventative control process helps bilinguals

manage cross-language interference and may have shared mechanisms with proactive cognitive control that requires goal maintenance and monitoring (Braver et al., 2007; Braver, 2012).

Most evidence supports reversed dominance as affecting an *entire language*, most often the dominant one (Declerck, 2020). For example, evidence for global control of the dominant language is found in *blocked language-order effects* in behavioral and ERP studies (e.g., Branzi et al., 2014; Kreiner & Degani, 2015; Misra et al., 2012; Van Assche et al., 2013; Wodniecka et al., 2020). In these studies, bilinguals are tested in just one language at a time but may exhibit order effects after previously completing a task in the other language. This interference is asymmetric, such that prior use of the nondominant language is especially likely to interfere with lexical access in the dominant language, a pattern that has been observed in different paradigms (e.g., Degani et al., 2020; Phillipp & Koch, 2009; see Kroll et al., 2008 for review) and across longer timescales (e.g., immersion; Baus et al., 2013; Linck et al., 2009). Furthermore, in a few studies this interference was observed even when nonoverlapping materials (e.g., different pictures) were used across testing blocks, implying that bilingual language control is applied globally to the entire non-target language (Branzi et al., 2014; Kreiner & Degani, 2015; Stasenko & Gollan, 2019; Van Assche et al., 2013; Wodniecka et al., 2020).

Converging literature suggests a tight coupling between bilingual language control and domain-general executive control (Bialystok, 2017; Lehtonen et al., 2018 for recent review and meta-analysis). Supporting this view, studies using the AX-CPT task¹ found that bilinguals outperformed monolinguals only in conditions that require the highest adjustment between proactive monitoring and reactive inhibitory control (Morales et al., 2013; 2015). Morales and

¹ In the AX-CPT task, participants are trained to press a button only when an X follows an A which happens on the majority of trials. Young adults quickly learn to anticipate this sequence and produce more errors on the minority of trials when a Y follows an A, while older adults do not spontaneously adopt this strategy (but can be trained to do so; Paxton et al., 2006; see discussion in Dunlosky & Hertzog, 2001).

colleagues found that bilinguals committed fewer errors than monolinguals only on AY trials and exhibited more negative N2 amplitudes to AY trials than monolinguals, together suggestive of enhanced conflict detection in bilinguals. Other studies provide more direct causal support for the relationship between bilingual language control and nonlinguistic executive control measured with the flanker task, in which participants have to indicate the direction of a central arrow that is flanked on both sides by arrows that either point in the same (congruent) or opposite (incongruent) direction, which interferes and slows responses. These studies reported smaller flanker interference effects when interleaved with a bilingual language switching task (e.g., Adler et al., 2019; Jiao et al., 2020), even when bilinguals were instructed to ignore the linguistic material (Wu & Thierry, 2013). These studies provide strong evidence that language context (encountering a language switch versus no switch) can modulate subsequent executive control processes on a moment-by-moment basis.

Studies with older bilinguals also suggest a tight relationship between bilingual language control and nonverbal conflict resolution. Gollan and colleagues (2011) reported an aging-related increase in flanker interference effects, as well as a strong correlation in older but not younger bilinguals between error rates on a difficult version of the flanker task (in which the arrows sometimes also appeared on the incongruent side of the screen) and cross-language intrusion errors (inadvertently saying an English word on a Spanish trial or vice-versa). This implied at least partially shared mechanisms between nonlinguistic executive control and language control, that might be apparent only in older bilinguals when a reduction in executive control processes reveals the connection with language control. It is generally accepted that executive control (or at least some forms of executive control) declines in aging (as suggested by task switching paradigms; Wasylyshyn et al., 2011; but see Verhaeghen, 2011), due to aging-related changes in

the frontal lobes (Raz et al., 2005; Tamnes et al., 2013; Zanto & Gazzaley, 2019 for review). This could affect how aging bilinguals manage dual-language activation, and the ability to control language switches.

A recent study replicated the aging-related increase in language intrusion errors, but reported intact language dominance reversal in older bilinguals, and even in bilinguals with Alzheimer's disease but using a very different language switching paradigm, in which bilinguals read aloud mixed-language passages (Gollan et al., 2017; 2020; Gollan & Goldrick, 2016). A small number of studies reported an aging-related increase in language switching or mixing costs (Hernandez & Kohnert, 1999; 2015; Weissberger et al., 2012; but see Calabria et al., 2015). However, none of these studies revealed significant dominance reversal (in young or older bilinguals) in the mixed-language blocks. One study seemed to suggest stronger dominance reversal in older than in younger bilinguals (-102 ms on stay (non-switch) trials and -172 ms on switch trials when subtracting dominant from nondominant RTs in older bilinguals, but just -47 ms on stay trials and -55 ms on switch trials for younger bilinguals; Gollan & Ferreira, 2009). However, these differences were not statistically significant, possibly because language switches were not required in this study (which used a voluntary switching paradigm in which participants were instructed to "name the picture in whatever language comes to mind") and only a small number of participants were included in analyses ($n = 11$ older and $n = 10$ younger bilinguals, after removal of participants who did not contribute usable data to all conditions). Interestingly, in this study older bilinguals also chose to switch languages as often as younger bilinguals, implying intact language control mechanisms. However, it remains an open question whether dominance reversal is intact in aging bilinguals.

A commonly cited model attributes most aging-related cognitive declines to reduced inhibitory control—the *Inhibitory Deficit Hypothesis* (Hasher et al., 1999; Hasher & Zacks, 1988; Zacks & Hasher, 1994). That is, aging leads to decline in the ability to suppress dominant responses and ignore irrelevant information (Levy & Anderson, 2008 for review). Although substantial evidence lends support to the Inhibitory Deficit Hypothesis (Hasher, 2015 for review), a general deficit in inhibition in aging is still debated (Rey-Mermet et al., 2018; Rey-Mermet & Gade, 2018) and differences in conclusions drawn across studies might be explained by moderating factors such as motivation, arousal, and practice (see Campbell et al., 2020 for discussion). However, if nonlinguistic inhibitory control mechanisms even partially overlap with whatever cognitive process leads bilinguals to reverse language dominance, an aging-related deficit in this signature of bilingual language switching performance would be expected.

The Current Study

We previously examined cued-language switching in one study with young and older Spanish-English bilinguals (Weissberger et al. 2012), but in which several factors might have limited sensitivity for detecting dominance reversal and aging effects. These include the use of digits as stimuli, which elicit smaller switch costs than pictures (Declerck & Philipp, 2015), and a relatively small number of trials in the mixed-language block ($n=80$), possibly a substantial limitation given recent evidence that inhibition accumulates with trial number in mixed-language blocks (Kleinman & Gollan, 2018). To address these possible weaknesses, in the present study we examined the emergence of dominance reversal in younger and older bilinguals using a cued language switching task with repeated presentation of pictures, and with a greater number of trials than in our previous study. To distinguish between language control at the lexical level versus the whole-language level, we initially presented just one set of pictures, henceforth List

A, and then halfway through the experiment we introduced a new set of pictures, henceforth List B.

We hypothesized that if executive control declines in older age— and assuming reversed language dominance at least partially reflects an inhibitory control process—then aging bilinguals should show reduced ability to reverse language dominance relative to younger bilinguals. Furthermore, if language dominance reverses primarily because of global control, then this should transfer from List A to List B, leading to dominance reversal for items in both lists. Additionally, if inhibition accumulates throughout the testing block, and is also at least partially specific to the items that have been repeated (i.e., perhaps via reactive inhibition between translation equivalents), then dominance reversal would be greater for List A than for List B items (and List B items would provide a purer index of global inhibition), with group differences in dominance reversal largest towards the end of the mixing blocks (where inhibition might be at a maximum for younger bilinguals; Kleinman & Gollan, 2018). Finally, the aging deficit might be especially pronounced on List B items, if only global inhibition is impaired in aging, and if List B provides a purer measure of global inhibition (while lexical-level effects affected by extensive repetition might be relatively intact in aging).

