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How aging and bilingualism influence language processing: theoretical and neural models

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Abstract

Healthy non-pathological aging is characterized by cognitive and neural decline, and although language is one of the more stable areas of cognition, older adults often show deficits in language production, showing word finding failures, increased slips of the tongue, and increased pauses in speech. Overall, research on language comprehension in older healthy adults show that it is more preserved than language production. Bilingualism has been shown to confer a great deal of neuroplasticity across the life span, including a number of cognitive benefits especially in executive functions such as cognitive control. Many models of bilingual language processing have been proposed to explain bilingual language processing. However, the question remains open of how such models might be modulated by age-related changes in language. Here, we discuss how current models of language processing in non-pathological aging, and models of bilingual language processing can be integrated to provide new research directions.

Language is often taken to be the aspect of cognition that makes us distinctly human. Until very recently, most research primarily considered the linguistic abilities of monolingual speakers. However, contrary to a monolingual view of the world, the majority of speakers live their life juggling more than one language. From recent census data, the number of bilingual speakers in the world and in the US is rapidly increasing. Fifty six percent of European speakers are considered bilinguals (2006 European Commission report); 35 percent of the population in Canada is bilingual, and the US follows the growing trend with 20% bilingual speakers (Grosjean & Li, 2012). The recognition that most of the world's speakers are bilingual, and that the number of multilingual speakers is increasing has sparked new areas of study that examines the ways in which bilinguals manage the presence of more than one language in the same mind and brain and also views bilingualism as a lens to understand the relation between language and cognition throughout the lifespan.

At the same time, given the statistics on the aging population, two major scientific and social challenges are able to define the major cognitive changes related to non-pathological aging, and how to deal with an increasingly aging population. Older adults are the largest growing segment of the US population, and current estimates anticipate that older adults will number 70.3 million by 2030 (Kempler, 2005). Healthy non-pathological aging is often

characterized by cognitive and neural decline in a number of cognitive abilities (Park et al., 2002), and although language is one of the more stable areas of cognition, older adults often show deficits in language production (Burke & Shafto, 2008; Shafto & Tyler, 2014). A number of factors have been correlated with maintenance and improvement in cognitive functions in older adults, including physical exercise (for a review see Colcombe & Kramer, 2003), engaged social activities (Carlson et al., 2012, Stine-Morrow et al., 2014), and targeted cognitive training (Basak et al., 2008; Park & Bischof, 2013).

Importantly, bilingualism has also been shown to be one of the factors conferring a great deal of neuroplasticity across the life span, especially in executive functions such as cognitive control, and working memory. The life-long experience of monitoring and controlling two (or more) languages seems to be the basis for bilinguals to exhibit a range of language-independent cognitive gains (e.g., Martin-Rhee & Bialystok, 2008; Bialystok, Craik, Klein & Viswanathan, 2004). Moreover, bilingualism has been shown to induce structural changes, with increased gray-matter-density in older adults (Abutalebi et al., 2015) and promotes a delay of up to four years in the cognitive symptoms related to Alzheimer's disease (Alladi et al., 2014; Craik, Bialystok & Freedman, 2010; Schweizer et al., 2012). These initial findings suggest overall that bilingualism might play a positive role in contributing to cognitive reserve (CR), and boost a number of executive functions, such as inhibitory control, conflict monitoring, selective attention and working memory. The reliability and replicability of the positive effects on cognition due to speaking and processing multiple languages, and the question of how to control for the multiple internal and external factors that characterize the variable nature of bilingualism are still a matter of debate, and goes beyond the scope of this work (but see, Kousaie et al., 2014; Paap & Greenberg, 2013; Paap & Liu, 2014; Paap et al., 2014; Valian, 2014, and Baum & Titone, 2014 for a critical discussion on this topic).

While in recent years much attention has been paid toward the importance of bilingualism for cognitive and neural plasticity in adulthood, the focus has been on the influence of bilingualism on extralinguistic areas of cognition, such as executive functions. Compared with other cognitive domains, less has been described about how bilingualism might shape age-related changes in language processing. More data on how cognitive and linguistic processes are shaped in older adults could inform the current literature on language processing in non-pathological aging and will also benefit bilingual research. Despite the growing body of work on the potential positive effects of bilingualism for domain-general cognitive functions especially in older adults, a number of questions remain unanswered. Specifically, the bilingualism literature of the past 30 years has seen the development of a number of very influential psycholinguistic and neural models that have been developed to account for phenomena observed in second language learning, and bilingual language processing more generally. However, the majority of these models have been based on experimental data collected in young adults, making it difficult to understand how these models may function in older adults, and how they could be extended to better understand bilingual language processing across the life span.

This work has been inspired by the idea that current models of bilingual language processing and models of language processing in older adults could mutually benefit from being

integrated. As we will propose, there are a number of important theoretical connections between the two fields that have not received sufficient attention and that have important implications for language processing, bilingualism, and aging. Here, we will review the most prominent accounts that have been put forward to explain cognitive and linguistic processes in healthy older adults, and integrate them with models developed for bilingual language production and comprehension. Importantly, as it will be described later, one of the major hypothesis to explain some of the advantages observed in bilinguals' executive functions has been specifically attributed to the feat of speaking and monitoring two languages in one brain. As such, *speech production* in two languages and control thereof has been the prime linguistic function thought to be at the basis of positive changes in cognitive abilities in bilingual speakers. Relatively less attention has been paid to research on the role of bilingual language comprehension, and how the need for constantly monitoring bottom-up information in both languages might have an effect on domain general cognitive processes. The relative contributions of language production and language comprehension mechanisms to the observed cognitive advantages in bilinguals are still partly unanswered. What is certain is that language production and comprehension are necessarily intertwined even at the single word level (Levelt, 1983; Levelt, 1989), and therefore throughout the paper, we discuss studies of both language production and comprehension. We will then suggest some guidelines and future directions for how these models could be integrated to better inform the two fields of research. In the first section we will outline the major models that have been proposed to explain cognitive and language processing in healthy non-pathological aging adults. Even though the scope of this work is to specifically to discuss language processing, many of the current models for aging are domain general, with only one language-specific model of aging. We will therefore provide a description of both domain-general and language specific theories of aging. In the second section we will discuss some of the major proposals for bilingual language processing. In this section, our review considers evidence primarily from lexical production and comprehension because that is where there has been the greatest number of studies to date and where these processes can be compared systematically, especially for models of bilingual language processing. Finally, in the last section, we will discuss some guidelines on how to integrate the two literatures to include data from language and aging. We will conclude by outlining what we think will be important future directions to advance this field of work.

