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# Bilingualism and domain-general cognitive functions from a neural perspective: A systematic review

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ABSTRACT

A large body of research has indicated that bilingualism – through continual practice in language control – may impact cognitive functions, as well as relevant aspects of brain function and structure. The present review aimed to bring together findings on the relationship between bilingualism and domain-general cognitive functions from a neural perspective. The final sample included 210 studies, covering findings regarding neural responses to bilingual language control and/or domain-general cognitive tasks, as well as findings regarding effects of bilingualism on non-task-related brain function and brain structure. The evidence indicates that a) bilingual language control likely entails neural mechanisms responsible for domain-general cognitive functions; b) bilingual experiences impact neural responses to domain-general cognitive functions; and c) bilingual experiences impact non-task-related brain function (both resting-state and metabolic function) as well as aspects of brain structure (both macrostructure and microstructure), each of which may in turn impact mental processes, including domain-general cognitive functions. Such functional and structural neuroplasticity associated with bilingualism may contribute to both cognitive and neural reserves, producing benefits across the lifespan.

## 1. Introduction

The ability to manage two languages has been a focal point for researchers in psychology, linguistics, and more recently cognitive neuroscience. When bilinguals use language, even in monolingual contexts, both of their languages remain “active”. That is, they cannot simply “shut off” one language and effectively function like monolinguals. To prevent words from the nontarget language being mistakenly retrieved, during either production or comprehension, bilinguals need mechanisms to restrict their language use to the target language and minimize cross-language interference (Declerck and Philipp, 2015; Kroll et al., 2012).

### 1.1. Bilingual language control

A prominent topic in bilingual language control mechanisms is inhibition (Declerck and Philipp, 2015; Kroll et al., 2008). An influential framework for language control is the Inhibitory Control (IC) model (Green, 1998), which has since been expanded to neurocognitive models, including the Language Control (Abutalebi and Green, 2007) and Adaptive Control models (Abutalebi and Green, 2016; Green and Abutalebi, 2013). The core principle in these models is that inhibitory processes are required to prevent the retrieval of items in the nontarget language, with a focus on processes during language production. The Bilingual Interactive Activation (BIA) model (Grainger and Dijkstra, 1992), and later extensions such as BIA+ (Dijkstra and van Heuven, 2002) and BIA-d (Grainger et al., 2010), on the other hand, focus on language control in comprehension. These latter models also postulate a role for inhibition, as a top-down control process to suppress competing items from the nontarget language, which may have been simultaneously activated during language comprehension. A further issue is that of stages of processing. Both production and comprehension entail a series of processing stages, involving access to items at the concept, lemma, and form (phonology and orthography) levels, though in opposing sequential order for production and comprehension. That is, production begins with a concept and ends with an output at the form level (Indefrey, 2011; Indefrey and Levelt, 2004), whereas comprehension is achieved when the concept is ultimately accessed following

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initial input of forms (Grainger and Holcomb, 2009). At each level, competing items from the nontarget language can be simultaneously activated along with the target item. In other words, language control needs to occur at multiple stages of linguistic processing (Declerck and Philipp, 2015).

To investigate language control, a commonly used behavioral paradigm is that of language switching. Inhibition has been suggested as an explanation for a number of language switching indicators, such as asymmetric switch costs, n-2 language repetition costs, and reversed language proficiency in mixed language conditions (see Declerck and Philipp, 2015, for a review). For example, compared to forward switch (switching from dominant/L1 to weaker/L2), backward switch (from weaker/L2 to dominant/L1) incurs a larger switch cost (e.g., Costa et al., 2006; Costa and Santesteban, 2004; Meuter and Allport, 1999). This asymmetric switch cost has been suggested to be due to a greater degree of inhibition required to suppress the dominant language, and thus greater cognitive resources required when needing to use that language again. Subsequently, researchers have explored the role of individual differences in inhibitory control ability in language control, and found that participants with stronger domain-general inhibitory control could better perform language switching tasks (e.g., Linck et al., 2012; H. Liu et al., 2014; Struys et al., 2019). To date, however, there remain inconsistencies in research findings, raising questions about whether language switching asymmetry could be considered as the main evidence to support the role of inhibitory control in bilingual language control (Bobb and Wodniecka, 2013; Gollan et al., 2014; Tabori et al., 2018).

### 1.2. *Bilingualism and cognition*

Since the proposal of the IC model, bilingualism has been linked to domain-general cognitive functions. It was put forward that continual practice with language control generalizes to nonlinguistic cognitive domains, leading to bilingual advantages in aspects of domain-general cognitive functioning (Abutalebi and Green, 2007; Bialystok et al., 2009; Green, 1998; Kroll et al., 2012). A large amount of research – with various bilingual populations, across the lifespan, and assessing various domain-general cognitive tasks – have found bilingual advantages in aspects of executive functions compared to monolinguals, particularly in inhibitory control and task switching (see Antoniou and Wright, 2017; Bialystok, 2017; Bialystok et al., 2009; Kroll and Dussias, 2018, for reviews). Such advantages have been shown to extend to aging, where proficiency in more than one language may help to increase cognitive reserve, which in turn helps to slow cognitive decline (see Antoniou and Wright, 2017; Kroll and Dussias, 2018, for reviews). Children and infant bilingual groups have also demonstrated advantages over monolinguals in aspects of cognitive, social, scholastic, and language learning abilities (see Kroll and Dussias, 2018, for a review).

Hilchey and Klein (2011) proposed two hypotheses for the bilingual cognitive advantage. In line with the IC model, the bilingual inhibitory control advantage (BICA) hypothesis suggests a bilingual cognitive advantage only in conditions requiring conflict resolution, such as the incongruent conditions in Stroop or flanker tasks. The bilingual executive processing advantage (BEPA) hypothesis, on the other hand, is motivated by the observation of a global response time advantage in cognitive control tasks, including both congruent and incongruent trials. There is evidence to support both hypotheses, though possibly with more to support the BEPA hypothesis (Hilchey and Klein, 2011). In recent years, however, many researchers have questioned the robustness, or even the existence, of the bilingual cognitive advantage, failing to replicate earlier findings (see Lehtonen et al., 2018; Paap et al., 2015, for reviews). Some have suggested that the mixed findings may be due to cultural differences (Samuel et al., 2018), a publication bias (de Bruin et al., 2015; Lehtonen et al., 2018), or methodological issues (Gasquoine, 2016; van den Noort et al., 2019).

### 1.3. *The present review*

Increasingly, researchers have focused on the neural (in addition to the cognitive) consequences of bilingualism. A number of studies have revealed that learning and using two or more languages can modify the brain, both in terms of functional brain responses when performing various tasks (see Bialystok, 2017; Calabria et al., 2018; Pliatsikas and Luk, 2016; Sulpizio et al., 2020b, for reviews), and in various aspects of brain structure (see Bialystok, 2017; García-Pentón et al., 2016; Gasquoine, 2016; Li et al., 2014, for reviews). The present review aimed to bring together the body of knowledge published to date on the relationship between bilingualism and domain-general cognitive functions from a neural perspective.

Previous reviews have mostly presented studies on either brain response differences between language control (e.g., switch) and baseline (e.g., single-language/nonswitch) conditions (e.g., Calabria et al., 2018; Sulpizio et al., 2020b), or brain response differences between bilinguals and monolinguals when performing domain-general cognitive tasks (e.g., Bialystok, 2017; Pliatsikas and Luk, 2016). The former type of studies often did not assess domain-general cognitive function tasks, and thus can only rely on reverse inference (which may be fallible; see e.g., Poldrack, 2006) to infer that language control engages neural mechanisms responsible for domain-general cognitive processing. The latter type of studies often did not assess bilingual language control, and thus cannot directly indicate the neural basis underlying language control, and whether it entails domain-general cognitive processing. A small number of studies have directly examined the overlap in neural responses between bilingual language control and domain-general cognitive functions, by assessing both types of tasks within the same sets of participants (e.g., reviewed in Calabria et al., 2018). However, these studies typically only assessed the task switching aspect of executive functions, and did not assess other crucial abilities such as inhibition. We thus attempt to provide a broader systematic review, covering all of these aspects relevant to the relationship between bilingual language control and domain-general cognitive functions at the neural level, to better see the whole picture regarding this topic, and to better identify any gaps in current research directions.