Methods

Participants and Recruitment

Forty-eight younger bilinguals and 25 older bilinguals² participated in the study for

² We originally recruited 34 total older bilinguals primarily from a pool of healthy control participants at the ADRC. Five were excluded for converting shortly after their participation from a diagnosis of Normal to a diagnosis of Mild Cognitive Impairment, and one to a diagnosis of probable AD. Two participants recruited from the community were excluded for having Dementia Rating Scale scores below 130. Another two participants were excluded for having mean RTs that were extreme outliers in mixed-language blocks (i.e., greater than 3 interquartile ranges in their respective group). This outlier labeling method is shown to be more robust against outliers than the mean or standard deviation (Hoaglin et al., 1986).

course credit or monetary compensation. This research was approved by the UCSD Institutional Review Board. Table 1 shows participant characteristics and demographics. Younger bilinguals were undergraduates at UCSD (ages 18-24). Older bilinguals (ages 62-91) were recruited from a cohort of cognitively healthy aging bilingual controls at the UCSD Alzheimer's Disease Research Center (ADRC; $n=17$) or from the community ($n=8$). Older participants were classified as cognitively healthy by the ADRC criteria using extensive neuropsychological and neurological exams reviewed independently by two neurologists. If recruited from the community, older bilinguals were administered the Dementia Rating Scale (DRS) and the Mini-Mental State Examination (MMSE) and were excluded for scores in the impaired range (see Table 1).³

Older bilinguals had significantly more years of education and higher picture naming scores than younger bilinguals (in this case in both languages; see also Gollan & Goldrick, 2019)⁴. Older bilinguals also reported learning English a few years later relative to younger bilinguals (6.9 vs 3.9 years old; Table 1). The younger group had a slightly higher proportion of English-dominant bilinguals based on an objective measure of proficiency in each language (the Multilingual Naming Test; Gollan et al., 2012), although the group difference was not significant

³ To measure age group differences in non-linguistic attention and inhibition, participants completed a Flanker task at the end of the testing session. Previously we administered a more difficult version of the task (e.g., with a shorter response deadline) and found a strong correlation with intrusion errors (Gollan et al., 2011). Here we attempted replication with a much easier version of this Flanker task, which appeared to be less sensitive to aging effects (for details see Supplemental Materials- Table S1; Figure S1).

⁴ It is not entirely clear why older bilinguals had higher scores than young bilinguals on the Multilingual Naming Test (MINT), especially given a significant negative effect of age on the MINT (Stasenko et al., 2019; see also Connor et al., 2004 for findings of decreased naming ability in aging). Several possible explanations include a slightly higher education level in older bilinguals and practice effects, given that the MINT is administered annually for the bilinguals who were enrolled in longitudinal research at the ADRC. Finally, previous studies that exhibited aging-related decline in naming ability might have included participants with prodromal Alzheimer's disease whereas in the present study bilinguals who converted to MCI or AD a year after their participation were excluded from analysis. This raises the possibility that previous reports of aging-related decline in picture naming ability should be attributed to prodromal AD.

(Table 1). Critically, bilinguals were matched on degree of bilingualism as measured by the Bilingual Index score (nondominant divided by dominant language) which has been shown to be a critical individual difference measure for predicting dominance reversal (Declerck et al., 2020).

Measures and Procedure

A highly proficient native Spanish-English bilingual experimenter administered all the tasks. The MINT is a 68-item picture naming test designed as an objective measure of proficiency in several languages. Participants first named pictures in their self-rated dominant language, followed by the same pictures in the nondominant language. Stimuli were presented on a MacBook laptop with a 15-in. display using PsychoPy version 1.81 (Peirce, 2007; 2009). Naming times were recorded using headset microphones connected to a response box and were also recorded with a digital recorder for off-line analysis.

Participants named 20 (10 in List A; 10 in List B) black and white line drawings of pictures repeatedly in Spanish or English based on a visual cue. Pictures were selected from Gollan and Ferreira (2009) for having high naming accuracy and agreement in both older and younger adults (>86%), and seven of these pictures exhibited large dominance reversal effects in Kleinman and Gollan (2018). See Appendix A for materials. English and Spanish picture names were equated for length in letters across lists and languages ($ps = .19$ and $.25$), although Spanish words had a slightly higher number of syllables in each list [$ps < .001$; $M = 2.40$ ($SD = 0.59$) and $M = 1.20$ ($SD = 0.49$), for lists A and B respectively). Assignment of items to List A (first half of the experiment) or List B (second half of the experiment) was counterbalanced across participants: For half of the participants, pictures 1-10 were in List A and pictures 11-20 were in List B, whereas for the other half of the participants, pictures 1-10 were in List B and 11-20 were in List A. Pictures were presented in a pseudorandom order such that the same picture was never

shown on consecutive trials. Also, each presentation of a given picture in a given condition and block was relatively spaced out such that it had to appear in every condition once (e.g., dominant language – switch trial) before it appeared in any condition a second time (e.g., Picture 1 appeared in trial 1, 11, 24 and 38). In mixed-language blocks, bilinguals were cued to name pictures in each language 50% of the time, with a 50% switch rate in each language. The maximum number of switch trials in a row was limited to 4. A practice (‘filler’) item was presented as the first trial of every block and was discarded from analyses. Four item lists were used so that item groups and the sequence of language cues were counterbalanced across subjects.⁵

Table 2 illustrates the block structure. Participants completed 12 practice trials before the first single-language block and before the first mixed-language block (with the same trial structure). The first half of the experiment consisted of List A items only using a sandwich design as employed by Rubin and Meiran (2005). Participants first completed two single-language blocks (naming in only English or only Spanish) of 20 trials each (40 critical trials total). Next, they completed two mixed-language blocks of 80 trials each (160 critical trials total) with a short break allowed between blocks. Finally, they named another set of two single-language blocks (40 trials total) to complete the ‘sandwich’ design for List A items, with language counterbalanced (i.e., English-first or Spanish-first, which was reversed in the second set of single-language blocks). In the first half of the experiment, each of the 10 List A critical pictures was repeated 16 times (8 times in each language) across the 160 trials in mixed-language blocks and 8 times (4 times in each language) across the 80 trials in single-language blocks.

⁵ In our final dataset, each counterbalancing group had 12 younger bilinguals and 6 (or 7) older bilinguals.

The second half of the experiment involved an additional and final repetition of List A pictures intermixed with 10 new (previously unseen) pictures (List B). Each of the 10 critical List B items was repeated 8 times (4 times in each language) across the 80 critical List B trials (intermixed with another 80 List A trials not included in the above count). In the List B single-language blocks, each picture was repeated 4 times (twice in each language). The second half of the experiment began with single-language naming of 40 trials of List B items⁶ followed by a final set of two mixed blocks comprising 80 trials each (160 critical trials total; 80 List A items and 80 List B items randomly intermixed). Within each block, there was no restriction on how many List A items appeared before the presentation of a List B item. As before, participants were able to take a short break after 80 trials.

Every trial began with a fixation cross presented for 500 ms. A language cue (flag) appeared on the screen above the fixation cross for 500 ms. This relatively long preparation time was chosen to minimize the effects of any possible age differences in cue processing. Target pictures then appeared in the center of the screen while the cue remained on screen. The cue and target remained until the bilingual responded, or for a maximum of 3000 ms. There was an 850 ms inter-stimulus blank screen prior to the onset of the next trial (Figure 1). The following instructions were given to participants: “When you see a U.S. flag, please name the picture in English. When you see a Mexican flag, please name the picture in Spanish. Please avoid saying ‘uh’ or ‘um’ or coughing.”

Statistical Analyses

⁶ Note that we included List B single-language blocks only so that bilinguals would have equivalent practice naming List A and List B items in single-language blocks prior to their inclusion in mixed-language blocks.

Across all included participants, 8,426 and 22,149 trials from the single- and mixed-language blocks, respectively, were submitted to RT analyses. Trials with incorrect responses or voice key errors, and trials that were faster than 250 ms were excluded. This resulted in a total exclusion of 5% of each age group's data for RT analyses. The RT data were analyzed using linear mixed-effects regressions (lme4 v. 1.1.21; Baayen et al., 2008) using R (version 3.6.3; R Core Team, 2017), and denominator degrees of freedom were estimated via the Satterthwaite approximation (lmerTest v. 3.1-0; Kuznetsova et al., 2017). In the omnibus model, fixed effects (and contrast weights) for analysis of mixed blocks included Language (Dominant = -0.5; Nondominant = +0.5; determined by each participant's MINT scores), Trial Type (Stay = -0.5; Switch = +0.5), Group (Younger bilinguals = -0.5; Older bilinguals = +0.5), List (List A = -0.25; List B = +0.75)⁷, and all possible interactions between these factors. For error analyses, we used generalized linear mixed models with the same factor structure. Error trials were coded as "1" and correct trials were coded as 0. An additional factor, *Trial Number* (range 1-320; values were centered and scaled), was added to one model to examine the influence of repetition in mixed-language blocks for List A items across the whole experiment. The 'emmeans' package in R (Lenth, 2016) was used for simple main effects and interaction contrasts. To adjust for age-related slowing, following the latest recommendations in aging research (Hedge et al., 2018), we converted raw RTs to z-scores separately for each individual based on their means and standard deviations across all conditions and repeated all models with RTs with z-scores as the dependent variable. We report whether key conclusions differed with transformed RTs (but see Supplemental Materials for detailed results).