Language processing in healthy aging

Aging is often characterized by general cognitive, behavioral, and neural declines (Park et al., 2002). However, one domain of cognition in which there are many examples of sparing is language (Park & Reuter-Lorenz, 2009). Specifically, many indices of semantic processing suggest that older adults have intact or improved semantic systems. Older adults tend to have larger vocabularies and greater lexical knowledge compared to younger adults (Alwin & McCammon 2001; Verhaeghen 2003). For example, older adults tend to produce longer and more lexically diverse utterances (Kemper & Sumner, 2001). Measures of semantic priming for both words and objects are at least as large for older adults compared to younger adults (e.g., Bowles, 1989; Burke et al., 1987; Madden et al., 1993). While these findings support a well-maintained semantic system, older adults often report difficulties in

language production. Older adults tend to speak more slowly overall, and to have an increased number of pauses and fillers in their speech (e.g., um, uh; Bortfeld, Leon, Bloom, Schober, & Brennan, 2001; Heller & Dobbs, 1993; Kemper, Rash, Kynette, & Norman, 1990; Vousden & Maylor, 2006). While these difficulties in lexical retrieval may seem to corroborate the well-established age-related declines in memory, and have led to theories of cognitive aging suggesting a decrease in general speed of performance (Salthouse, 1996; Hale, Lima & Myerson, 1991) others have suggested that these retrieval deficits may be language specific and phonological in nature. One piece of evidence to support this is from tip-of-the tongue (TOT) experiences (Brown & McNeill, 1966). TOTs occur when an individual knows what he or she would like to say but is unable to recall the lexical label. During a TOT experience individuals are able to recall many semantic aspects of the item (e.g., hops, native to Australia, has a pouch), but are unable to recall the specific word (e.g., kangaroo). Often times during a TOT partial information about the phonology is available (e.g., starts with /k/), further suggesting that the basis of the phenomenon is phonologically based. Indeed, older adults report more TOT experiences than younger adults (Burke, 1991), and fewer successful resolutions of TOT experiences.

This pattern of behavioral performance suggests semantic and phonological abilities may be dissociable. The *Transmission Deficit Model*, -TDM- (Burke, et al., 1991) is one theory that has been proposed to account for these behavioral effects. The TDM is a node-based hierarchical theory. As an item, or an aspect of an item is recalled, activation is propagated through the network by means of spreading activation. The theory hypothesizes that as we age, all connections between links weaken. While both semantic and phonological links weaken, the inherent structure of the semantic system is more redundant and interconnected than the phonological system. For example, if a link between 'dog' and its attribute 'furry' is weaker, there are many other semantic attributes about dog to facilitate knowledge and retrieval (e.g., barks, wags, has four legs, domesticated). In contrast, the phonological system, especially in terms of item labels, has less redundancy. If one cannot retrieve the /d/ or /g/ phoneme, when trying to recall 'dog', this results in a retrieval failure. Thus the TDM has been used as one model to explain why behavioral impairments in older adults are more apparent in the phonological system.

While the TDM provides a language-specific theoretical framework, there are other domain-general cognitive theories for explaining language changes in healthy older adults. One consistent finding is that older adults perform behavioral and cognitive tasks (including speed of language processing) more slowly than younger adults. Because this is one of the largest and most robust findings in the aging literature, these observations have led to the hypothesis that *Generalized Slowing* is responsible for much of the age-related differences that are observed (e.g., Salthouse, 1996). While it is tempting to simply attribute slowing to age-related differences in motor function, measures of speed on relatively simple reaction time tasks such as the digit symbol task are often highly correlated with measures on other cognitive measures such as Stroop task performance, verbal fluency, and reading time (Salthouse, 1996).

Another major hypothesis that has been proposed to explain cognitive performance in older adults is the *Inhibition Deficit Theory* which suggests that age-related performance

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differences in older adults are related to a decline in inhibitory processes, in particular those involved in non-automatic executive control (Hasher, Stoltzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988). Inhibition can serve to focus our attention, and ignore or delete irrelevant information (Lustig, Hasher, & Zacks, 2007). The inhibitory deficit theory has been supported by data showing that older adults tend to have more 'off-topic' conversational statements (e.g., Arbuckle, Nohara-LeClair, & Pushkar, 2000), which may be related to inhibitory deficits in controlling the train of thought and maintaining the conversational focus. However, other studies have failed to find that older adults show more off-topic speech (e.g., Beaudreau, Storandt & Strube, 2006), and revealed that adults' speech is even rated more positively than younger adults' (e.g., James et al., 1998; Pratt & Robins, 1991). These results call into question whether older adults' conversational behavior has in fact qualitatively declined.

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Studies on reading comprehension have demonstrated that older adults read aloud more slowly in the context of unpredictable distractions (Carlson, Hasher, Connelly, & Zacks, 1995), suggesting that decreased inhibitory mechanisms enhance the influence of distracting information. In another study on memory and reading comprehension, Hamm & Hasher (1992) found that while older adults had comparable memories for the story, they also maintained more details. On the one hand, this seems to be evidence in favor of enhanced memory and comprehension for older adults. However, they hypothesized that one of the key functions of an efficient memory and comprehension system is the ability to maintain the core details and inhibit the secondary ones. Thus this finding may reveal a deficit in inhibiting these side details. Interestingly enough, if distracting information is relevant to the task, older, but not younger adults, show improvements in performance (May, 1998) and this again has been taken as evidence for increased attention to peripheral details and a reduced ability to ignore such information. Potential effects of inhibitory processing changes have also been examined in non-linguistic tasks such as go/no-go tasks in which withholding a response is required but only on a subset of trials. Older adults are typically less accurate in withholding their responses compared to younger adults (e.g., May & Hasher, 1998). In summary, several hypotheses about age-related differences in cognition have been proposed. While there is evidence in support of both age-related slowing and changes in inhibition, these in and of themselves do not fully account for the differential decline that has been observed in phonological, but not semantic aspects of language production. At the same time, these hypotheses are not mutually exclusive, so it may be that several factors contribute to age-related cognitive and linguistic differences.

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Age-related changes have also been reported in language comprehension, especially for complex sentences (Payne et al., 2014; Wlotko et al., 2010). Given the age-related changes in a number of cognitive abilities (including verbal and non-verbal working memory, cognitive speed, and attention) which are central for successful on-line processing of syntactically complex and/or at times ambiguous sentences the question of how changes in memory resources affect language comprehension has been a central issue in the literature on language processing and aging. Up to date, the findings have been at best mixed. Some studies report that older adults' language processing abilities do not decline as shown by similar performance in behavioral measures (Davis, Zhuang, Wright, & Tyler, 2014; Shafto & Tyler, 2014; Tyler et al., 2010). Despite similar behavioral performance, Davis et al.

(2014) and Tyler et al. (2010) report that older adults show a more bilaterally distributed functional network than younger adults, suggesting that older adults might recruit additional neural resources to accomplish the task. Tyler et al. (2010) discuss how given the natural decline in memory functions during aging, it is quite remarkable that behavioral changes in sentence comprehension in healthy older adults are not more apparent. The authors reason that because verbal communication in a naturalistic setting is by nature extremely redundant, it might help compensate for qualitative and/or quantitative changes in language comprehension. Tyler et al. (2010) utilized however sentences which were either syntactically and semantically correct (“Jane didn’t enjoy herself very much. Her neck was stiff because she had a bad cold and she couldn’t lift anything properly”), syntactically correct but semantically incorrect (“Stephen didn’t catch himself very much. Her tooth was driven because he had a weak nail and she couldn’t heat anyone properly”), or in with a random word order (“Very Stephen catch much himself didn’t. Her nose because properly had anyone couldn’t he and nail weak a heat driven was”). Thus, this manipulation examined semantic complexity as opposed to grammatical complexity.