## 2. Method

### 2.1. *Literature identification*

Literature identification and selection were conducted following the Preferred Reporting in Systematic Reviews and Meta-Analysis (PRISMA) Statement guidelines (Moher et al., 2009), as well as more recent guidelines on conducting systematic reviews (Harari et al., 2020; Siddaway et al., 2019). Literature search was first carried out via three online databases: PubMed, Scopus, and Web of Science. To be as inclusive as possible, the keywords used were: “bilingual*” (covering bilingual, bilinguals, bilingualism) AND “brain OR neural” AND “executive OR cognitive”. Records up to the end of February 2020 were obtained. The initial search yielded 1906 entries across the three platforms. After removing duplicates (755), 1151 remained.

Two complementary search methods were additionally carried out, namely backward search (reference lists in published articles) and manual search (individual journals). Backward search via relevant review articles (Bialystok, 2017; Calabria et al., 2018; Pliatsikas and Luk, 2016; Sulpizio et al., 2020b) yielded 5 additional entries not previously identified. Manual search via field-leading journals (*Bilingualism: Language and Cognition*; *Brain*; *Brain and Language*; *Cerebral Cortex*; *Cortex*; *Human Brain Mapping*; *Journal of Neuroscience*; *Nature* and affiliated; *NeuroImage*; *Neuropsychologia*; *PNAS*; *Science* and affiliated) yielded 8 additional entries not previously identified. The total number of entries for first screening was 1164.

### *2.2. Screening and selection*

First screening was conducted using titles and abstracts. Papers were excluded if they were: a) not in English (38), b) not a peer-reviewed journal article (123), c) not pertaining to bilingualism or second language (L2) learning (44), d) not an empirical study (e.g., was a review, commentary, or theoretical paper; 242), or e) did not use a neural data acquisition method (316). Total number included for second screening was 401.

For second screening with full texts, an additional criterium was imposed, where papers were excluded if they were not relevant to the relationship between bilingual language control and domain-general cognitive functions (202), for example, studies that presented findings solely on the processing of one language versus another, rather than control between languages. Although some studies have found involvement of domain-general cognitive mechanisms during single-language processing among bilinguals, such as engagement of dorsolateral prefrontal cortex when naming pictures in a weaker L2 (e.g., Hernandez and Meschyan, 2006), many have found minimal differences (i.e., largely overlapping neural responses) between L1 and L2 processing (see Sulpizio et al., 2020b, for a meta-analytic review). Therefore, for greater clarity and relevance, studies reporting bilingual language processing in each language separately were not included. Additionally, studies that examined performance in a more extreme case of bilingual language control, namely translation or simultaneous interpretation, were excluded (unless they also investigated more typical bilingual language control processes, e.g., language switching or cross-language competition). This is because a) these studies often investigated mechanisms underlying expertise performance, or mechanisms underlying specific strategies for translation, rather than bilingual language control per se; and b) the type of language control required during interpretation and translation differs, and is somewhat less relevant, to the typical language control required of bilinguals in everyday language use settings. The initial sample included 199 studies. When reviewing an earlier version of this work, an anonymous reviewer suggested additional studies (12), 11 of which were subsequently incorporated.

The final sample included 210 studies (see Fig. 1). Screening was independently conducted by two authors, and cases of disagreement were discussed and resolved. Studies were included under the assumption that all were approved by their respective ethics committees prior to data collection.

### *2.3. Classification*

The final sample of studies span from 1999 to the cutoff date of February 2020, and cover a range of neural data acquisition methods, including electrophysiology ($n$ = 59), magnetophysiology ($n$ = 7), functional imaging ($n$ = 76), structural and diffusion imaging ($n$ = 45), multimodal and other methods ($n$ = 23). Due to the relatively large number of studies, full lists will not be included in the main text, but can be found in Supplementary Information (SI). SI Tables 1–5 present for each study the participant sociodemographic and language experience characteristics, behavioral tasks and neural data acquisition methods used, and an outline of main behavioral and neural results.

Within electrophysiology, magnetophysiology, and functional imaging, studies were further divided into those that investigated domain-general cognitive functioning [SI Tables 1A ($n$ = 28), 2A ($n$ = 1), 3A ($n$ = 21)], bilingual language control [SI Tables 1B ($n$ = 27), 2B ($n$ = 6), 3B ($n$ = 40)], or both language control and cognitive functions [SI Tables 1C ($n$ = 4), 3C ($n$ = 9)], functional imaging studies also included a subdivision on resting-state brain function [SI Table 3D ($n$ = 6)]. Of the task-related functional imaging studies, the majority examined brain activations, with 13 studies also analyzing task-related and/or resting-state functional connectivity, one of which also examined resting-state brain activity. All but two electrophysiology studies employed electroencephalography (EEG), one study used intracranial recording, and another used direct electrical stimulation. One of the EEG studies employed dual-EEG (i.e., two-participant simultaneous recording) to investigate interbrain synchronization during interpersonal bilingual language control. All magnetophysiology studies used magnetoencephalography (MEG). The majority of functional imaging studies used functional magnetic resonance imaging (fMRI), three studies used functional near-infrared spectroscopy (fNIRS), and two used positron emission tomography (PET).

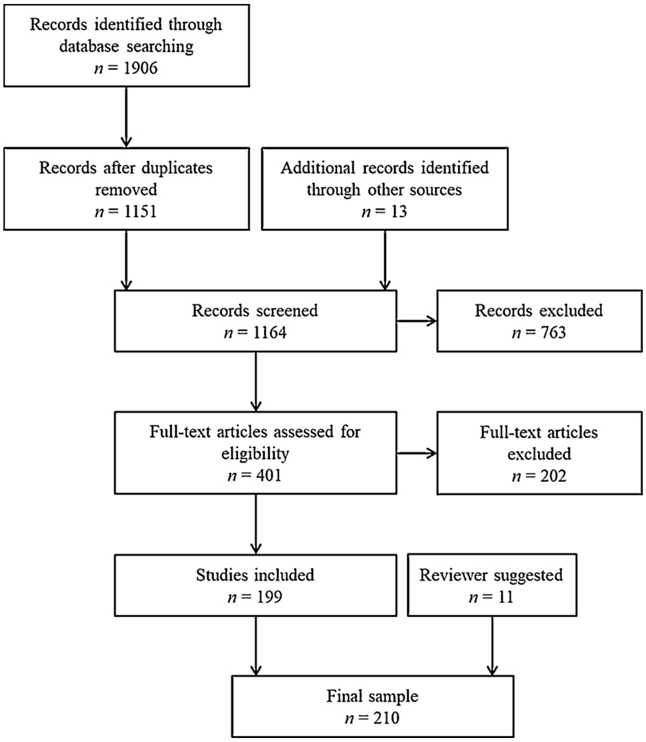

**Fig. 1.** Flow diagram of the literature identification and screening process (in accordance with PRISMA Statement guidelines; Moher et al., 2009).

Structural and diffusion imaging studies were subdivided into those that employed either structural imaging [SI Table 4A ($n$ = 33)], diffusion imaging [SI Table 4B ($n$ = 10)], or both [SI Table 4C ($n$ = 2)]. All but two structural imaging studies employed structural MRI (sMRI) to investigate grey and white matter macrostructure, one study used computed tomography (CT) to investigate cortical and subcortical pathology, and the other used quantitative MRI (qMRI) to investigate macromolecular structure. All diffusion imaging studies investigated white matter microstructure; one of those studies also investigated structural connectivity.