⁷ As each participant named List A pictures on three times as many trials as List B pictures in mixed-language blocks, the contrast weights for each level of List reflected this imbalance, so that every trial was weighted equally.

For all reported models, we used a consistent three-step data-fitting strategy: (1) A model with a maximal random effects structure was fitted: random intercepts, all within-factor random slopes and their interactions, and correlations between random slopes. If this model did not converge (which was the case for all initial models), (2) we removed correlations between random slopes. If the resulting model still did not converge or converged with boundary issues (which was the case for all models) (3) we identified random slopes that accounted for less than 1% of the variance of their associated random factors, and then simultaneously removed all such slopes from the model (Bates et al., 2015). Trial-level data and analysis scripts are publicly available at osf.io/8h4dq.

Results

Appendix B presents means and standard deviations for RTs and errors across all conditions in the experiment. Z-score transformed means are presented in Supplemental Table S2 and Figure S2.

Single-Language Blocks

We began by examining standard language dominance effects within List A single-language blocks for the first 40 trials (i.e., prior to language-mixing trials; labeled as “Block X” in Table 2) in separate Group $\times$ Language analyses for reaction times and errors. Foreshadowing the results, bilinguals responded more quickly and with fewer errors in the dominant than in the nondominant language, and these language-dominance effects were equal in size in young and older bilinguals. Bilinguals responded more quickly in the dominant than in the nondominant language (a significant main effect of Language; $B = 82.42$; $SE(B) = 16.29$; $t(69) = 5.06$; $p < .001$), and younger bilinguals responded more quickly than older bilinguals (a significant main effect of Group; $B = 98.46$; $SE(B) = 22.92$; $t(70) = 4.30$; $p < .001$). The two-way interaction was

not significant ($p = .15$). The interaction of interest remained nonsignificant in a z-score analysis (Supplemental Table S3).

An analysis of errors provided converging evidence, revealing that bilinguals made fewer errors in the dominant than in the nondominant language (a significant main effect of Language; $B = 1.05$; $SE(B) = 0.50$; $z = 2.13$; $p = .03$). The two-way interaction was not significant ($p = .25$). Importantly, assignment of different pictures to List A versus List B (equivalent of first versus second half of the experiment) was counterbalanced between participants. Thus, it is not necessary to examine language dominance effects in single-language blocks for List B items, which were presented only *after* language-mixing (which could influence the size of language dominance effects).

Mixed-Language Blocks

Figure 2 and Table 3a show means and results of the mixed-language blocks analysis of RTs (i.e., Blocks 1-4 in Table 2). Supplemental Figure S2 and Table S4 show matching z-score results. Older bilinguals responded more slowly than younger bilinguals, a significant main effect of Group. Bilinguals also responded more slowly on List B than List A items, a significant main effect of List; and responded more slowly on switch versus stay trials, a significant switch cost indicated by a main effect of Trial Type. Of greatest interest, there was a significant interaction between Language $\times$ Group such that younger bilinguals exhibited larger reversed language dominance effects than older bilinguals⁸. Specifically, planned comparisons collapsing

⁸ Given a slightly (although not significantly) higher proportion of English-dominant subjects in the younger than in the older bilingual group as well as a significantly longer mean number of syllables for Spanish versus English words, we added a language covariate to the model (Spanish or English trial). The two-way interaction between Language (Dominant or Nondominant) and Group remained significant ($B = 33.4$; $SE(B) = 12.4$; $p = .01$), as did the z-score analysis that controlled for age-related slowing ($p < .001$). We also re-analyzed the data with English-dominant subjects only (with $n=40$ younger and 17 older bilinguals), and found that the interaction remained significant ($B = 32.5$; $SE(B) = 14.0$; $p = .02$).

across Trial Type and List revealed that whereas younger bilinguals named pictures more slowly in the dominant than in the nondominant language ($B = 28.55$, $SE(B) = 7.95$, $z(72) = 3.59$; $p < .001$), older bilinguals did not exhibit significant language dominance effects ($B = -6.33$, $SE(B) = 10.62$, $z(86) = -0.60$; $p = .55$). Finally, older bilinguals exhibited larger switch costs relative to younger bilinguals (a significant Group $\times$ Trial Type interaction). Critically, the Language $\times$ Group interaction remained significant in a model with z-scored RTs (Supplemental Table S4). However, the aging-related increase in switch costs was less robust to control for response slowing; the Group $\times$ Trial Type interaction was no longer significant ($p = .117$). Mixing cost analyses did not reveal significant age effects (see Supplemental Table S5).

The fact that older bilinguals exhibited smaller reversed dominance effects than young bilinguals (the Language $\times$ Group interaction⁹) provides critical support for the Inhibitory Deficit Hypothesis. Given the importance of the interaction to our theoretical account, we examined whether the critical interaction could have been driven by a less precise estimate of older (vs. younger) bilinguals' dominance effects due to an imbalance in sample sizes ($n = 25$ older vs. $n = 48$ younger bilinguals). To test this, we (repeatedly) equated the sample sizes by randomly selecting 25 young bilinguals (without replacement) and analyzed their data alongside the sample of 25 older bilinguals using the same statistical model described above. Of the 1,000 times this process was repeated, the Language $\times$ Group interaction was significant ($p < .05$) for 72.0% of the samples and marginally significant ($.05 < p < .10$) for another 18.7%. Additionally, young bilinguals showed significantly reversed language dominance effects in 81.9% of the samples and marginally significant effects in another 10.0%. These results indicate that the

⁹ We also examined this interaction with a mixed repeated measures ANOVA, which revealed identical results with a medium effect size for the interaction of interest (see Supplemental Table S6).

observation of significant reversed dominance effects in young adults—and the significantly different dominance effects between young and older adults—likely should not be attributed to the difference in sample sizes between groups.

Finally, in single-language blocks administered prior to the cued language-switching task (see above section entitled Single-Language Blocks), both younger and older bilinguals exhibited normal (not reversed) language dominance effects, and language dominance effects were also equally strong in young and older bilinguals. This is important given recent suggestions that dominance reversal per se may not be the critical signature of inhibition, but rather the extent to which language dominance shrinks when going from single-language to mixed-language blocks (Declerck et al., 2020). Therefore, to further increase confidence that older adults' failure to reverse language dominance effects in mixed-language blocks did not simply reflect subtle differences in language dominance between populations, we repeated the omnibus model controlling for each individual's standard dominance effects computed from single-language blocks prior to language-switching (i.e., Block X in Table 2). We found that young bilinguals demonstrated greater dominance reversal than older bilinguals in the mixed-language blocks even with this control—that is, the interaction between Group and Language remained significant ($B = 30.88$; $SE(B) = 12.27$; $t(60) = 2.52$; $p = .01$).

Errors

Table 3b presents the output of a matching error analysis collapsing all error types. Error rates were generally low in mixed-language blocks (4%). The majority of errors made in mixed-language blocks across both age groups were intrusions (43%; i.e., naming the picture in the wrong language); 24% were partial intrusions (i.e., starting to name the picture in the wrong language but then self-correcting); and 29% were incorrect, no-response, or don't-know

responses. Older bilinguals made significantly more errors than younger bilinguals, and bilinguals made more errors on switch versus stay trials—significant main effects of Group and Trial Type. Older bilinguals produced more intrusion errors than younger bilinguals in mixed-language blocks ($B = 0.63$; $SE(B) = 0.18$; $z = 3.61$; $p < .001$; see Figure 3).