A number of studies have addressed the question of how changes in working memory resources throughout the life-span (and also individual variability in working memory capacities) impact high-order language comprehension for syntactically complex sentences. For example, Payne et al. (2014) used a self-paced reading task to investigate the correlation between working memory abilities and relative clause processing across the life-span. Ninety-one individuals (ranging in age from 18 to 81) read sentences that contained relative clauses that were temporarily syntactically ambiguous until the disambiguating point (the reflexive pronoun), such as “The son of the princess who scratched himself/herself in public was humiliated”. Previous research that looked at parsing preferences and working memory abilities in younger adults has revealed that individuals with higher working memory abilities prefer a “high-attachment preference” strategy. That is they show an advantage in processing when the reflexive pronoun refers to the first noun phrase (i.e., the son), while individuals with lower working memory scores adopt a “low-attachment” strategy and are facilitated in processing sentences in which the reflexive pronoun refers to the lower noun-phrase, i.e., the princess (Traxler, 2007). Contrary to these predictions, Payne et al.’s results showed that working memory modulated sentence processing, especially in older adults. However, older adults with higher working memory resources showed a larger comprehension bias for the second lower noun phrase, while individuals with lower working memory resources preferred the high-attachment strategy. The authors interpret these results as being consistent with Swets et al.’s working memory and prosodic segmentation hypothesis (Swets et al., 2008) which posits that one possible way that older adults with lower working memory compensate for the increased cognitive workload of processing syntactically ambiguous sentence is to chunk long constituents into smaller units. A number of recent studies have supported this idea, showing that during normal reading older adults’ pauses after major syntactic constituents (clause boundaries and sentence-final boundaries) increase (Miller & Stine-Morrow, 1998; Stine-Morrow, Noh, & Shake, 2010). Pauses also increase in frequency, so that older adults tend to chunk longer syntactic constituents into smaller chunks (Stine-Morrow & Miller, 2009).

While a number of models proposed to account for language processing in healthy older adults have relied on behavioral data, the rapid growth and efficiency of neuroimaging techniques has increased the opportunity to investigate the qualitative and quantitative differences that occur in language processing in healthy older adults at the neural level. Among the increasingly growing literature on functional changes of cognition and aging, functional neuroimaging studies have highlighted two important patterns related to older brain functioning: 1) older adults typically have smaller and more variable hemodynamic responses in regions where they do show activation and 2) older adults typically engage more brain regions than younger adults (e.g., homologous regions in the right hemisphere (Logan et al., 2002). While the lower levels of functional activation within task relevant regions is typically taken as a reflection of age-related changes in the neural and vascular systems, there has been great disagreement with how the increased recruitment of brain regions is interpreted. Critically, the interpretation depends on the corresponding level of cognitive function or behavioral performance. When increases in activation occur with improved or maintained performance, fMRI activation is generally interpreted as being compensatory (e.g., Cabeza, 2002). Additional regions are recruited to supplement and compensate for structural or functional declines in core regions. In contrast, when increases in brain activation have corresponded to declines in performance, this has been characterized as reflecting dedifferentiation (e.g., Ghisletta & Lindenberger 2003; Park et al. 2004). That is, increased patterns of activation reflect a decline in efficiency of the neural networks. Indeed some have suggested that dedifferentiation arises from reduced inter-hemispheric inhibition in aging in which deficits in inhibiting activation of the right hemisphere decreases the efficiency of the left hemisphere (Fling et al., 2012; Fling et al., 2011).

Moreover, there are a number of factors that may further influence the relation between performance and brain activation. One such general factor may be task difficulty. A third hybrid model has been proposed to account for this: the compensation-related utilization of neural circuits hypothesis (CRUNCH, Reuter-Lorenz & Cappell, 2008). The CRUNCH model proposes an interaction between task difficulty and brain activation such that at low levels of task difficulty there are increases in brain activation which function to compensate for reduced efficiencies and neural decline in older adults (i.e., increased functional activation corresponds to maintained or improved behavioral performance). However, as task demands begin to outstrip cognitive resources, brain activation plateaus or declines, and behavioral performance worsens which results in weaker or no relationships between functional activation and behavioral performance. Beyond task difficulty, other factors also influence the relationship between behavior and functional activation. Older adults tend to be more variable in both performance and neural activations (Garrett et al. 2011; MacDonald et al. 2006). Thus the absence of significant correlations between behavior and neural activation may be due to this increased variability in the measures. Moreover, fMRI studies often recruit smaller samples than traditional behavioral studies which further challenges the detection of significant effects. Thus, small but important differences may be more difficult to detect in older adults.

Bilingual language processing

Despite the difficulty of learning a second language (L2) past a putative critical period, a growing body of research suggests that the brain often reveals learning before it is apparent in behavior. Recent studies have shown that sensitivity to newly learned L2 words can be extremely rapid and efficient even at very early stages of L2 learning and in the absence of a behavioral response (McLaughlin et al., 2004; Osterhout et al., 2008). At the same time, one of the strongest findings in research over the last 20 years is that bilinguals cannot turn off one of their two languages in either production (Kroll et al., 2006), nor during comprehension (Marian & Spivey, 2003). The phenomenon of language co-activation is incredibly pervasive, suggesting that once new vocabulary is acquired and consolidated in the L2 it competes for selection with the native language (L1), even at lower proficiency levels. At the same time, under normal conditions, bilinguals rarely make mistakes in uttering an intended word in the wrong language, and under special socio-linguistic circumstances they are able to code switch with one another, moving in and out of each language with fewer processing costs than might be expected (e.g., Kootstra et al., 2010). All these data suggest that bilinguals might possess a very powerful neuro-cognitive mechanism for monitoring and controlling the relative activations of the two languages.

Among the models that have been proposed for bilingual language lexical access, the Revised Hierarchical Model -RHM- (Kroll and Stewart, 1994) proposes that bilinguals access translation equivalents both through concept-mediation and also through direct associative links. Importantly, the relative strengths of these connections change as a function of proficiency, so that beginning L2 learners rely more on associative connections and develop more conceptual connections as proficiency increases (Talamas, Kroll, & Dufour, 1999). Importantly, translating or naming from the second language (L2) to the first more dominant language (L1) is faster than translating or naming from the L1 to the L2. The RHM proposes that these translation asymmetry effects occur because the L2 has stronger lexical connection to L1, as translating from the L2 to the L1 constitutes the primary learning pathway for new L2 words. The nature of the asymmetry between translation directions proposed by the RHM might be of a different nature relative to the one observed in other experimental paradigms which have utilized item by item language switching paradigms (Meuter & Allport, 1999). The data reported by Meuter and Allport, showed that naming in the L1 after having named in the L2 is more costly than naming in the L2 after naming in the L1. It is exactly thanks to these data, together with the evidence from the translation asymmetries proposed by the RHM, that have lead to the idea that the bilingual's two languages are highly coactivated, even at early stages of language learning. As mentioned before, bilinguals cannot turn off one of the two languages at will (e.g., Costa, 2005; Kroll et al., 2006; van Hell & Dijkstra, 2002). Language co-activation is incredibly pervasive, suggesting that it is virtually impossible for bilinguals to avoid the activation of both languages, even when they intend to speak one language alone (e.g., Costa, 2005; Kroll et al., 2006). Remarkably, language co-activation has been reported in a number of very diverse bilingual language contexts including bimodal bilinguals, (i.e., speakers who speak a spoken and a signed language, Morford et al., 2011), and also for bilinguals whose languages have different scripts (Hoshino & Kroll, 2008), indicating that bilinguals