The remaining studies included those employing multimodal methods [SI Table 5A ($n$ = 15)], multimodal with neuromodulation methods [SI Table 5B ($n$ = 3)], lesion reports [SI Table 5C ($n$ = 2)], or metabolic imaging [SI Table 5D ($n$ = 3)]. Multimodal studies included three that employed electrophysiology (EEG or direct electrical stimulation) with functional imaging (fMRI), one that employed MEG (to investigate resting-state functional connectivity) and sMRI, and the remaining employing fMRI (activation and/or connectivity) with sMRI and/or diffusion MRI. Of the multimodal studies that involved diffusion imaging, most investigated white matter microstructure (like all of the diffusion imaging studies in SI Table 4), whereas one study investigated structural connectivity. Multimodal with neuromodulation studies included two that used transcranial direct current stimulation (tDCS) with EEG and one that used transcranial magnetic stimulation (TMS) with fMRI. Neuromodulation effects were either excitatory (anodal tDCS) or inhibitory (cathodal tDCS, TMS). Lesion studies investigated the effects of damage to specific brain regions on language and cognitive functions, one of which also employed fMRI (to investigate resting-state functional connectivity). Metabolic imaging studies used fluorodeoxyglucose PET (FDG-PET) to investigate brain metabolic function via glucose metabolism, one of which also investigated brain structure with sMRI.

### 2.4. Integration and analysis

In subsequent sections, we first present findings on neural responses when performing bilingual language control tasks, section 3.1. Findings on differences between bilinguals and monolinguals on neural responses to domain-general cognitive tasks are then presented in section 3.2. Section 3.3 presents studies that examined neural responses to both language control and cognitive functions among the same sets of participants. These first three sections cover all task-related neural data acquisition methods (electrophysiology, magnetophysiology, functional imaging, neuromodulation). In section 3.4, we present coordinate-based meta-analyses of relevant functional imaging studies, including single dataset analyses on language switching and task switching, and conjunction analysis of the two domains. Section 3.5 presents findings on differences between bilinguals and monolinguals in brain structure, covering grey matter macrostructure (structural imaging) and white matter microstructure (diffusion imaging).

The studies reviewed in sections 3.1 to 3.5 mainly concern healthy, younger adults. For better clarity and ease of access, findings relating to children, older adults, and neurological disorder patients are presented separately, in section 3.6. Like for healthy younger adults, this section covers findings regarding differences between bilinguals and monolinguals in task-related brain function and in brain structure. This section in addition covers non-task-related brain function – including resting-state brain function and brain metabolic function – which were not examined among healthy young adults in the present set of studies reviewed. Lastly, section 3.7 presents findings regarding the influences of various individual difference factors within bilingual groups.

## 3. Results

The following subsections present only neural findings from the studies reviewed, since a full review of all relevant behavioral studies is beyond the scope of the present work. Nonetheless, behavioral findings as reported in the studies reviewed are provided in SI.

### 3.1. Neural basis for bilingual language control

#### 3.1.1. Language production

A large number of studies have examined bilingual language control in production, mostly via language switching and/or language mixing in picture naming tasks, but also in digit naming, quantity naming, card naming, verb generation, property generation, sentence completion, or translation tasks. Many imaging studies have found involvement of a frontoparietal-subcortical network in bilingual language control, with particular involvement of domain-general cognitive control areas – such as dorsolateral prefrontal cortex (dlPFC), inferior frontal gyrus/ventrolateral prefrontal cortex (IFG/vlPFC), pre-supplementary motor area/dorsal anterior cingulate cortex (pre-SMA/dACC), caudate nucleus of the basal ganglia, and parietal areas (Abou-Ghazaleh et al., 2020; Abutalebi et al., 2008; Blanco-Elorrieta and Pylkkänen, 2016; Branzi et al., 2016; de Bruin et al., 2014; Garbin et al., 2011; Guo et al., 2011; Hernandez, 2009; Hernandez et al., 2000, 2001; Lei et al., 2014; L. Li et al., 2016; Ma et al., 2014; Price et al., 1999; Sierpowska et al., 2013, 2018; Y. Wang et al., 2007, 2009; Y. Zhang et al., 2014, 2019; Zou et al., 2012). Such findings have been observed for bilinguals from a wide array of language backgrounds, including cross-modal languages (i.e., spoken and signed); for those with a wide range of ages of L2 acquisition (AoAs; i.e., from early childhood, mid-childhood, adolescence, to adulthood); for those who are strongly dominant in one of their languages (either L1 or L2) or have relatively balanced proficiency; for those who are immersed in their dominant language or their weaker language. On the other hand, the vast majority of these studies assessed young adults (up to about 40 years), with only a few studies specifically assessing bimodal bilinguals that have involved middle-aged adults (40–50 years).

For event-related potentials (ERPs), language switch costs were characterized by larger P2, N2, late positive complex (LPC)/P3b, and N400 amplitudes, indicating involvement of domain-general conflict monitoring and inhibitory control processes, and the presence of linguistic conflict (Guo et al., 2013; Massa et al., 2020; Naylor et al., 2012; Yi et al., 2018). Source estimation showed that language selection mainly occurred in frontoparietal domain-general processing areas, such as dlPFC, precentral gyrus, and inferior parietal lobule (IPL; Khateb et al., 2007). Patterns of findings with N2 and LPC components have indicated that domain-general inhibitory control may modulate language switch costs specifically at the lexical selection phase (LPC), and not during language task schema phase (N2; Guo et al., 2013; H. Liu et al., 2014, 2016, 2017). However, some have found switch cost effects during language task schema phase (Christoffels et al., 2013; Y. Liu et al., 2018). Additionally, two subcomponents in cued language switching have been dissociated, namely *switching to* a new language and *switching away* from the previous language. Specifically, switch-away involved larger N2 and smaller LPC amplitudes compared to switch-to and nonswitch conditions, suggesting that switching away may be the main driving force for language switching effects (H. Liu et al., 2020c).

Within the domain-general neural responses involved in language control, different patterns have been observed under different language control task requirements:

1) *Switch direction*: Some have found additional activation for switching into a weaker L2 in right frontal, medial frontal, parietal, and ACC areas (de Bruin et al., 2014; Y. Wang et al., 2007), whereas others have found the opposite pattern, that is, greater engagement of cognitive and language control areas for switching into a dominant L1 (Tabassi Mofrad and Schiller, 2019; Y. Zhang et al., 2014). Within the control areas, left caudate was more engaged for switching into a weaker language, whereas left PFC was more involved for switching into a dominant language (Abutalebi et al., 2013; Branzi et al., 2016). Furthermore, task related functional connectivity patterns appeared to differ depending on switch direction, with IPL showing increased connectivity with posterior cerebellum and decreased connectivity with frontal and other parietal areas when switching into a dominant L1, but increased connectivity with precentral gyrus and ACC when switching into a weaker language (Tabassi Mofrad and Schiller, 2019).

   Differences in switch direction have also been observed in ERP responses. Compared to nonswitch trials, switching into a dominant L1 involved smaller N2 amplitude (Christoffels et al., 2007), whereas switching to a weaker L2 involved larger P3 (Timmer et al., 2019). When compared directly to L2 switch, switching in to L1 involved larger P2 and smaller N400 amplitudes, indicating greater cognitive effort to access the inhibited L1 and to extract semantic information in L2 respectively (Yi et al., 2018).