Reversed Dominance for List A versus List B items

To examine whether younger bilinguals reversed language dominance significantly more for items named repeatedly in mixed-language blocks than for items for less practiced items, we performed two comparisons between List A and List B items. First, we compared Lists A and B within the second half of the experiment (Blocks 3 and 4; Table 2) to examine the effects of local inhibition on language dominance. In these blocks, List A items had been named many more times previously than List B items, so any item-specific component of reversed dominance effects should affect List A more than List B (while global inhibition would be equal across lists). Second, we compared List A items from the first Block (before intermixing lists in the first half of the experiment; Block 1 in Table 2) to List B items (Blocks 3 and 4) to examine the effects of global inhibition on language dominance (with lexically-specific inhibition equated across lists). In these blocks, List A and List B items had been previously named the same number of times. However, List B was preceded by more language mixing than List A (in Block 1), so global changes to the balance of language activation had more time to accumulate prior to List B and should thus affect those items more.

The results of these analyses are shown in Figure 4. For these analyses, we removed trial type to avoid overfitting the model and given that language dominance effects did not significantly vary by trial type in the omnibus model. This analysis revealed a significant interaction between Block and Language ($B = -25.56$ ms, $SE(B) = 11.90$ ms; $t(18) = -2.15$, $p =$

.045). Simple main effects suggested that bilinguals responded slower in the dominant than the nondominant language in the second half of the experiment for both List A and List B items ($p = .02$ and $p < .001$, respectively) but not in the first half (Block 1; $p = .12$). Contrasts revealed that reversed language dominance in List B items was significantly greater compared both to Block 1 List A items ($B = -12.70$, $SE(B) = 5.91$, $t(18) = -2.14$; $p = .046$) and to List A items in the second half ($B = -10.10$, $SE(B) = 5.02$, $t(150) = -2.01$; $p = .046$). Importantly, the greater dominance reversal effect in List B relative to Block 1 of List A was driven by slower responses in the dominant language in List B than List A ($M = 848$ vs 805 ms; $SD = 252$ vs 219 ms; $B = -43.64$; $SE(B) = 13.37$; $t(59) = -3.27$; $p = .01$), whereas pictures were named in the nondominant language at a similar speed across lists ($p = .37$).

Effects of Repetition in Mixed-Language Blocks

To test whether inhibition increases continuously over time for repeated items and whether this might have modulated aging effects, we conducted a final analysis with all presentations of List A pictures across the four mixed-language blocks, and with the linear effect of Trial Number as an additional factor (removing Trial Type to avoid overly complex models). The linear effect of trial number was not significant and did not interact with other factors (Table 4 and Figure 5). We examined the same model in younger bilinguals only and found a significant main effect of trial number ($B = 9.21$; $SE(B) = 4.33$; $t(47) = 2.13$; $p = .04$), which did not interact with language ($p = .70$).

Discussion

The results of the present study revealed several key findings. First, in mixed-language blocks, younger bilinguals exhibited significantly larger reversed language dominance effects than older bilinguals, who in fact exhibited no dominance effects at all. In contrast, both groups

exhibited standard (non-reversed) language dominance effects in single-language blocks. Second, older bilinguals produced more cross-language intrusion errors than younger bilinguals. Third, we observed *larger* reversed dominance effects in List B (which was repeated less) than in List A in younger bilinguals, an effect in the opposite direction of what we predicted and that seemed to be driven by slower responses in the dominant language in List B relative to List A. Finally, we did not replicate the finding of increased dominance reversal with increased trial number; the aging-related deficit in dominance reversal did not increase in size with repetition; and in young bilinguals only, responses slowed with repetition in mixed-language blocks, but equally so for both languages.

Joint Support for Bilingual Inhibitory Control and Inhibitory Deficits in Aging

Our finding of reversed language dominance in younger bilinguals supports a core assumption of the Inhibitory Control Model (Green, 1998) and replicates previous findings of several studies with young bilinguals (Christoffels et al., 2007; Costa & Santesteban, 2004; Costa et al., 2006; Gollan & Ferreira, 2009; Heikooop et al., 2016; Kleinman & Gollan, 2016; 2018; Peeters & Dijkstra, 2017; Verhoef et al., 2009; for review see Declerck, 2020). Previously, we suggested that the most parsimonious explanation for reversed dominance is inhibition (Declerck et al., 2020; Gollan & Goldrick, 2018; Kleinman & Gollan, 2018). On this view, reduced language dominance reversal in older bilinguals provides what is perhaps the clearest evidence reported thus far in the literature on language production for the Inhibitory Deficit Hypothesis (Hasher et al., 1999; Hasher & Zacks, 1988; Zacks & Hasher, 1994).

A reasonable question is whether the smaller (and nonsignificant) dominance reversal in aging should be taken as evidence of a processing deficit, or if it could instead reflect an aging-related difference in some other cognitive process. This idea is consistent with aging studies

outside the domain of language which suggested that what seems to be a deficit can sometimes instead reflect a processing advantage or difference in priorities and strategic approach (e.g., Amer & Hasher, 2014; Kemper, et al., 1989; Ramscar et al., 2014; for reviews see Amer et al., 2016; Kavé & Goral, 2017). A relevant consideration here is that reversing language dominance might not be an efficient strategy for language mixing (Declerck et al., 2020). This puts a potentially different spin on the ‘failure to reverse dominance’ observation, possibly suggesting that older bilinguals—who have had many more years of managing dual-language activation—might be better able to gauge (whether implicitly or explicitly) how much control they need to apply to keep both languages about equally accessible. A strong argument against the possibility of an aging-related processing advantage, however, is that older bilinguals also produced significantly more intrusion errors than younger bilinguals. This replicates previous findings in different speaking tasks (in verbal fluency; Gollan et al., 2011 and in reading aloud; Gollan & Goldrick, 2016), and provides independent evidence for reduced language control in aging, which better fits the failure to reverse language dominance in older bilinguals as reflecting inhibitory control deficits.

Although older bilinguals did not reverse language dominance, they also did not exhibit significant normal language dominance effects in mixed-language blocks, whereas they did in single-language blocks, prior to language mixing. Thus, older bilinguals may have been attempting to equalize activation of the two languages (see Figure 6, which summarizes dominance effects across the experiment). However, the absence of dominance effects could simply reflect the greater benefit of repetition to the nondominant (than to the dominant) language (Francis et al., 2003). Supporting this view, neither young nor older bilinguals exhibited significant dominance effects in the single-language blocks that were presented *after*

language mixing (younger bilinguals: $B = -1.81$; $SE(B) = 10.52$; $t(35) = -0.20$; $p = .87$; older bilinguals: $B = 15.82$; $SE(B) = 19.51$; $t(25) = 0.80$; $p = .43$). Thus, the absence of dominance effects in older bilinguals in the mixed-language block was not specific to language switching, and might have simply reflected greater repetition effects on the nondominant than the dominant language.

The Cognitive Mechanism Underlying Dominance Reversal: Global Inhibition

A unique feature of our study design was the introduction of a new list of pictures halfway through the mixed-language blocks. This manipulation was intended to test which of two loci of inhibition accounts for dominance reversal—global (with inhibition spread via language nodes that inhibit all representations in the non-target language) or local (with inhibition spread at the lexical level, with competing translation equivalent lexical representations mutually inhibiting each other; Green, 1998). Of particular interest, reversal of language dominance not only transferred to previously unpracticed never-language-mixed (List B) items, but reversal was also *greater* in List B than in List A items in younger bilinguals. Importantly, assignment of specific pictures to each list was counterbalanced between participants, and thus this effect was not an artifact of item assignment to list condition. The apparent transfer of inhibitory control of the dominant language to novel items suggests that inhibition operates at a whole-language level, and the cognitive mechanism underlying this transfer effect may also cause block order effects (Christoffels et al., 2016; Wodniecka et al., 2020), which sometimes were found in brain response measures (ERPs) but not in behavioral responses (e.g., Misra et al., 2012; but see Branzi et al., 2014). The experimental manipulation applied here may be more powerful for revealing the effects of global language control because

of the interleaving of List A items when List B was presented, and because language mixing was interrupted only very briefly by short single-language blocks (see Table 2, Block Z).