constantly need to juggle their languages. Interestingly, studies looking at the earliest stages of L2 learning show that brain sensitivity to novel L2 words arises very rapidly, speaking to the high plasticity of the neural system. For example, McLaughlin et al. (2004), tested English L2 learners of French and showed that just after 14 hours of L2 instruction the neuropsychological signature of those learners revealed sensitivity as evidenced by an enhanced N400 component when comparing L2 words and L2 pseudo-words. Importantly, the effect was observed in the absence of behavioral sensitivity, suggesting that the brain response can outpace behavior and reveals early sensitivity to new linguistic information. Evidence for language co-activation has been observed even in tasks in which participants were unaware of the bilingual nature of the task (Thierry & Wu, 2007; van Hell & Dijkstra, 2002), suggesting an extremely high level of language co-activation that is beyond voluntary consciousness. Bilingual language coactivation has been observed even in the domain of language comprehension. In a seminal study Marian and Spivey (2003) reported that there is an effect of phonological competitors not only within languages, but also between languages when bilinguals perform the task in one of their two languages. Coactivation in comprehension has also been shown to persist when these tasks are placed in sentence context (e.g., Libben & Titone, 2009). There is therefore compelling evidence in all domains that bilinguals activate both languages in comprehension and in production.

One primary model that has been proposed to explain bilingual language comprehension is the Bilingual Interactive Activation Plus (BIA+) model of word recognition (Dijkstra & van Heuven, 2002) that proposes a late account of language selection by assuming that words in the two languages are stored in an integrated lexicon and that task demands (e.g., language of the task) do not influence the earliest stages of word recognition. Language cues function to distinguish different language alternatives only after activation of both languages has occurred. Models like the BIA+ assume therefore that bottom-up processes govern the earliest stages of word recognition, increasing the activation of all form-related features regardless of the language that is actually presented. Evidence for the model has been provided by eye-tracking data showing that semantic constraints decrease cognate effects in late but not early measures of fixation duration (e.g., Libben and Titone, 2009), and in studies looking for switching effects in a sentence context (Gullifer, Kroll & Dussias, 2013). Curiously, there has been little direct comparison of the evidence for bilingual coactivation in comprehension and production, and how bilinguals might resolve the competition in production and comprehension. Cross-language co-activation may be resolved quite differently in comprehension than in production because the intended language may not always be explicitly selected in comprehension, while in language production, selection is forced by the fact that, at least for unimodal bilinguals, there is only one output channel, making it is physically impossible for a bilingual to produce both languages at the same time. The discussion of this topic goes beyond the scope of this work, but we refer the reader to a recent review on the topic (Kroll et al., in press).

The development of models of bilingual language production and comprehension, and the realization that bilinguals rarely manage to switch off one language at will, have raised questions about which linguistic and or cognitive mechanisms are at play during bilingual language processing, and how bilinguals manage to resolve competition for selection between the two languages. Among the hypotheses that have been formulated the *Inhibitory*

Control-IC-model (Green, 1998) proposes that bilinguals successfully manage to resolve cross-language competition and achieve successful language selection by actively inhibiting their dominant language (L1) to allow fluent production in the weaker language (L2). This active inhibition is accomplished by engaging a dynamic domain-general neural network involving cortical and subcortical structures to optimally resolve cross-language language competition (Abutalebi & Green, 2007). According to this model, the prefrontal cortex is viewed as the set of cortical areas that is connected with other cortical and subcortical structures that subserve a range of sensory and motor tasks. Prefrontal cortex structures have been observed to be involved in top-down control that can facilitate task selection. The prefrontal cortex and the anterior cingulate cortex (ACC), together with the basal ganglia are activated and recruited during L2 speech production. Specifically, prefrontal cortex is involved preferentially during response selection and response inhibition, while the ACC is involved during conflict monitoring and attention, and the basal ganglia are involved during language selection and set switching. Importantly, along the lines of the IC model, Abutalebi and Green (2007) assume that the proposed neural network is engaged differentially depending on L2 proficiency.¹

The theoretical and neural bases of the IC model (Abutalebi & Green, 2007; Green 1998) have been tested in a number of studies that have examined bilingual performance using blocked naming task procedures in which simple pictures are named in one of the bilingual's two languages in separate blocks of trials (Misra et al., 2012; Guo et al., 2011). For example, Misra et al. (2012) used event-related potentials (ERPs) while proficient Chinese (L1)-English (L2) bilinguals named pictures in each of their languages, in separate blocks one after the other. Ordinarily, repetition of pictures would be expected to produce response facilitation in the subsequent blocks, regardless of which language needs to be spoken. However, if active inhibition of the native language (L1) occurs when bilinguals produce speech in the second language (L2), then a cost for switching from the L2 into the L1 should be hypothesized and repetition priming would be expected to diminish. Misra et al.'s behavioral results (2012) revealed that Chinese-English bilinguals were overall less accurate in naming in their L2, but there was no interaction between naming accuracy and block order. However, the naming latency analysis showed that naming in the L2 after naming in the L1 was significantly faster than naming in the L1 after naming in the L2, revealing that there was no benefit of repetition priming when naming in the L1 following the blocks of naming in the L2. The ERP data confirmed that when pictures were named first in the L2 and then were repeated in the L1, a sustained modulation of the N200 component (an ERP index of response conflict, e.g., Jackson et al., 2001) was observed even following many trials, while that was not the case for when the pictures were named first in the L2 and then in the L1. Overall, Misra's et al.'s (2012) results suggested that there is inhibition of the L1 during the planning of spoken words in the L2. When L1 naming is then required, there appears to be an inhibitory component that overrides priming to diminish any substantial facilitation in the behavioral data and to create negativity in the ERP record. Guo et al. (2011) capitalized on a similar design using functional magnetic resonance imaging (fMRI) to determine the neural basis of bilingual language processing. The design in the Guo et al.