2) *L1 vs. L2*: Related to the above, in mixed language contexts, naming in a more dominant L1 requires more neural resources, particularly in brain areas relating to domain-general cognitive control such as right dlPFC and SMA; whereas in single-language contexts, naming in a weaker L2 requires greater neural resources than L1 naming (Fu et al., 2017; Ghazi-Saidi and Ansaldo, 2017). Such a pattern has been observed even for L2 words that share phonological and/or semantic features with L1 words, namely cognates (shared phonology and semantics) and clangs (shared phonology but not semantics; Ghazi-Saidi and Ansaldo, 2017). ERPs have found that proactive

preparation for L2 may require greater resources than for L1 (Verhoef et al., 2010; Y. J. Wu and Thierry, 2017). (See also point 4.)

3) *Switching vs. mixing*: Differences have been observed between transient local control (trial-to-trial switching), sustained local control (mixing), and global control (block-to-block switching), though with inconsistent findings. Some have found that SMA and dACC may be more involved for sustained local control (mixing), whereas left dlPFC and parietal areas may be more involved for global control of switching (Guo et al., 2011). On the other hand, some have found dlPFC, parietal, and SMA areas to be involved in local control, both sustained (mixing) and transient (switching), though with different patterns of activation for mixing and switching within these broad brain regions (Y. Wang et al., 2009). Some, however, have not found significant differences between mixing and switching (Blanco-Elorrieta et al., 2018). ERPs for sustained local control (nonswitch trials in mixed compared to blocked conditions) were characterized by larger N2 (for both languages), smaller N450 (only for L1), and larger P2 amplitudes, as well as earlier P2 latency, supporting differences in processing mechanisms between sustained and transient language control (Christoffels et al., 2007; Massa et al., 2020).
4) *Proactive vs. reactive control*: When proactive control was required (long cue-target interval), anterior vlPFC may play a greater role, whereas mid-vlPFC was more involved when reactive control was required (short cue-target interval). Furthermore, increased functional connectivity has been observed between anterior and mid-vlPFC bilaterally for proactive as opposed to reactive control (Branzi et al., 2019). Cue-locked ERPs revealed a posterior positivity (previously associated with domain-general top-down control) for proactive preparation of language switching, and that larger posterior positivity amplitude was associated with faster switching (Lavric et al., 2019). Findings have also distinguished two processes for proactive (endogenous) control during language switching, namely disengaging attention from nontarget language – indicated by an early posterior negativity (particularly for L2), and engaging in target language – a late anterior negativity (Verhoef et al., 2010). A cue-locked contingent negative variation (CNV) has also been observed, with a larger amplitude for L2 than for L1, indicating that preparation for L2 production involved greater proactive control (Y. J. Wu and Thierry, 2017). Some, however, found no effect of preparation interval, specifically on L1 nonswitch trials, supporting an L1-repeat-benefit hypothesis, rather than inhibition of the nontarget language (Verhoef et al., 2009).
5) *Preparation vs. execution*: Studies that distinguished between preparation and execution stages of language control or selection have found that the typical language and cognitive control areas – such as lateral PFC, ACC, caudate – were specifically involved at the execution stage, and not during the preparation stage. During preparation, other frontoparietal and temporal areas – such as medial PFC, bilateral precuneus, right superior parietal lobule (SPL), middle temporal gyrus (MTG) – were more involved (Reverberi et al., 2015, 2018).
6) *Language switching with or without meaning switch*: When naming pairs of pictures, both shared and distinct areas of activation were found for a) language switching when the meaning stayed the same within the pair, b) meaning switch within a language, and c) double switch. Shared activation were mostly found in frontoparietal areas, distinct activation mostly in PFC areas (Y. Zhang et al., 2019).
7) *Voluntary vs. cued switching*: Differing involvement of domain-general control areas has also been observed for free-choice or voluntary switching, as opposed to the forced-choice or cued switching that is commonly investigated in laboratory settings. Specifically, free choice language switching was found to engage more bilateral PFC and ACC areas, whereas forced choice engaged more bilateral SMA, cingulate, basal ganglia, and parietal areas (Reverberi et al., 2018; Y. Zhang et al., 2015b). On the other hand, some have found minimal involvement of domain-general control areas in voluntary language switching (Blanco-Elorrieta and Pylkkänen, 2017).
8) *Type of cue*: When natural cues – either script or identity of interlocutor – were used for cued switching, as opposed to the more artificial cues typically used in laboratory settings (e.g., color, shape, flag), ACC was found to be sensitive to cue type; ventral PFC areas were more engaged when there was cue-target mismatch, that is, when needing to overcome prepotent associations between cues and corresponding languages (Blanco-Elorrieta and Pylkkänen, 2015).
9) *Cross-modal language control*: Studies examining bimodal bilinguals have distinguished between disengaging (switching off) the previous language – namely switching from code-blending to producing only one language – and engaging (switching on) a new language – namely switching from producing one language to code-blending – during language control, which is not possible to examine among unimodal bilinguals. Domain-general control areas – dlPFC and ACC – were found to be involved specifically for disengaging a previous language, and not for engaging a new language (Blanco-Elorrieta et al., 2018). Within the control areas, dACC and left caudate may play different roles during bimodal language switching, with the former area more supporting a spoken language (or dominant L1) and the latter more supporting a signed language (or weaker L2). More specifically, dACC reduced connectivity with the spoken language area – left superior temporal gyrus (STG) – while continuing to modulate the signed language area – left dorsal pre- and postcentral gyrus, whereas left caudate showed the opposite pattern (L. Li et al., 2016). Furthermore, cross-modal mixing (code-blending) and switching may not involve domain-general control areas to the same extent as unimodal language control, but may involve more language-specific areas, such as left STG/MTG (Wernicke's area; Blanco-Elorrieta et al., 2018; Kovelman et al., 2009).

Studies using tDCS to modulate neural function in a particular area – in this case right dlPFC, a key domain-general inhibitory control area – have found a causal role of this area in changing language control (switching) patterns. For example, both anodal and cathodal tDCS induced symmetric switch costs, whereas under sham tDCS – that is, no neuromodulation – switch cost was larger for switching into a dominant L1 (B. Li et al., 2018). During voluntary language switching, when no switch cost was observed under sham tDCS, both anodal and cathodal tDCS induced a language switch cost (H. Liu et al., 2020b). Further, cathodal tDCS was found to reduce switch cost – that is, improve language control – possibly by allowing better inhibition of interference from the nontarget language, but only during cued switching (B. Li et al., 2018) and not during voluntary switching (H. Liu et al., 2020b).

### 3.1.2. *Language comprehension*

Studies have also examined bilingual language control in comprehension, via either language switching/mixing or cross-language competition, using various comprehension tasks, including both auditory comprehension – such as word-picture matching or narrative listening – and visual comprehension – such as lexical decision, semantic decision, picture semantic categorization, cross-language semantic priming, or silent reading. Like for language production, domain-general cognitive control areas – such as PFC, SMA, ACC, and caudate – were found to be engaged for bilingual language control during comprehension. Again, these findings have been observed for young adult bilinguals with varying language backgrounds, AoAs, proficiency levels, and immersion environments (Abutalebi et al., 2007; Blanco-Elorrieta and Pylkkänen, 2016; Bradley et al., 2013; Branzi et al., 2016; Crinion et al., 2006; Hsieh et al., 2017; Marian et al., 2014, 2017; Peeters et al., 2019; Rodriguez-Fornells et al., 2002; Stasenko et al., 2020).