Though our results provide clear support for the proposal that dominance reversal reflects global inhibition of the dominant language much more than lexical-level effects, other aspects of the results raise questions. First, if dominance reversal exclusively reflected global inhibition, it should have been equal for List A and List B items. We speculate that, contrary to what prior research led us to predict, extensive repetition of List A items may have *weakened*, rather than strengthened, dominance reversal (for similar arguments see Misra et al., 2012). Note that by the time participants encountered List B items they already had extensive practice with language switching and had time for global inhibition to accumulate—but the relatively larger effect on List B suggests that extensive repetition of List A items served to *offset* instead of magnify lexical-level competition for selection between languages, and reactive inhibition between translation equivalents. However, this would still not explain why dominance reversal in List B was greater than the *initial* block of List A items (because in this comparison, the effects of repetition for specific items were equated). Thus, an alternative possibility is that younger bilinguals over-applied inhibition to less practiced items, though this would require distinguishing old from new list items in fractions of a second and modulating the amount of inhibition trial-to-trial, which seems less likely.

If List B provided a purer index of global control than List A, and the aging deficit is localized primarily at the level of global control, a second question arises as to why the aging deficit was not significantly greater for List B than List A items. Although this appears to be the case when visually examining Figure 6, the three-way interaction was not significant (Table 3). To further explore this issue, we examined the aging effect on dominance reversal within each

list alone (the Group $\times$ Language interaction). Although both contrasts were significant (List A: $B = -26.90$; $SE(B) = 13.02$; $p = .04$; List B: $B = -42.90$; $SE(B) = 16.12$; $p = .01$), the effect size for List B was numerically larger than for List A. If this difference had reached significance, a magnified aging deficit for List B relative to List A items (which were repeated much more in the course of the entire experiment) could have suggested that intact lexical repetition allowed older bilinguals to partially compensate for a deficit in global control. On this view, we have to assume that the lack of a three-way interaction either reflected insufficient power to detect it, or the presence of more complex interactions between lexical-level and global control that obscure the modulation of aging effects by list type.

Finally, we did not replicate the finding that inhibition continuously accumulates over time as in Kleinman and Gollan (2018). Several methodological differences between the two studies could have caused this difference, including a smaller sample size; inclusion of four (vs. one) mixed-language blocks (with concomitant ramping-up effects on RTs at the beginning of each block as observed in Figure 5); and more regular spacing of consecutive presentations of each picture in the current study, which permitted an overall analysis of Trial Number but not its decomposition into separate facilitative and inhibitory components.

Challenges to the Inhibitory Deficit Hypothesis and Alternative Accounts

Previous support for the Inhibitory Deficit Hypothesis mostly comes from studies that targeted attention and memory rather than linguistic processing per se (e.g., suppression of unwanted memories; Anderson et al., 2011; Murray et al., 2015). Indeed, in the domain of *language production*, the Inhibitory Deficit Hypothesis has been criticized for failing to support existing empirical evidence (e.g., Taylor and Burke, 2002; Burke, 1997 for review). Some of these included studies of the tip-of-the-tongue (TOT) phenomenon (e.g., by examining whether

prior presentation of a movie character name would lead speakers to inhibit the actor's name, blocking its subsequent retrieval; Cross & Burke, 2004). However, unlike the present study, which produced robust evidence for inhibitory control in young bilinguals, young adults in the TOT study did not exhibit significant evidence of blocked retrieval. Thus, the TOT paradigm may not be well suited for examining between-group differences in inhibitory control, either due to the (in)sensitivity of the paradigm or because inhibitory control is simply not relevant to TOT resolution. Another study examined blocking effects using a picture-word retrieval paradigm and found greater semantic interference effects in older than in younger speakers (Taylor & Burke, 2002), but the authors attributed this result to older adults having a richer semantic network – a between-group difference that cannot explain the global control effects we report here. Although it is possible that the present aging effects reflect greater demands associated with *bilingual language selection*, which is arguably more challenging than monolingual speech production, this topic merits further investigation.

Although we have assumed that dominance reversal reflects global inhibition of the dominant language, it could be conceptualized more broadly as reflecting *proactive control* (see Declerck, 2020 for discussion), which (outside the domain of language processing) has been proposed as the most reliable aging-related decline in executive control—specifically, that proactive control is more impaired than reactive control (e.g., Braver et al., 2001; 2005; Wasylyshyn et al., 2011). Recent research reveals a link between language switching ability and proactive control as measured by the AX-CPT task (e.g., Beatty-Martínez et al., 2020; Gullifer & Titone, 2020; Zhang et al., 2015), which also reveals robust aging-related failure to apply proactive control (Braver et al., 2001; Braver et al., 2007; Braver, 2012; but see Xiang et al., 2016). To link this to reversed language dominance—a bilingual must continuously monitor and

prepare for an upcoming switch, which may lead them to anticipate interference from the dominant language, and to inhibit it globally—a proactive control strategy. On this analogy, our recent finding that dominance reversal does not lead to faster responding overall in mixed-language blocks (Declerck et al., 2020) further requires assuming that strategies do not always lead to more efficient performance (a fact supported by the observation that bilinguals can switch languages more efficiently in some situations where they have *less*, as opposed to more, control over when to switch; Kleinman & Gollan, 2016).

An alternative to the inhibition account is that reversed language dominance reflects global *over-activation of the nondominant language*, another form of proactive control that in turn produces greater competition for selection between languages in mixed-language blocks (e.g., Bobb & Wodniecka, 2013; Koch et al., 2010; Verhoef et al., 2009). These possibilities are not mutually exclusive, as reversed language dominance effects may even reflect a combination of both activation and inhibition (Branzi et al., 2014; for discussion see Declerck & Philipp, 2015). However, our data challenge the activation-only account: dominance reversal in our study was greater for List B than List A, and when we directly compared responses in the two lists, this difference was driven by slowing of *the* dominant language by language mixing (in List B relative to List A), whereas the nondominant language did not become faster (which is expected under the activation account). Although it could be the case that increased activation of the nondominant language was offset by an overall slowing process that affected both languages, this is a less parsimonious account, requiring two mechanisms rather than just one.

Outside the literature on language processing, aging deficits in inhibitory control have also been challenged (e.g., Verhaeghen, 2011; Rey-Mermet et al., 2018). Many of these studies relied on the absence of significant correlations between different tasks purporting to measure

the same construct. However, such correlations are only informative when there are robust and stable individual differences, which these tasks were not designed to measure (Draheim et al., 2020; Hedge et al., 2018; Segal et al., in press); and the interpretation of null effects is necessarily limited, requiring high power to observe the effects, inclusion of well-matched groups, and exclusion of older participants with mild cognitive impairment. Recent meta-analytic evidence suggests that the most robust aging-related declines in executive control include the ability to inhibit a *prepotent response* as measured by stop-signal or go-no-go tasks (Rey-Mermet & Gade, 2018; Rey-Mermet et al., 2018), which speculatively, could be analogous to a failure to reverse language dominance in the aging group in the present study. In fact, using the go-no-task—Li and colleagues (2021) found that faster go-no-go response times (i.e., better inhibitory control) were associated with larger reversed language dominance effects. This invites future avenues for examining more directly the effect of response inhibition on global language control in aging bilinguals using similar tasks.

Conclusion

Our findings provide unique evidence that bilinguals globally inhibit the dominant language to switch languages, supporting the Inhibitory Control Model (Green, 1998); and this language control ability decreases in aging, supporting the Inhibitory Deficit Hypothesis (Hasher & Zacks, 1998, Hasher, 2015). Although the Inhibitory Deficit Hypothesis has been criticized, it provides the most ready explanation of our findings. It is possible that bilingual language switching tasks requires greater inhibitory control, or control at a higher processing level (proactive instead of reactive), relative to monolingual speech production, but it might also be possible to observe similar aging deficits in monolinguals with a different task than those previously used. It has recently been suggested that inhibition is not a domain that should show a

bilingual advantage (e.g., Bialystok, 2017). However, research on bilingual language processing strongly implicates inhibition in the language domain, including the work presented herein.

Although the concept of an inhibitory deficit in aging continues to be debated (see Psychology and Aging special issue; Campbell et al., 2020), it is clear that more work is needed to fully characterize aging-related changes in both linguistic and nonlinguistic inhibitory control.