¹For a thorough description of the model, and broader implications for language processing see Abutalebi and Green (2007).

study was identical to the blocked picture naming procedure in Misra et al. except that following the blocked picture naming trials, Chinese-English bilinguals named pictures in a mixed language block. Critically, different patterns of brain activation were found when comparing the blocked and mixed naming trials (hypothesized to reflect local inhibition) and the spillover effect of naming in different block orders (hypothesized to reflect global inhibition). The dorsal anterior cingulate cortex (ACC) and the supplementary motor area (SMA) appeared to play important roles in local inhibition, while the dorsal left frontal gyrus and parietal cortex appeared to be important for global inhibition. Results also showed that the dorsolateral prefrontal cortex and parietal cortex were more activated when the L1 followed the L2, relative to when the L2 followed the L1. The functional results were paired with a behavioral trend that showed that naming in the L1 after naming in the L2 elicited more errors (but it was not slower) than when naming pictures in the opposite order. However, neither of these two studies permitted a direct assessment of the scope and the time-course of inhibition because the same items were named across blocks, and the experimental designs were short and did not permit to observe how long the inhibition lasted. In other words, these first studies were not designed to address the question of whether the active inhibition on the L1 (as proposed by the IC model) applies only to the lexical items that have been previously named in the L2, or whether the inhibition has to extend beyond the single lexical item, or even more broadly to the whole language. Also, the question of how long inhibition of the L1 lasts is still a matter of open debate. To address these questions, Van Assche, Duyck, and Gollan (2013) examined verbal fluency performance in two groups of relatively proficient bilinguals. Like the Misra et al. (2012) and Guo et al. (2011) studies, they varied the order of the languages in which bilinguals performed the verbal fluency task. The two groups tested by Van Assche et al. differed in whether they were immersed in the L1 or L2 environment. The results showed evidence for multiple components of inhibitory control but in this study, the pattern of inhibitory control depended on the type of bilingual. Dutch-English bilinguals in Belgium and Chinese-English bilinguals in the US both produced lexically-specific inhibition when producing exemplars from verbal fluency categories that were repeated from L2 to L1. However, only Chinese-English bilinguals produced global inhibition for new categories in the verbal fluency task. Taken together, the results of these studies provide evidence for multiple mechanisms of inhibitory control that are modulated by proficiency, and immersion. Using a similar logic, McClain, Rossi and Kroll (under review), conducted an ERP study in which bilinguals named pictures in alternating language across blocks. Critically, to investigate the scope of inhibition, the named items were not identical, but drawn deliberately from different semantic categories. Additionally, to examine the time-course of bilingual language inhibition (i.e., how long it lasts in time), the design included eight L1 naming blocks after the intervening L2 naming block. We predicted that if inhibition occurs only for specific words that were previously named in the L2 block, then only the repetition of the same pictures should reveal a pattern consistent with inhibition. Instead, if inhibition generalizes within a semantic domain, the new items drawn from previously named categories might also be expected to produce inhibition, and if inhibition is an even more global phenomenon that affects the entire language, then an inhibitory pattern might be expected even for new items from categories that have not been previously named. Preliminary results provided evidence for significant inhibition in naming in L1 after an intervening block of L2, as

revealed by a trending effect towards naming fewer correct pictures and longer naming latencies in the L1 in blocks that followed the intervening block in the L2 (Figure 1). McClain et al. also observed more negative ERP waveforms during an early N200 window (200–270 ms) for each of the blocks of L1 spoken after the L2 relative to Block 1 (i.e., the first block of L1 naming). Because the ERP pattern was found even when completely new pictures were named, this suggests the presence of global inhibition when the L1 is spoken after the L2. However, ERPs from a control group of bilinguals who only named pictures in the L1 revealed similar patterns behaviorally and neurally, suggesting that the global modulation of the L1 may reflect other mechanisms. Additional research is needed to determine the source of inhibitory patterns in L1-only production and the extent to which these patterns overlap with mechanisms associated with alternated language production. Generally, though, these results are in-line with the results reported by Van Assche et al. (2013) and taken together, these results provide important evidence that suggests that the scope of inhibition during bilingual speech production extends more globally beyond the word level and that its time course is relatively long.

While the IC model proposes that active inhibition is the primary executive function that is at play during bilingual language control, and that allows bilingual speakers to successfully resolve cross-language competition, others have proposed that *language selection is language specific* (e.g., Costa, Miozzo, & Caramazza, 1999; Finkbeiner, Almeida, Janssen, & Caramazza, 2006; Finkbeiner, Gollan, & Caramazza, 2006). According to this view, lexical items in both languages might indeed be coactivated, but the activation of those words does not automatically make them candidates for selection. In essence, the activation of lexical candidates in the unselected language does not create competition for selection. This solution to the selection problem draws heavily on mechanisms that enable the bilingual to attend only to candidates within the target language. This view would logically require that bilinguals are able to exploit cues about language status that enable them to identify the language in use. Those cues may be related to linguistic features of the two languages, but also to features of the context in which the two languages were acquired and are used. Yet other evidence suggests that even very obvious features that might distinguish two languages are not exploited in this way, as revealed by studies of language production in different script bilinguals (e.g., Hoshino & Kroll, 2008) or studies in bi-modal bilinguals (e.g., Emmorey, Borinstein, Thompson, & Gollan, 2008). These studies show that despite overt and transparent differences in the bilingual's two languages, there is persistent activity of the language that is not in use.

Although many studies support the idea that bilingualism may confer benefits through the increased inhibitory and monitoring demands that bilingualism entails, there are other plausible mechanisms. One hypothesis proposes that the observed costs to the dominant language can be understood with respect to frequency of use rather than in terms of temporary suppression of the L1 to allow L2 production, giving rise to the weaker links or *frequency-lag hypothesis* (e.g., Gollan, Montoya, Cera, & Sandoval, 2008; Gollan et al., 2011). This account starts from the observation that bilingual speakers have more tip-of-the-tongue (TOT) phenomena than monolinguals, they are slower to name pictures in their L2 (but also in their L1), and they perform more poorly than monolinguals on measures of verbal fluency in which they are asked to generate as many exemplars of a category as they

can in a fixed time period (see Kroll & Gollan, 2013, for a recent review). According to this account, the pattern of language performance observed in bilinguals is caused by the fact that bilinguals divide their time over the two languages in such a way that they necessarily speak each of their languages less frequently than monolinguals. The question that is raised by this hypothesis is whether the observed costs to bilingual lexical access in production are due to reduced functional frequency for both languages, including the dominant L1, or whether they can be explained as a consequence of cross-language competition, and inhibitory control exercised on the L1 to allow L2 selection (see Kroll & Gollan, 2013 for an in depth discussion of the two alternatives). It is quite possible that both alternatives can co-exist in characterizing bilingualism speech planning. The competition for selection alternative can be understood as a top-down process, which requires that cognitive control mechanisms be recruited for even the simplest task of producing the name of a single object in one language to avoid interference from the other language, while at the same time reduced frequency of use, and relative reduced accessibility of both languages can be thought as a more bottom-up process that modulates lexical access in the two languages. It is highly possible that the combination of these two mechanisms could provide a cohesive account for bilingual language lexical processing.