Neurophysiology studies have found that language switch within a sentence context, relative to nonswitch trials, elicited a larger LPC amplitude, and a lexical switch involved a larger N400 amplitude (E. M. Moreno et al., 2002). The effects were modulated by switch direction, with switching into L2/weaker language showing larger LPC and N400 amplitudes, whereas switching into L1/dominant language showed mixed results (C. B. Fernandez et al., 2019; Hut et al., 2017; Liao and Chan, 2016; Litcofsky and Van Hell, 2017; Pellikka et al., 2015). Time-frequency analyses showed that switching into a dominant language elicited increased power in alpha and theta oscillation bands, whereas switching into a weaker language elicited decreased beta band power. These findings indicate that dominant-to-weaker language switch may engage not only lexical processes but also greater effort to perform sentence-level reanalysis, whereas weaker-to-dominant switch may engage additional cognitive processes to release inhibition of the dominant language (C. B. Fernandez et al., 2019; Litcofsky and Van Hell, 2017). Cross-language competition during an auditory memory retrieval task also impacted brain oscillations. Specifically, between-language retrieval elicited larger and delayed theta event-related synchronization (ERS) and later-appearing alpha event-related desynchronization (ERD), compared to within-language retrieval, suggesting involvement of domain-general executive processes (Leinonen et al., 2007).

Like for production, minimal involvement of domain-general cognitive control areas was found during voluntary language switching in comprehension (Blanco-Elorrieta and Pylkkänen, 2017). Some have distinguished between a task/decision neural system and a conflict monitoring and lexical selection neural system involved in bilingual language control during comprehension. The task/decision system – comprising bilateral IFG, SMA, caudate – was more engaged for controlling competing responses between languages, while the conflict monitoring and lexical selection system – comprising ACC and left MTG respectively – was more engaged for semantic conflict resolution such as that induced by interlingual homographs (shared orthographic form but different meanings across two languages; Hsieh et al., 2017).

Neuromodulation using inhibitory TMS over left IFG – an area more for language-specific control and processing, but may also play a role in domain-general control – revealed a causal role of this area in bilingual language control during comprehension, but its involvement depended on switch direction. That is, temporary cortical inhibition of left IFG impaired performance for switching into a weaker L2 during semantic categorization, whereas there was no effect when switching into a dominant L1 (Nakamura et al., 2010).

### 3.1.3. *Communication*

In addition to studies investigating language control in production or comprehension separately, one study examined language switching (during picture naming) in a communication setting using dual-EEG, simultaneously recording the brain signals of a speaker and a listener. When switching into L2, relative to L1 switch, higher interbrain synchronization was observed for delta band oscillations. That is, increased requirements for inhibiting cross-language interference produced greater synchronization in brain signals between speaker and listener. Additionally, participant switching, in the absence of language switching, also produced higher delta-band interbrain synchronization, likely due to suppression of interpersonal interference. Thus, during cross-language interpersonal communication, inhibitory control processes may be required not only to inhibit cross-language interference but also interpersonal interference (H. Liu et al., 2019). Another study investigated language switching in a virtual reality environment with virtual listeners, and found that ERP responses for a listener switch cost were similar to that of a language switch cost, although switching listeners and languages at the same time delayed lexical processing more than switching listeners without language switch (Peeters, 2020).

### 3.1.4. *Morphosyntactic processing*

The majority of studies investigating bilingual language control have examined such control at the word level of processing, during either production or comprehension as outlined above. Some studies have examined bilingual language control at the morphosyntactic level of processing. When performing a bilingual morphosyntax rule execution task, similar domain-general control areas as found above – such as dlPFC, SMA, ACC, caudate – were found to be engaged, though with differing involvement across different stages of the task (Seo et al., 2018; Seo and Prat, 2019). Specifically, ACC was more involved in top-down language preparation, that is, detection of language conflict at the earliest stage, and using that information to trigger a frontostriatal signal biasing system for subsequent controlled processing. Left caudate was more involved in keeping track of the target language in use throughout the various levels of language selection, including language preparation, rule selection, and rule execution stages. Right caudate, on the other hand, may be more involved in inhibitory processes to overcome competing responses. Frontal areas – particularly dlPFC – were also involved in all stages, but increased in involvement towards later stages, showing greatest involvement at the task execution stage (Seo et al., 2018). Furthermore, frontal areas – dlPFC, SMA – showed even greater involvement during execution when a more reactive type of control was required, that is, when proactive cuing of the target language at the preparation stage was removed (Seo and Prat, 2019).

## 3.2. *Effects of bilingualism on brain function relating to domain-general cognitive tasks*

Studies investigating the effects of bilingualism on domain-general cognitive functions have assessed a range of cognitive processing abilities, using a variety of tasks. These cognitive functions largely fall into three broad types: executive functions, attention, and working memory. Components within each type of function sometimes overlap with components of another. To ensure clarity in definition and terminology, we first provide a brief outline of the various components of these cognitive functions, on the basis of widely accepted frameworks (see Fig. 2):

1) Executive functions comprise a) *inhibition*– resolving conflict by suppressing a prepotent response or interference from competing stimuli, b) **shifting**– switching between task sets, and c) *updating*– monitoring and updating working memory representations (Miyake et al., 2000; Miyake and Friedman, 2012). Inhibitory control has been further separated into two aspects, *interference suppression* and *response inhibition* – that is, overcoming conflict caused by competing stimuli or by prepotent response tendencies respectively (Blasi et al., 2006; Brydges et al., 2012; Bunge et al., 2002).
2) The inhibition component of executive functions overlaps with the *executive control*component of attention, for overcoming conflict from competing stimuli. The other two components of attention involve taking advantage of warning cues, namely *alerting*to the presence of a cue, or *orienting*to the target location indicated by a cue (Fan et al., 2002, 2005).
3) The updating component of executive functions also load on to a broad working memory capacity construct, termed central executive in Baddeley's (2003) model of working memory. Another ability that load on to this broad working memory construct is *working memory capacity* defined in the narrow sense, which assesses the number of pieces of information that can be held temporarily and manipulated (Wilhelm et al., 2013). *Short-term memory*, on the other hand, assesses only the number of pieces of information that can be held temporarily without manipulation (Jonides et al., 2008).

### 3.2.1. *Response inhibition*

Compared to monolinguals, bilinguals have shown more efficient recruitment of domain-general cognitive control areas – such as dlPFC and ACC – for conflict resolution during stop-signal and Stroop tasks (Rodríguez-Pujadas et al., 2014; Waldie et al., 2009), and less extensive engagement of posterior brain areas during Stroop task, possibly indicating less elaborate stimulus evaluation (Waldie et al., 2009). Bilinguals have also shown greater reliance on language-specific control

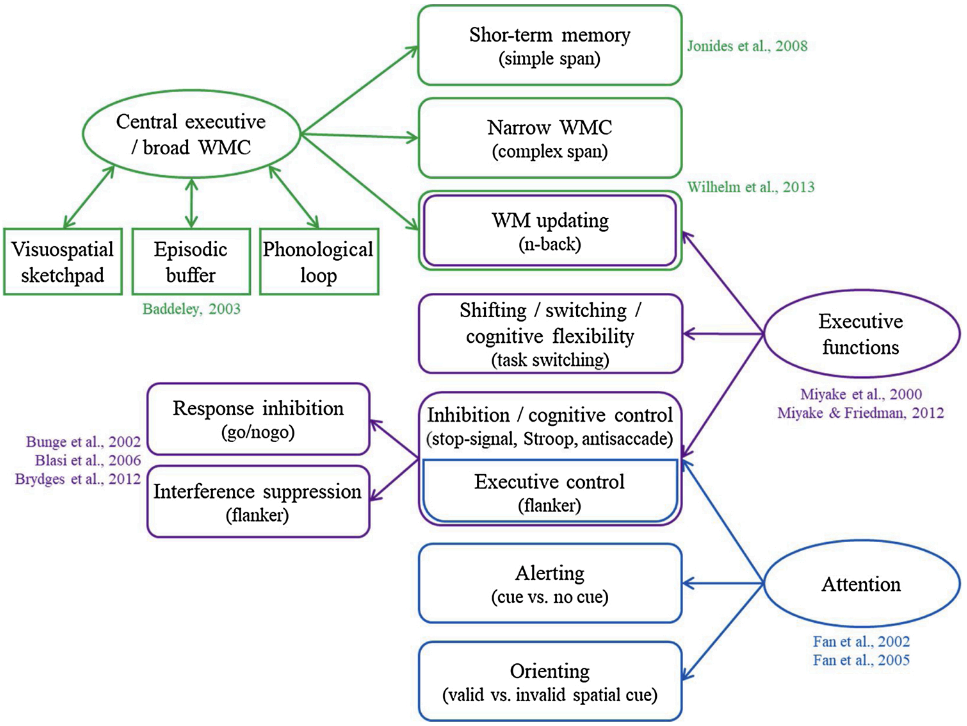

**Fig. 2.** Components of, executive functions, attention, and working memory. Examples of the type of tasks used to assess each construct are given in parentheses. Green = working memory components; purple = executive function components; blue = attention components; WM = working memory; WMC = working memory capacity.