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Figures

Figure 1

Cued Language Switching Task: Experimental Design

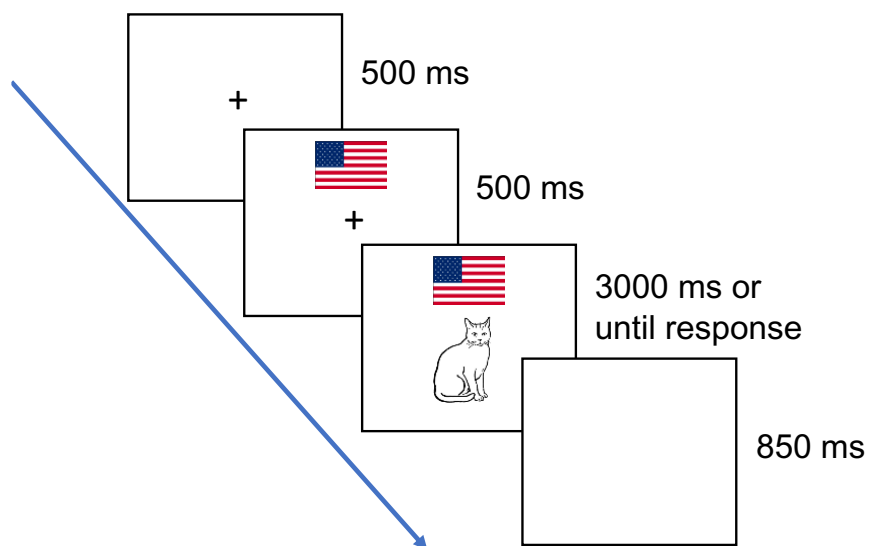
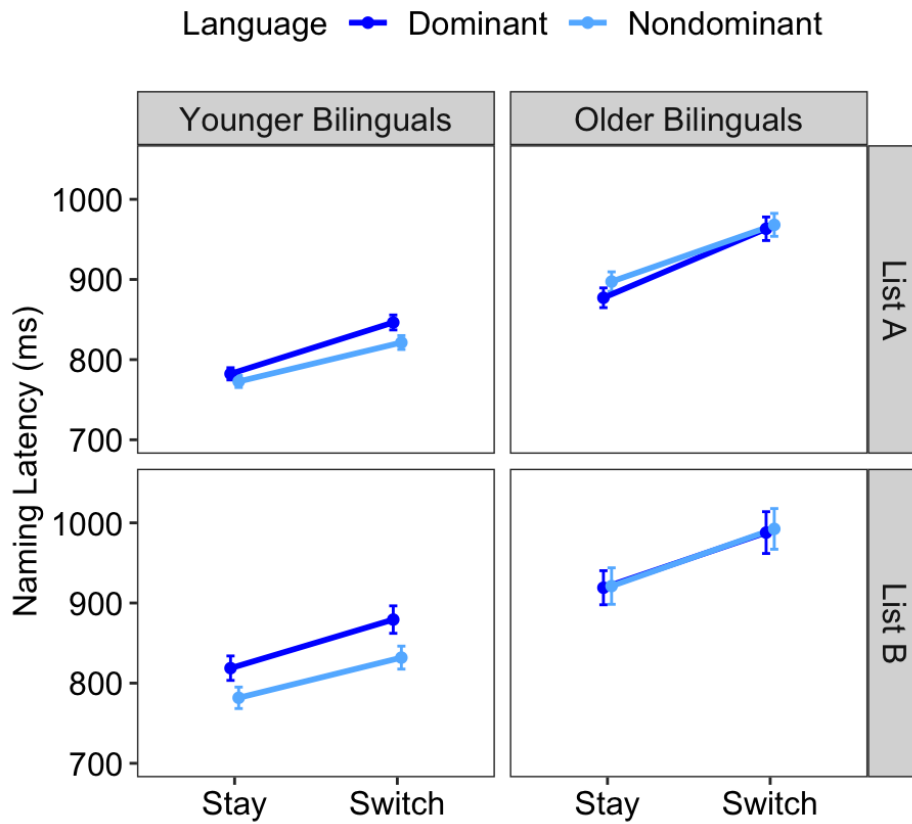


Figure 2

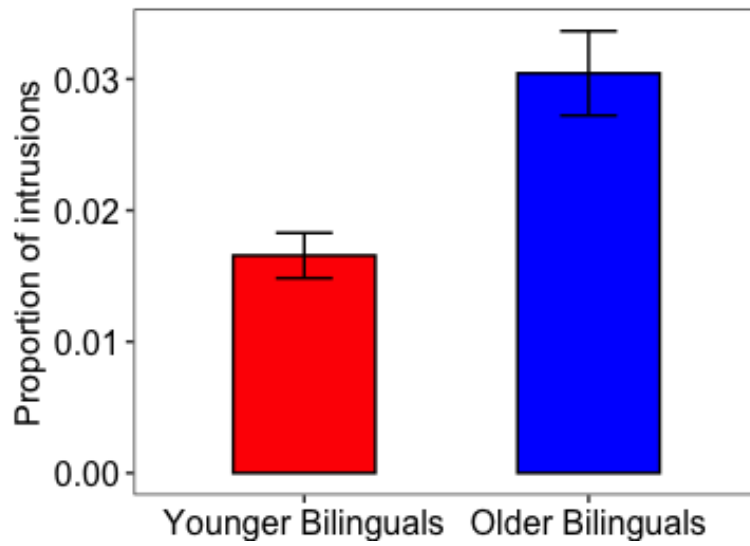
Naming Latencies in All Mixed-Language Blocks Plotted by Trial Type (x-axis) and Language, separately by Age Group and Picture List



Note. Error bars represent 95% confidence intervals.

Figure 3

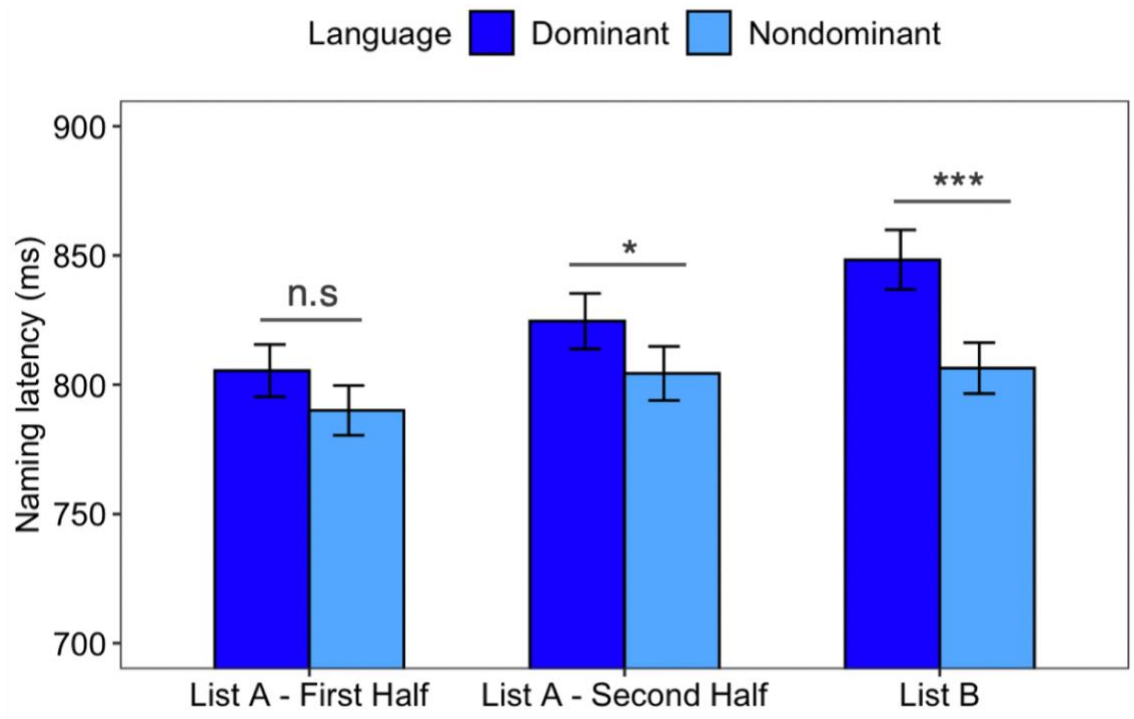
Proportion of Intrusion Errors (e.g., saying “casa” instead of “house”) Produced by Young versus by Older Bilinguals During Language Switching



Note. Error bars represent 95% confidence intervals.