Connecting models of bilingual language processing and language processing in healthy aging

Recent literature has suggested that the long-life task of processing two languages might be at the basis for the enhancements in a range of language-independent cognitive domains that provide protection for older bilinguals against the rate of decline associated with normal and pathological cognitive aging (e.g., Bialystok et al., 2007; Bialystok, Craik, Klein & Viswanathan, 2004; Craik et al., 2010; Gold et al., 2013; Martin-Rhee & Bialystok, 2008). It is appealing to think that the requirement for bilinguals to juggle the competition across their two languages creates expertise that benefits general cognitive functions. In other words, by virtue of negotiating the competition across the two languages, bilinguals may become more efficient at resolving conflict more generally. More recently, the research has extended to answer questions of how to best control for the multiple internal and external variables that characterize the variable nature of bilingualism in order to better measure those effects. According to the strongest version of the IC model (Green, 1998), the aspect of bilingualism that leads to the development of domain general cognitive advantages is the primary act of speech production. That is, the active inhibition that allows bilinguals to resolve competition during language production through the latest stages of language articulation has been hypothesized to be the driving cognitive task that underlies the putative benefits in executive functions in bilinguals. Though studies in pre-verbal bilingual children demonstrating that bilingual children exhibit cognitive advantages relative to their monolingual peers have raised the question of whether the nature of those advantages can be attributed to a more complex set of variables which include managing the two languages (Kovács & Mehler, 2009a; Kovács & Mehler, 2009b).

The body of research about the connection between comprehension and cognitive control in bilinguals is still growing, showing however that (Blumenfeld & Marian, 2011; Martín,

Macizo, & Bajo, 2010) control processes involved in language selection during comprehension are shorter lived than the ones reported for language production. For example, Martín et al. (2010) reported that inhibitory effects in language comprehension were significant at a time interval between 500 ms and 750 ms, while after an interval of 750 ms, participants seemed to have recovered from inhibition. These findings indicate that inhibitory control processes that are involved in the resolution of cross-language competition in comprehension have a different time-course than the one observed for language production, and might be of a fundamentally different nature. More recent accounts of bilingual language processing (Green & Abutalebi, 2013) have highlighted how not all forms of bilingualism impose the same cognitive and therefore neural demands which may influence how bilingualism affects cognitive control. Bilinguals differ from one another in whether they are dominant in a majority or minority language and whether the society is itself bilingual, affecting the choices that are made in how and when the two languages are spoken. Along the same line of reasoning, the cognitive demands and mechanisms for language selection in production and comprehension in bilinguals might be of a different nature and might require different levels of cognitive control (Kroll et al., in press).

As the previous sections of this paper demonstrated, there is a wealth of literature, behavioral and neural models that have been proposed to account for bilingual language processing and language processing in healthy aging. What emerges from the (far from exhaustive) review of the literature in the two fields is that there are many observable similarities between the mechanisms that have been proposed to account for the observed performance in these two populations. In what follows we will first discuss how current models of bilingual language processing could be integrated to account for patterns of performance observed in non-pathological language processing in aging, and we will outline a series of predictions that will be generated by virtue of integrating bilingual and aging language processing models. We will also outline some additional points of discussion to illustrate how such integrative models could help clarifying current important topics in bilingualism.

Among the domain-general cognitive theories that have been proposed to explain cognitive aging is the Inhibition Deficit Hypothesis (Lustig, Hasher, & Zacks, 2007; Hasher, Stoltzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988) that posits that age-related performance in older adults can be related to a general decline in inhibitory processes, in particular those involved in non-automatic executive control. For example, older adults were slower than younger adults when reading text that contained unpredictable font changes (Carlson, et al., 1995), which have been connected to difficulties in suppressing irrelevant information. However, other studies have failed to find that older adults show more off-topic speech (e.g., Beaudreau, Storandt & Strube, 2006), and revealed that adults' speech is even rated more positively than younger adults' (e.g., James et al., 1998; Pratt & Robins, 1991). On the bilingualism side, the IC model (Green, 1998) proposes that bilinguals rely on active inhibition for successful language production, and this in turn makes them better inhibitors overall. Consequently, the expectations for domain general functioning would be that older bilinguals exhibit an advantage in inhibitory control, as indeed reported in a number of studies showing that older bilingual adults score better in domain general tasks such as the Simon task, and other cognitive control tasks (Bialystok, Craig, & Klein, 2004; Bialystok &

Craik, 2010; Bialystok, Craik, & Freedman, 2007; Fernandes et al., 2007; Keijzer, 2013; see keynote by Baum & Titone, 2014 for a thorough discussion on the topic of bilingualism, executive control and aging).

The question of what neural areas are at play and to what extent changes at the neural level give rise to the observed changes in behavioral performance in bilingual older adults relative to monolingual older adults is still partly open. Among the latest neural models that have been proposed for bilingual language processing, the dorsolateral pre-frontal cortex and the ACC, together with the basal ganglia (more specifically the left caudate) are consistently reported as active areas (Abutalebi & Green, 2007; Abutalebi et al., 2007; Green & Abutalebi, 2013) engaged during bilingual language tasks and more cognitive-general tasks. In particular, the dorsolateral pre-frontal cortex, and the dorsal part of ACC have been proposed to be important for domain-general executive control, and have therefore been proposed to be part of a domain-general supervisory attentional system. A number of studies have reported that bilinguals make more efficient use of this area (showing less activation) than monolinguals even during non-linguistic domain-general tasks (Abutalebi et al., 2013). Importantly bilinguals also exhibit structural differences in the ACC - increased gray matter GM density relative to monolinguals. These data overall suggests that the life-long experience of monitoring and controlling two languages results in functional and structural changes in areas of the brain that are utilized for domain-general executive control functions. As such, if bilingualism tunes domain-general executive function areas, such as the ACC (Abutalebi et al., 2013), bilingual older adults should show fewer neural changes than monolingual older adults. More specifically, at the functional level, it could be predicted that older bilingual adults should utilize the ACC more efficiently than monolingual older adults controls exhibiting relatively less ACC activation during domain-general executive control tasks. Moreover, despite the general neural decline in gray and white matter observed in aging (Good et al., 2001; Raz, 2005; Resnick et al., 2003), older bilingual adults should show increased GM density than older monolingual controls in areas engaged during cognitive control. In other words, speaking two or more languages might be representative of one of the cognitive activities that can boost cognitive reserve, leading to better behavioral performance. Abutalebi et al. (2015), provided a first confirmation of these hypotheses showing that older bilingual adults showed increased GM density in the ACC than older monolingual controls. Importantly, in Abutalebi et al. (2015) aging was correlated with performance and decreased GM density in the dorsolateral pre-frontal cortex only for monolinguals and not for bilinguals, confirming that the daily activity of juggling two languages helps to maintain -and potentially boost- neural reserve.