areas – such as left IFG/vlPFC – during go-nogo and Stroop tasks (Costumero et al., 2015; Teubner-Rhodes et al., 2019), and that engagement of such areas was associated with faster conflict resolution on Simon task (Bialystok et al., 2005). However, studies have also shown similar neural engagement between bilinguals and monolinguals for go-nogo and Simon tasks (Bialystok et al., 2005; Grady et al., 2015; Luk et al., 2010), though expressed more strongly in bilinguals (as imaged using MEG; Bialystok et al., 2005).

Bilinguals and monolinguals have also differed in neuroelectric responses, particularly in ERP components related to conflict monitoring and resolution. In particular, bilinguals have shown smaller N2, P3, and error related negativity (ERN) amplitudes, as well as earlier P3 and later N450 latencies, during tasks requiring inhibition of prepotent responses – such as Stroop, Simon, antisaccade, and AX-Continuous Performance tasks – suggesting that bilinguals may require less active conflict monitoring or may be better able to allocate resources during such tasks (Coderre and van Heuven, 2014; Heidlmayr et al., 2016; Kousaie and Phillips, 2012; Morales et al., 2015). Additionally, bilinguals showed larger N450 amplitude during Stroop task non-conflict trials in either language, but not for Stroop conflict trials, suggesting that the possible bilingual advantage is not about conflict-specific control but more global cognitive control (Coderre and van Heuven, 2014). On the other hand, when performing go-nogo tasks – which requires less conflict monitoring, but more purely inhibition of a response – bilinguals showed larger N2 and P3 amplitudes and earlier N2 and P3 latencies on nogo trials, suggesting better inhibitory control compared to monolinguals. This was particularly the case for auditory go-nogo tasks (M. Fernandez et al., 2013, 2014), but has also been found for the visual modality (S. Moreno et al., 2014), and has been observed after relatively brief (about 6 months) L2 learning (Sullivan et al., 2014). Bilinguals have also shown larger N2 and P3a amplitudes on a condition that required efficient adjustment between proactive and reactive control during AX-Continuous Performance Task, suggesting that bilinguals are better able to selectively adjust and engage proactive and reactive control depending on task demand, whereas monolinguals mainly rely on one of the two types of control (Morales et al., 2015).

### 3.2.2. *Interference suppression*

Brain activation and ERP differences between bilinguals and monolinguals have also been observed for interferences suppression. During flanker task performance, monolinguals engaged a network comprising temporal pole and SPL, whereas bilinguals engaged a wider network covering areas associated with language control – dlPFC, IFG, SMA, IPL, fusiform gyrus, and basal ganglia (Luk et al., 2010).

For ERPs, compared to monolinguals, bilinguals have shown a) a smaller delay in P3 latency between incongruent and congruent flanker conditions, indicating bilinguals categorized stimuli more quickly (Kousaie and Phillips, 2012); b) earlier P2 latency, indicating bilinguals attended to the stimuli more quickly (Y. J. Wu et al., 2016); c) smaller sequential congruency effect at N2 and P3 amplitudes, indicating bilinguals experienced less interference from previous trial congruency, that is, they were better able to disengage attention from incongruency contexts and refocus on current relevant information (Grundy et al., 2017b); and d) larger correct related negativity (CRN) and ERN amplitudes, indicating bilinguals experienced higher post-response conflict when encountering errors (Kałamała et al., 2018; Kousaie and Phillips, 2012).

### 3.2.3. *Task switching/cognitive flexibility*

Compared to monolinguals, bilinguals have been found to engage language control areas – such as left IFG, left caudate and putamen, and thalamus – when performing color-shape judgement switching tasks (Garbin et al., 2010; Rodríguez-Pujadas et al., 2013) or when executing novel tasks during Rapid Instructed Task Learning (Stocco and Prat, 2014). Greater activation of such areas were further associated with faster performance (Stocco and Prat, 2014). Another key control area – ACC – has been found to play differing modulatory roles between bilinguals and monolinguals. Among bilinguals, ACC showed a weaker positive influence (effective functional connectivity) on other control areas – dlPFC and basal ganglia, whereas among monolinguals there was a stronger negative influence. The weaker influence of ACC may contribute to a bilingual advantage in cognitive flexibility, since stronger influence of ACC has been associated with lower performance accuracy on Rapid Instructed Task Learning (T. M. Becker et al., 2016b).

For electrophysiology, when performing a bivalency switching task, bilinguals showed smaller ERN and error positivity (Pe) amplitudes, as well as greater brain signal complexity (entropy) at occipital sites, suggesting that bilinguals were better able to process stimuli and disengage from it than monolinguals (Grundy et al., 2017a; Grundy and Bialystok, 2018). Bilinguals also showed larger N2 amplitude than monolinguals for both switch and nonswitch trials, suggesting a group difference in general cognitive processes, rather than a bilingual advantage in cognitive flexibility per se (López Zunini et al., 2019).

### 3.2.4. *Working memory updating*

Compared to monolinguals, bilinguals were found to more engage left supramarginal gyrus (SMG) and left dlPFC when performing n-back tasks. There were also differences between groups for different task modalities, where bilinguals engaged ventral ACC for spatial n-back performance and right MTG for nonspatial n-back, whereas monolinguals showed the reverse pattern (Alain et al., 2018).

For ERPs, bilinguals showed a larger P3 amplitude than monolinguals during n-back performance. Furthermore, although both groups showed decreasing P3 amplitude as load increased (from 0- to 1- to 2-back), bilinguals showed a larger decrease, and that such decrease was associated with higher accuracy. These results indicate that bilinguals may have more neural resources available to allocate to changing task demands than monolinguals (Barker and Bialystok, 2019; Morrison et al., 2019a, 2019b).

### 3.2.5. *Short-term memory*

When performing a short-term memory task (delayed match-to-sample), bilinguals showed larger P3b, smaller N2b and negative slow wave (NSW) amplitudes during retrieval, and a marginally larger P3b amplitude during encoding, compared to monolinguals. These results indicate that bilinguals may find short-term memory tasks easier than monolinguals, and that group differences in performance were mainly due to processing differences during retrieval, rather than during encoding (Morrison et al., 2019a)

### 3.2.6. *Orienting attention*

When performing a selective listening task, bilinguals showed larger late negative difference (Ndl) and reorienting negativity (RON) amplitudes compared to monolinguals, indicating that bilinguals were better able to maintain attention and process attended sounds, as well as to reorient attention (Rämä et al., 2018).

## 3.3. *Direct overlap in neural responses between language control and cognitive functions*

So far, we have presented findings from studies that have examined either bilingual language control or domain-general cognitive functions (sections 3.1 and 3.2 respectively). As mentioned in the Introduction, neither type of studies can directly reveal whether bilinguals engage domain-general cognitive processes for managing two languages, but instead need to rely on reverse inferencing. A relatively small number of studies examined both language control and domain-general cognitive processing within the same set of participants.