Figure 4

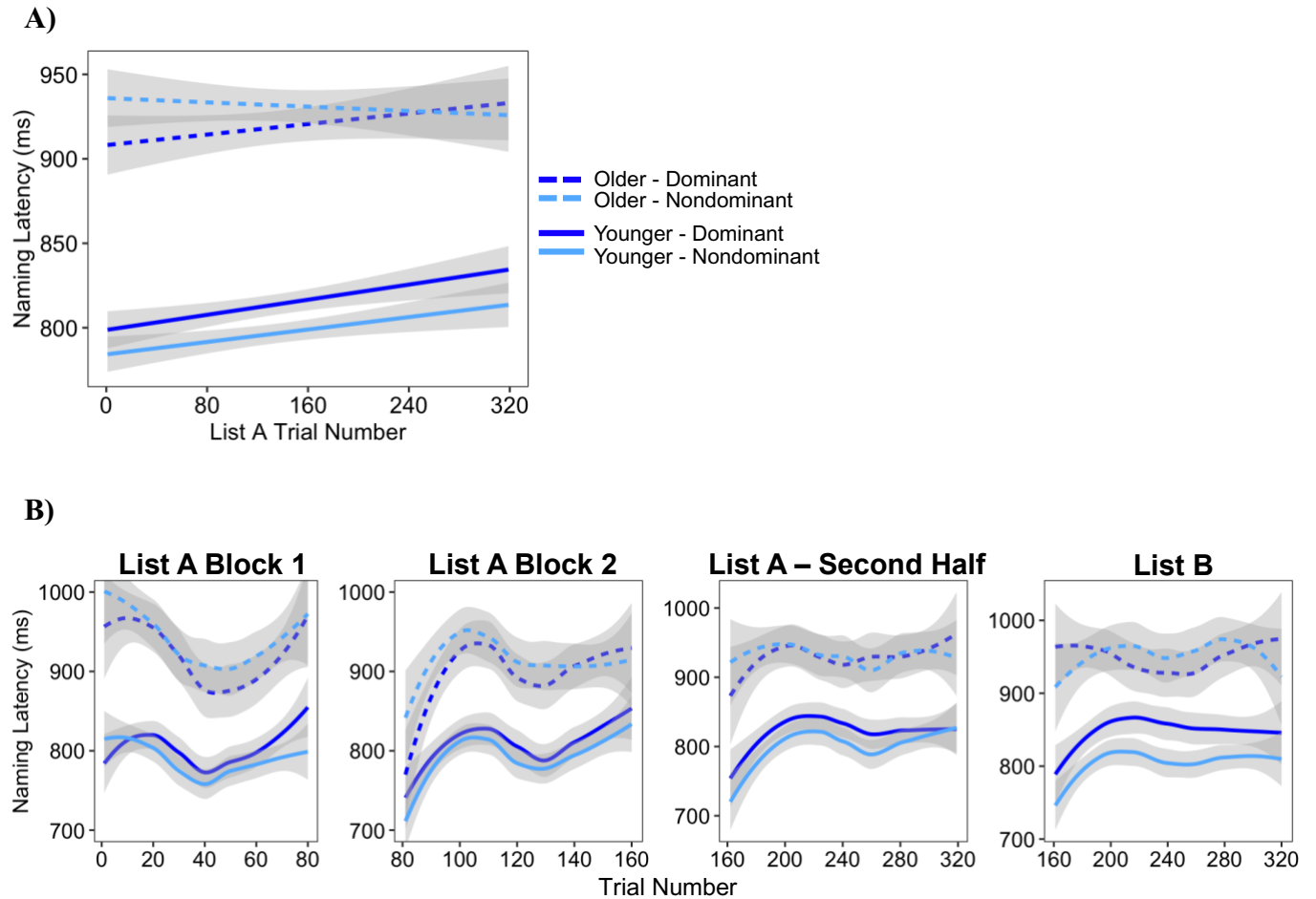
Younger Bilinguals' Naming Latencies Plotted Separately by List A items (Before Inter-mixing Lists; First Half) and List A and B Items when Intermixed (Second Half)



Note. Asterisks signify where reversed dominance effects are significant in simple-main effects analyses (* $p < .05$; *** $p < .001$).

Figure 5

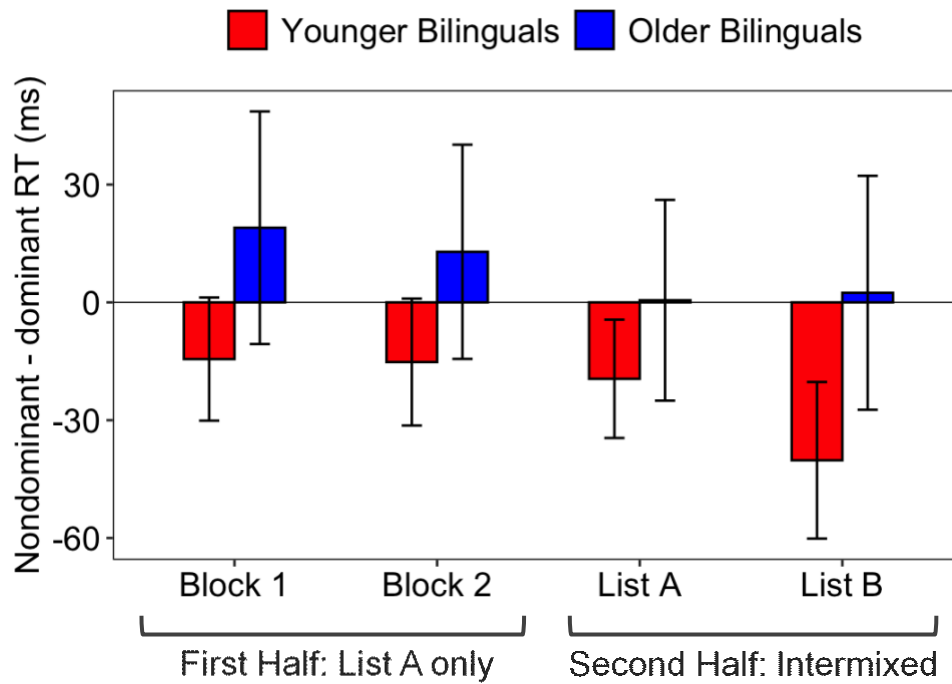
Naming Latencies as a Function of Trial Number Plotted for A) List A Items with a Linear Model and B) Separately by Mixed-Language Block with Local (LOESS) Regression



Note. Panel A matches the linear mixed effects analysis presented in Table 4. Panel B shows trial-level RT data, in which each figure represents data from 80 picture naming trials (40 per language) per participant, not counting data loss from naming errors. Due to the experimental design, these 80 trials were presented consecutively in Blocks 1 and 2, whereas they were spread out across 160 trials in List A – Second Half and in List B (which were intermixed but are plotted separately in the figure). In Panel B, trial-level RTs are LOESS-smoothed, which is represented by the 95% confidence interval ribbons. Naming latencies collapsed across stay and switch trials.

Figure 6

Summary of Language Dominance Effects (Nondominant – Dominant RTs) by Experimental Block



Note. Error bars represent 95% confidence intervals.

Tables

Table 1

Participant Demographics, Language Background Characteristics, and Cognitive Performance

	Younger bilinguals (n=48)		Older bilinguals (n=25)		p-value
% Female	85		72		.214
% Right-handed	88		88		1
% Hispanic/Latino(a)	98		100		1
% English-dominant based on MINT	81 ^a		68		.148
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>p</i> -value
Age	19.85	1.40	73.04	7.73	<.001
Education	13.46	1.13	15.28	2.73	.003
Mean parental years of education	11.06	4.04	10.11	4.94	.421
Age first exposure to English	3.89	3.44	6.90	7.49	.072
Age first exposure to Spanish	0.11	0.56	0.30	1.50	.555
% grow up using English	49.44	21.33	42.08	34.39	.192
% current using English	81.67	18.50	63.72	31.67	.023
Self-rated English proficiency ^b	6.51	0.68	6.30	0.72	.240
Self-rated Spanish proficiency ^b	6.04	0.73	5.66	1.36	.205
Self-rated dominant proficiency ^b	6.71	0.48	6.62	0.52	.470
Self-rated nondominant proficiency ^b	5.84	0.70	5.35	1.21	.070
MINT					
Dominant	60.88	2.92	65.12	2.13	<.001
Nondominant	47.19	8.80	52.60	10.34	.031
English	59.50	4.82	63.16	4.10	.001
Spanish	48.56	9.87	54.56	11.74	.035
Bilingual Index ^c	0.77	0.14	0.81	0.16	.373
MMSE	--	--	28.68	1.75	--
DRS-2	--	--	137.48	3.74	--

Note. MINT=Multilingual Naming Test; DRS-2 = Dementia Rating Scale-Second Edition; MMSE = Mini-Mental State Examination. *p*-values correspond to independent samples *t*-tests for continuous variables (equal variances not assumed) or Fisher's exact tests for categorical variables.