Similarly, it could be hypothesized that older bilinguals should perform better than older monolingual peers in linguistic tasks that require executive control and other tasks that involve the engagement of “fluid intelligence” which relies on executive control processes. To exemplify, one of the linguistic behaviors that has been related to aging and diminished inhibitory processes is a higher number of off-topic statements (Carlson, et al., 1995). If bilingualism modulates inhibitory control abilities, we would expect older bilingual adults to show fewer off-topic statements than matched older adults. While the dorsolateral pre-frontal cortex and the ACC exercise domain-general cognitive control in linguistic and non-linguistic tasks, the basal ganglia, in particular the left caudate, has been shown to be

specifically involved during bilingual language selection and language set switching (Crinion et al., 2006). Lesions to the left caudate in bilinguals have resulted in patterns of pathological language switching in adults (Abutalebi, Miozzo & Cappa, 2000), and in child subcortical aphasia (Mariën et al. (2005), confirming that the left caudate is implicated in controlling the relative activations of the two languages. Importantly, the caudate plays an important role for specifically controlling language even in monolinguals. For example, the caudate is part of a larger language-related network that promotes language selection and inhibition (Gil Robles et al., 2015) and discourse maintenance and coherence (Sabb et al., 2010). Again, with the assumption that bilinguals engage the caudate both for within and between language selection and control, it could be predicted that bilinguals should show a better level of language control, and potentially exhibit fewer off-topic statements during language production. Importantly, this prediction would vary depending on additional internal and external factors such as level of proficiency in the two languages and the linguistic environment. For example, the question of whether a positive effect of enhanced executive control for language production performance would vary from the more dominant L1 to the less dominant L2, is an open question for research.

Another general cognitive theory that has been proposed for explaining cognitive decline in aging posits that performance changes in older adults results from general decreases in the processing speeds of cognitive operations (Salthouse, 1996). At the same time, bilinguals (even at younger ages) are reported to be slower than age-matched monolinguals in many measures of language production both in their L1 and in their L2 (Gollan et al., 2011; Ivanova & Costa, 2008) due to processing two languages at the same time. Extending the generalized cognitive slowing hypothesis to older bilinguals, a combinatorial effect in processing speed would be predicted. In other words, if generalized slowing in cognitive performance impacts language processing performance in monolingual adults, then decreases in speed of language processing due to bilingualism would add to the observed generalized slowing. However, language proficiency may influence these trends especially for bilinguals. For example, if a decrease in processing speed due to bilingual language competition reaches a plateau and stabilizes once individuals attain a certain level of proficiency in both languages, it may be possible to distinguish age-related effects of slowing from effects of bilingualism. Inhibitory mechanisms in bilingual language selection processes have been shown to be much shorter lived than the ones observed in speech production (i.e., Martín, Macizo, & Bajo, 2010). A general decrease in cognitive processing speed would therefore shrink or eliminate the short window of time in which bilinguals have been shown to actively inhibit lexical competitors during language selection, potentially delaying or disrupting the process of language comprehension, especially during auditory language comprehension in which the signal is extremely rapid and has to be processed in real time. The impact of a generalized decrease in cognitive processing speed could be less salient for reading in a natural environment in which speed of processing could be more controlled.

One observation that arises looking at the data between the two fields of research is the fact that monolingual older adults and bilinguals show partly similar epiphenomena in language production. Both populations show a generalized slowing in speech production rate, reduced verbal fluency and a high number of TOTs, suggesting problems in lexical and phonological

retrieval. For bilinguals the TOTs have been related to a diminished relative frequency in usage for the two languages (Gollan et al., 2005; Gollan et al., 2011) causing therefore a generalized problem in lexical access and retrieval. The frequency lag hypothesis however, is general, in that it proposes that declines in bilingual language performance are due to insufficient lexical and phonological access. For older adults on the other hand, it has been proposed that TOTs primarily reveal a problem in phonological retrieval (Burke et al., 1991), while lexical access is preserved. It would be tempting to propose that older bilinguals should then show an even greater deficit in phonological access, consequently showing an even greater rate of TOTs than elderly monolinguals. This prediction will need to be further tested. What seems fundamental to mention, is that despite the similarity in the linguistic pattern of performance observed in the two populations, the underlying mechanisms might be fundamentally different. Part of the differences may be in language- or experience-induced weakness (i.e., in bilinguals), while a biologically induced weakness could be at the basis of older adults linguistic performance.

Merging bilingualism into aging: future research directions

Finally, there are a number of additional exciting topics that deserve to be mentioned to highlight how connecting research in bilingualism and language processing in aging could help clarify and advance the understanding of linguistic and cognitive processes. We mention here only a few.

L1 attrition phenomena

In recent years, the literature has provided a lot of new evidence on L1 attrition, during which speakers who fully acquire a native language “lose” it as a consequence of being immersed in a second language environment for a prolonged amount of time. Importantly, the majority of L1 attriters who have been tested in the attrition literature are older adults. In essence, potential changes in language processing in L1 attriters could be partly confounded with more general age-related language declines both in production and in comprehension. Developing models that integrate data on bilingual language processing and language changes in healthy aging could provide a beneficial lens to understand the process of language attrition (see also Goral, 2004).

Differential changes in language beyond Age of Acquisition -AoA- and proficiency

Whether and to what extent age-related language changes have a differential effect on the two languages is still unclear, and this issue has received little attention. However, the idea that the two languages can be differentially modulated by typical language changes in adulthood has been examined. For example, Goral, Spiro & Obler (in prep) tested 78 English-Spanish speakers between the ages of 50 and 78 using the Boston Naming Task and a semantic fluency task in both languages. Their findings revealed that age was a predictor for language performance but only for one of the two languages (i.e., the L1 English), despite the fact that, as indicated from language proficiency measures, these speakers were equally proficient in both languages. This suggests that changes in language processing due to aging might affect the bilingual’s languages differentially. These data, and the idea that a bilingual’s two languages might be differentially impacted by changes in language

processing due to aging independent of proficiency, are especially valid when taking into consideration that the two languages could have been acquired via very distinct learning and memory strategies. For example, the language(s) that are acquired later in life are often learned through more explicit memory strategies, while the native language is acquired through more implicit learning. Bilingual aphasia cases in which the patients recover the second language (or the language that was learned through more explicit memory strategies) also corroborate the view that different memory mechanisms influence the language retention in the face of neural decline. For example, patient EM (Aglioti, Beltramello, Girardi, & Fabbro, 1996) selectively recovered her second language (standard Italian) while losing Venetian (the L1 variant of Italian that EM acquired from birth), after a stroke located to the left subcortical structures, specifically the head of the caudate.

Bilingualism as cognitive training

recently, research that utilizes cognitive training as a way to investigate cognitive flexibility in older adults has conveyed compelling results. Various types of shorter or longer cognitive training in older adults have positively influenced cognitive performance. For example, Buschkuhl and Jaeggi (2008) trained older adults (80 years old on average) twice a week for three months using tasks that were designed to train working memory. An aged-matched control group performed an active physical task. Results showed a positive effect of the cognitive training for the test group, during training and immediately after training, indicating that targeted cognitive training can enhance cognitive performance in older adults. The positive effect of the training seemed however to be relatively short-lived. When the two groups were tested at one year post training, there were no significant differences between the groups. Other studies have replicated these effects in older adults (Basak et al., 2008), and in children (Jaeggi et al., 2001) using real-time strategy videogames that train executive functions such as cognitive control, memory and inhibition. These results suggest overall that specific types of cognitive training can help maintain or even improve cognitive functions in older adults and throughout the life-span. Along the same lines, second language learning, even for older post-critical period speakers can be viewed as one type of cognitive training that capitalizes on inhibitory control and other executive functions (comparable to other activities such as video game playing). Zhang et al. (2015) examined how a short period of language switching training could affect measures of nonverbal proactive and reactive cognitive control. Twenty-eight young Chinese-English bilinguals (and 28 Chinese-English bilinguals for the control group) were trained for a period of ten days using a cued picture naming task, during which bilinguals named pictures either in Chinese or English according to the color of the frame. Proactive and reactive control were measured before and after the training using the AX version of the Continuous Performance Test (AX-CPT). Results showed that only the participants who received the active language-switching training showed an increased measure of proactive control, suggesting that a short language-switching training enhanced measures of cognitive control. The idea however, that bilingualism might provide a type of long-lasting continuous cognitive training throughout life has been reflected in recent studies that have discussed the neural benefits of bilingualism in a more naturalistic and uncontrolled setting. For example, Bak et al. (2014) tested 853 participants from the larger Edinburgh area in Scotland who were first tested in 1974 through the Scottish Mental Survey (when they were 11 years old). These participants