Some studies have found overlap in neural activations between language switching and domain-general task switching – particularly in control related brain areas such as right dlPFC, left IFG, pre-SMA, cingulate, caudate, and bilateral parietal areas (Anderson et al., 2018a; De Baene et al., 2015; Hosoda et al., 2012; Weissberger et al., 2015; Yamasaki et al., 2019). Some have also found overlapping activations in occipital and cerebellar areas (Anderson et al., 2018a; De Baene et al., 2015). Such overlapping activation patterns has been observed specifically among bilinguals. For monolinguals, the recruitment of these areas was sensitive to task and condition. For example, the switch condition of a language switching task and the nonswitch condition of task switching involved one set of areas, while the nonswitch condition of language switching and the switch condition of task switching involved another set of areas. Furthermore, behavioral switch costs for both language and task switching were found to covary with the same set of brain areas for bilinguals, whereas for monolinguals, switch costs covaried with different sets of brain areas for language and task switching (Anderson et al., 2018a). One study also examined switching between lower-level motor (tapping) sequences, and also found overlapping neural activations with language switching – mainly in left IFG, ACC, bilateral parietal areas (Hosoda et al., 2012). The extent of overlap observed varied between studies, with some finding extensive overlap (De Baene et al., 2015) and others showing less. For example, within left IFG, the more dorsal portions were more involved for domain-general functions, whereas the more ventral portions were more involved for language control (Hosoda et al., 2012).

Studies examining effective functional connectivity have also suggested convergence in neural mechanisms between language switching and task switching. One study found that both domains involved signal routing via the basal ganglia (Yamasaki et al., 2019). Another study found numerous shared connections across the two domains – within frontal, within subcortical, and between frontal and subcortical areas – and that pre-SMA/dACC and right thalamus were hubs in the functional networks of both domains. The language control brain network is thus suggested to be reconfigured from that for domain-general cognitive control, by increasing connectivity from frontal to subcortical areas and among subcortical areas, while retaining dorsal-frontal connectivity and core-periphery structures (J. Wu et al., 2019).

For ERPs, some have found bilinguals to show more similar ERP responses across language and task switching domains, compared to monolinguals (Timmer et al., 2017). However, some have found an interaction between domain (language or task switching) and condition (mixed or single), suggesting that language selection and task selection do not rely on the same pattern of brain activity. On the other hand, source estimation showed that language switching processes occurred in brain regions associated with domain-general cognitive functions. It is possible that language control and domain-general cognitive processing entail different mechanisms, but similar neuro-anatomical bases (Magezi et al., 2012).

Some studies have found overlapping neural activations between bilingual language control and interference suppression. Specifically, both language switching and flanker task performance involved bilateral ACC (Abutalebi et al., 2012). Another study examined language processing, that is, each language separately rather than control or switching between languages. Overlapping activations between flanker tasks (with either linguistic or nonlinguistic flankers) and semantic categorization tasks (in either L1 or L2) were observed – in left orbital frontal and posterior cingulate areas – specifically for bilinguals, whereas no overlapping areas were observed for monolinguals (Coderre et al., 2016). ERPs also showed that the neural efficiency when facing interference is comparable across linguistic and nonlinguistic cognitive domains (Chen et al., 2017).

## 3.4. *Functional imaging meta-analysis*

Coordinate-based meta-analyses were conducted with data from functional imaging studies. Coordinates from whole-brain analyses were obtained for language switching ($n = 21$) and task switching ($n = 9$; see Table 1). Meta-analyses for other domain-general cognitive functions (e.g., inhibition) and other bilingual language control tasks (e.g., cross-language competition) could not be carried out due to limited numbers of studies. Activation Likelihood Estimation (ALE) analyses were performed using GingerALE 3.0.2 software, with Non-Additive correction to minimize within-experiment effects (Turkeltaub et al.,

**Table 1**
Functional Imaging Studies Included in Meta-Analyses.

| Study | Contrasts | Participants | L1 | L2 |
|---|---|---|---|---|
| *Language switching (n = 21)* | | | | |
| Abutalebi et al., 2007 | 1 | 12 | Italian | French |
| Coderre et al., 2016 | 2 | 14 | Spanish | English |
| De Baene et al., 2015 | 2 | 32 | Spanish | Basque |
| de Bruin et al., 2014 | 3 | 17 | Dutch | English |
| Fu et al., 2017 | 1 | 21 | Chinese | English |
| Garbin et al., 2011 | 3 | 19 | Spanish | Catalan |
| Guo et al., 2011 | 4 | 24 | Chinese | English |
| Hernandez et al., 2001 | 4 | 6 | English | Spanish |
| Hernandez, 2009 | 1 | 12 | Spanish | English |
| Hosoda et al., 2012 | 8 | 20 | Japanese | English |
| Kang et al., 2017 | 2 | 17 | Chinese | English |
| Lei et al., 2014 | 2 | 8 | Korean | Chinese |
| Ma et al., 2014 | 3 | 22 | Chinese | English |
| Reverberi et al., 2015 | 3 | 21 | German | English |
| Tabassi Mofrad and Schiller, 2019 | 1 | 45 | Dutch | English |
| Wang et al., 2007 | 1 | 12 | Chinese | English |
| Weissberger et al., 2015 | 1 | 20 | Spanish | English |
| Yamasaki et al., 2019 | 1 | 17 | non-English | English |
| Zhang et al., 2014 | 1 | 21 | Chinese | English |
| Zhang et al., 2015a, 2015b | 4 | 22 | Chinese | English |
| Zhang et al., 2019 | 1 | 22 | Chinese | English |
| *Task switching (n = 9)* | | | | |
| De Baene et al., 2015 | 1 | 32 | Spanish | Basque |
| Garbin et al., 2010 | 1 | 19 | Spanish | Catalan |
| Gold et al., 2013a, 2013b | 1 | 20 | non-English | English |
| Hosoda et al., 2012 | 1 | 20 | Japanese | English |
| Rodríguez-Pujadas et al., 2013 | 1 | 18 | Catalan | Spanish |
| Van de Putte et al., 2018 | 1 | 18 | non-Dutch | Dutch |
| Weissberger et al., 2015 | 1 | 20 | Spanish | English |
| Wu et al., 2019 | 1 | 63 | Chinese | English |
| Yamasaki et al., 2019 | 1 | 17 | non-English | English |

2012). Coordinates reported in Talairach space were first converted to MNI space using the conversion tool within GingerALE. The number of participants was then specified for each selected contrast. ALE maps were thresholded at uncorrected $p < 0.001$ with 1000 permutations and a minimum cluster size of 150 mm$^3$, following a recent meta-analysis on bilingual language processing (Sulpizio et al., 2020b). In order to identify overlapping brain regions of activation across language and task switching, a conjunction analysis was conducted in GingerALE. The single dataset ALE maps for each domain provided the basis for this analysis. Overlapping regions were identified if they passed a threshold of $p < .01$ with 5000 permutations and a minimum cluster size of 100 mm$^3$. The choice of this threshold was based on its use in prior meta-analysis conjunctions (e.g., Pollack and Ashby, 2018; Sokolowski et al., 2017).