^a One younger bilingual had equivalent scores on the English and Spanish MINT; they were re-classified as English-dominant based on immersion in a primarily English-context

^b Self-rating was based on a 7-point scale: 1 = almost none, 2 = very poor, 3 = fair, 4 = functional, 5 = good, 6 = very good, and 7 = like native speaker.

^c Bilingual Index = Nondominant MINT/Dominant MINT

Table 2

Structure of the Sandwich Design

Experimental Half	Block Type	Block ID	Picture List	<i>n</i> trials
First	Single	Block X	A	40
	Mixed	Block 1	A	80
	Mixed	Block 2	A	80
	Single	Block Y	A	40
Second	Single	Block Z	B	40
	Mixed	Block 3	A and B	40A, 40B
	Mixed	Block 4	A and B	40A, 40B

Note. Single-language blocks (i.e., “Single”) are labeled as X-Z and mixed-language blocks (i.e., “Mixed”) are numbered 1-4.

Table 3

Results of a Linear Mixed Effects Model with Reaction Times (RTs; 3a) and Errors (3b) as the Dependent Variable for Mixed-Language Blocks

3a. RTs ^a	<i>B</i>	<i>SE (B)</i>	<i>df</i>	<i>t</i> -value	<i>p</i> -value
(Intercept)	873.22	13.48	74	64.80	<.001
Language	-7.13	6.52	60	-1.09	.279
Group	123.38	27.07	75	4.56	<.001
Trial Type	66.95	5.68	54	11.80	<.001
List	27.15	7.70	29	3.53	.001
Language × Group	30.88	12.26	60	2.52	.014
Language × Trial Type	-13.68	7.00	26	-1.96	.061
Group × Trial Type	21.87	10.40	71	2.10	.039
Language × List	-15.91	8.36	22	-1.90	.070
Group × List	8.01	10.15	39	0.79	.435
Trial Type × List	-3.40	8.84	21	-0.38	.705
Language × Group × Trial Type	0.77	13.64	70	0.06	.955
Language × Group × List	15.98	15.22	21	1.05	.306
Language × Trial Type × List	8.54	13.60	21572	0.63	.530
Group × Trial Type × List	-3.91	13.60	21562	-0.29	.774
Language × Group × Trial Type × List	7.86	27.19	21568	0.29	.772
3b. Errors	<i>B</i>	<i>SE (B)</i>	<i>z</i> -value	<i>p</i> -value	
(Intercept)	-3.67	0.11	-33.54	<.001	
Language	0.11	0.16	0.72	.470	
Group	0.47	0.22	2.17	.030	
Trial Type	1.07	0.09	11.90	<.001	
List	-0.28	0.15	-1.89	.059	
Language × Group	-0.25	0.30	-0.82	.415	
Language × Trial Type	-0.22	0.15	-1.49	.136	
Group × Trial Type	0.15	0.18	0.82	.410	
Language × List	0.51	0.28	1.79	.074	
Group × List	-0.02	0.23	-0.10	.917	
Trial Type × List	0.01	0.18	0.06	.951	
Language × Group × Trial Type	0.01	0.30	0.05	.961	
Language × Group × List	-0.71	0.53	-1.34	.180	
Language × Trial Type × List	-0.54	0.36	-1.53	.127	
Group × Trial Type × List	-0.63	0.36	-1.77	.077	
Language × Group × Trial Type × List	0.43	0.71	0.60	.549	

Note. Effects significant at $p < .05$ are bolded and marginally significant effects ($p < 0.10$) are italicized. The Language factor has two levels: dominant and nondominant which was determined based on individual MINT scores. ^a See Supplemental Table S4 for model output with z-score transformed RTs (adjusted for age-related slowing).

Table 4

Results of a Linear Mixed Effects Model for all List A items with Trial Number as a Factor to Index Repetition Effects

	<i>B</i>	<i>SE (B)</i>	df	<i>t</i> -value	<i>p</i> -value
(Intercept)	865.22	13.60	74	63.60	<.001
Language	-2.82	6.30	54	-0.45	.656
Group	120.22	27.28	75	4.41	<.001
Trial Number	5.88	3.67	63	1.60	.114
Language × Group	27.57	12.47	53	2.21	.031
Language × Trial Number	-6.08	3.78	23	-1.61	.121
Group × Trial Number	-6.50	7.00	71	-0.93	.358
Language × Group × Trial Number	-8.89	6.98	21	-1.27	.217

Note. Effects significant at $p < .05$ are bolded. The Language factor has two levels: dominant and nondominant which was determined based on individual MINT scores.

Appendix A

Items Used in the Language Switching Task

Picture List^a	Item Type	English	Spanish
A	Filler	box	caja
A	Critical	bell	campana
A	Critical	cheese	queso
A	Critical	horse	caballo
A	Critical	tree	árbol
A	Critical	hand	mano
A	Critical	clown	payaso
A	Critical	sun	sol
A	Critical	grapes	uvas
A	Critical	knife	cuchillo
A	Critical	book	libro
B	Filler	cow	vaca
B	Critical	bone	hueso
B	Critical	bed	cama
B	Critical	strawberry	fresa
B	Critical	iron	plancha
B	Critical	house	casa
B	Critical	ring	anillo
B	Critical	clock	reloj
B	Critical	dress	vestido
B	Critical	star	estrella
B	Critical	heart	corazón

^aAssignment of pictures to List A versus List B was reversed for 50% of participants.

Appendix B

Table 1B

Means and (Standard Deviations) of Reaction times and Errors in the Language Switching Task

<i>Reaction Times</i>		Mixed-Blocks List A			Mixed Blocks - List B		
Group	Language	Stay	Switch	Switch Cost	Stay	Switch	Switch Cost
Younger	Dominant	782 (205)	846 (247)	64	819 (239)	879 (263)	61
	Nondominant	773 (200)	821 (230)	49	782 (206)	832 (218)	50
Older	Dominant	877 (239)	963 (276)	86	919 (238)	988 (286)	69
	Nondominant	897 (236)	968 (270)	71	921 (253)	992 (278)	71
		List A – First Half Only			List B		
		Single	Stay	Mix Cost	Single		
Younger	Dominant	739 (192)	774 (200)	35	808 (237)		
	Nondominant	762 (231)	765 (189)	3	827 (241)		
Older	Dominant	809 (180)	870 (231)	61	869 (239)		
	Nondominant	871 (249)	893 (237)	22	959 (294)		

<i>Errors</i>		Mixed-Blocks List A			Mixed Blocks - List B		
Group	Language	Stay	Switch	Switch Cost	Stay	Switch	Switch Cost
Younger	Dominant	0.02 (0.14)	0.05 (0.21)	0.03	0.01 (0.09)	0.04 (0.20)	0.03
	Nondominant	0.02 (0.15)	0.05 (0.22)	0.03	0.03 (0.17)	0.06 (0.24)	0.03
Older	Dominant	0.03 (0.17)	0.09 (0.28)	0.06	0.02 (0.15)	0.07 (0.25)	0.04
	Nondominant	0.03 (0.17)	0.08 (0.27)	0.05	0.03 (0.18)	0.06 (0.24)	0.03
		List A – First Half Only			List B		
		Single	Stay	Mix Cost	Single		
Younger	Dominant	0.01 (0.10)	0.02 (0.14)	0.01	0.001 (0.03)		
	Nondominant	0.03 (0.17)	0.03 (0.16)	-0.003	0.05 (0.22)		
Older	Dominant	0.01 (0.12)	0.03 (0.17)	0.02	0.01 (0.08)		
	Nondominant	0.02 (0.14)	0.03 (0.17)	0.01	0.02 (0.15)		

Note. Switch cost (RT switch - RT stay trials); Mix cost (RT stay – RT single trials). Due to the nature of the experimental design for List B (i.e., half as many trials as for List A), we do not report mixing costs for List B. Determination of the dominant and nondominant languages was based on each individual's English and Spanish MINT scores.