were then retested between 2008–2010 for a number of cognitive abilities, including general fluid intelligence, memory, processing speed, reading and verbal fluency. All participants in the study completed a bilingual language questionnaire to determine their level of bilingualism. Two-hundred sixty-two participants reported that they learned at least one language other than English proficiently enough to be able to communicate, and reported variable ages at which the second language was learned. The results showed that bilinguals tested as older adults performed significantly better than monolinguals in measures of general intelligence and reading independent of childhood intelligence levels, or other variables such as socio-economic status, gender, immigration, or age of L2 acquisition². These encouraging results suggest that bilingualism may function as a type of cognitive training that has benefits across the lifespan. Importantly, the cognitive benefits that have been associated with bilingualism (e.g., improvements in executive function, inhibition, working memory) are precisely the kind of fluid intellectual abilities that often show the most pronounced age-related decline (e.g., Park et al., 2002). At the same time, improvements in these basic abilities are likely to influence processing across several cognitive domains. Conversely, the idea of utilizing non-linguistic cognitive training paradigms could provide a parallel mechanism to benefit older adults' language processes by possibly tapping into diverse types of cognitive functions such as those that have been shown to be involved in language processing in bilinguals (i.e., executive function and inhibition).

Towards a new neural dynamic model of bilingual language processing across the life-span

One of the most striking observations in the aging literature is the recognition that the brain starts its decline at a relatively early age. Although reliable behavioral cognitive changes are not observable till later in life, neural changes start to be observed relatively early. The last 15 years of neuroimaging research have however highlighted the high level of neural plasticity marked by changes and reorganization processes that continue into adulthood. Older adults recruit a wider network of brain areas to support cognitive processing, and also show some level of neurogenesis (Eriksson et al., 1998), revealing a promising picture of neural plasticity throughout the life-span, even though more considerable in younger adults (Gutchess, 2014). Importantly, research has highlighted how engaging in new learning behaviors in older age promotes neural survival, thus slowing neural decline (Zimerman et al., 2010). Bilingualism has been proposed to be one such mechanism that contributes to the maintenance and the build-up of neural reserve, functioning as a protective mechanism both in healthy and pathological aging (Craik et al., 2010).

Current models of bilingual language processing propose that bilinguals engage a well-defined neural network composed by language-specific and domain general areas that enables bilingual language processing and control. This network encompasses the prefrontal cortex, ACC, basal ganglia and the inferior parietal lobule (Abutalebi & Green, 2007). However, the recognition that bilingualism is not a unitary phenomenon, but one that varies along a number of dimensions (e.g., age of acquisition, immersion experiences), has led to a reevaluation of the existing neural models of bilingual language processing. Green &

²For a full discussion of this study, see Bak's chapter in the current special issue.

Abutalebi's adaptive control hypothesis (Green & Abutalebi, 2013) explores the view that control mechanisms in bilingual speech production are malleable and adaptable depending on the external demands of the bilingual interaction context. More specifically, the adaptive control hypothesis analyses eight main control processes (among which goal maintenance, conflict monitoring, interference suppression, and selective response inhibition) and their relevant neural networks and examines how different interactional contexts (single language, dual language, and dense code-switching) might modulate the relative activation of those networks. To exemplify, in a dense code switching interactional context in which a bilingual speaker routinely mixes her languages while interacting with other bilingual speakers who similarly code-switch, the authors assume that the two language's schemas are in co-operative relationship. Consequently, the adaptive control hypothesis predicts that bilingual speakers in such a context might show a distinct profile in the recruitment of the basal ganglia-cerebellar-frontal circuit than during a single language or dual language context.

An important question that is still partly unanswered even in recent neural models of bilingualism is how to integrate the structural, functional and cognitive changes that occur throughout the life-span and more specifically in older adults. More specifically, we propose that future neural models of bilingual language processing will need to account for: 1) how functional and structural changes due to aging modulate the functioning of the bilingual language control network and how its functionality might therefore change between younger and older bilinguals, 2) how bilingualism might account for the differences observed in the functional and structural patterns in bilingual older adults compared to monolingual older adults, and 3) how learning and speaking two languages might influence the connectivity between the neural hubs of the language system. In answering these questions, it will be relevant both to compare younger monolinguals and bilinguals, but also to compare older monolinguals to bilingual healthy speakers.

A first set of data towards answering these questions has been reported by Luk et al. (2011) and Grady et al. (2015). Luk et al. showed that older bilinguals show stronger intrinsic connectivity and white matter integrity in the frontoparietal control network (FPC), which includes dorsolateral and inferior frontal and parietal regions relative to older monolingual controls. A similar set of hypotheses was tested by Grady et al. (2015) who predicted that the life-long experience of processing and monitoring two languages would increase functional connectivity in networks engaged in executive control. Their results confirmed that older bilingual adults showed an enhanced functional connectivity within the cognitive control networks. Extending these set of results, Olsen et al. (2015) measured differences both in white and grey matter volume in older bilingual and monolingual speakers, and revealed that older bilinguals showed greater levels of white matter in the frontal lobe, and no decrease in gray matter volume in bilinguals in the temporal pole (one of the regions that is renowned for showing gray matter volume decline in aging).

Overall, these data suggest that the life-long experience of speaking two languages not only affects behavior, but also shapes the structure and the functionality of the brain across the life-span. We propose that future neural models of bilingual language processing will need to include hypotheses about how the proposed networks change during aging. Importantly, it will be important to also include a dynamic view of bilingualism. Future research will need

to consider how proficiency in the two languages and mode of use of the two languages impacts the neural network across the life-span.

Advancing the understanding of bilingual language processing and language processing in healthy aging, and most importantly, attempting to merge the two fields will yield to a broad scientific and societal impact. Slowing (or even reversing) age-related cognitive decline has social, but also health and fiscal implications. Bilingualism is one potential mechanism that may provide a way to accomplish this. Improving our understanding of the relations between age-related cognitive changes and the cognitive changes associated with bilingualism will allow us to better inform educational and intervention policies. Understanding how bilingualism affects the aging brain and how bilingualism is affected by the aging brain are two questions that will shape the research agenda in the immediate future.

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Figure 1.
Mean L1 Response Latency (ms): Block 1 and new pictures during the later blocks. Error bars represent standard error.