ALE meta-analysis for language control (language switch > non-switch) revealed activations in a number of cortical, subcortical, and cerebellar areas, including the pre-SMA/dACC complex (BA 6/24), bilateral dlPFC (BA 9), right IFG, (BA 45), left caudate, left precentral gyrus, left STG, bilateral MTG, superior parietal areas including left SPL and bilateral precuneus (BA 7), bilateral occipital areas including fusiform and lingual gyri, and left cerebellum. These results are largely consistent with a recent meta-analysis on bilingual language processing that also included a section on language switching (Sulpizio et al., 2020b). The analysis for task switching revealed activations in left inferior parietal areas including IPL and angular gyrus (BA 39/40), pre-SMA (BA 6), right insula (BA 13), left caudate, and right dlPFC (BA 9). The conjunction analysis of language and task switching showed common areas of activation across the two domains in pre-SMA (BA 6), left inferior parietal areas including IPL and angular gyrus (BA 39/40), left dlPFC (BA 9), left IFG (BA 44), and left posterior cerebellum (see Fig. 3 and Table 2).

### 3.5. *Effects of bilingualism on brain structure*

#### 3.5.1. *Grey matter volume, cortical thickness, and surface area*

Numerous studies have found differences between bilinguals and monolinguals in grey matter volume or density, in various brain areas, though with mixed findings in regard to the direction of the difference and brain areas implicated:

1) Bilinguals have shown higher grey matter volume or density compared to monolinguals in cortical, subcortical, and cerebellar areas – particularly in domain-general control areas such as bilateral ACC, dlPFC, IFG, IPL, precentral gyrus (Burgaleta et al., 2016; Del Maschio et al., 2018; Mechelli et al., 2004; Olulade et al., 2016), with the effect in IPL more pronounced for early as opposed to late bilinguals (Mechelli et al., 2004). However, some have found lower grey matter volume among bilinguals – such as in bilateral PFC, right MTG, left MTG/STG, right postcentral gyrus, bilateral parahippocampal gyrus, left cerebellum (Burgaleta et al., 2016; Claussenius-Kalman et al., 2020; Olulade et al., 2016). Studies have also found group differences in the relationship between grey matter volume and behavioral performance. Specifically, better response inhibition (Simon task) was associated with higher volume in right SMG for bilinguals, but with lower volume for monolinguals (Vaughn et al., 2019). Bilinguals have also shown a stronger relationship between better interference suppression (flanker task) and higher volume in ACC than monolinguals (Abutalebi et al., 2012).
2) Different results may be observed depending on the type of analysis examined. For example, among the same groups of participants, the more traditional voxel-based grey matter volume analysis showed bilinguals to have higher grey matter volume than monolinguals in mostly temporal areas and lower volume in left dlPFC and IFG. Surface-based grey matter volume analysis (where grey matter volume = cortical thickness × surface area), on the other hand, showed bilinguals to have higher grey matter volume in right superior parietal areas, and lower volume in right MTG, right dlPFC, and right postcentral gyrus. The same study also examined grey matter density (voxel-based grey matter concentrations), and found it to be higher in bilinguals in widespread bilateral frontal, temporal, and parietal areas (Claussenius-Kalman et al., 2020).
3) Higher grey matter volume have also been found among young adult to middle-aged bimodal bilinguals, in both language processing and domain-general control areas – including bilateral frontal, left temporal, left caudate, left insula (L. Li et al., 2017; Zou et al., 2012). Another study, however, found lower grey matter volume in young adult bimodal bilinguals in right precentral gyrus (Olulade et al., 2016). Higher grey matter volume in left caudate has been associated with greater activation in this area during language control (switching during picture naming; Zou et al., 2012). Moreover, increasing age was associated with lower grey matter volume in monolinguals, but was marginally associated with higher volume in bilinguals – in left insula, bilateral anterior temporal lobe, left hippocampus and amygdala (L. Li et al., 2017).
4) L2 learners have shown higher grey matter volume compared to monolinguals after relatively brief periods of L2 training (3 weeks to 4 months), such as in left putamen, left IFG pars triangularis, and bilateral IFG pars opercularis (Hosoda et al., 2013; Legault et al., 2019a; 2019b). Adult learners of a new language have also shown a larger increase in right hippocampus grey matter volume (after 10 weeks of L2 training), whereas monolingual controls showed a smaller increase or a decrease (Bellander et al., 2016; Mårtensson et al., 2012). Grey matter volume increases in bilateral IFG and right hippocampus were associated with higher L2 proficiency after

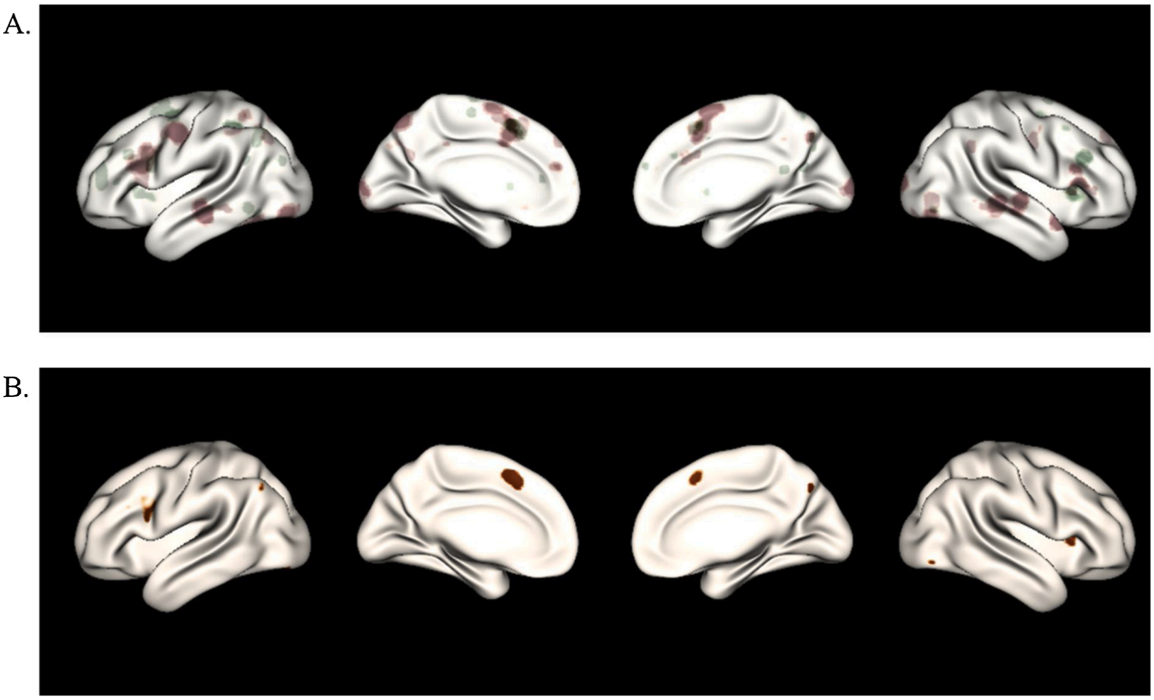

**Fig. 3.** Results of functional imaging meta-analyses. A) single dataset analyses, $p < 0.001$; red = language switching, green = task switching, lighter colors indicate results at $p < 0.01$. B) conjunction analysis of language and task switching, $p < 0.01$.

training (Hosoda et al., 2013; Legault et al., 2019b; Mårtensson et al., 2012).

5) Some have found no differences between bilinguals and monolinguals in grey matter volume (Gold et al., 2013b; Vaughn et al., 2019).

Compared to monolinguals, bilinguals have shown higher cortical thickness – in right ACC, bilateral orbital frontal, temporal, and occipital areas (Claussenius-Kalman et al., 2020; Felton et al., 2017). Even for learners with relatively brief L2 experience (3 weeks to 4 months), higher cortical thickness has been observed in various brain areas – including right dlPFC, bilateral IFG, left ACC, and right MTG – compared to monolinguals with no L2 experience (Legault, Fang, et al., 2019; Legault et al., 2019b). Adult learners have also shown larger increases after training (10 weeks), whereas monolingual controls showed smaller decreases – in left dlPFC, IFG, and STG (Mårtensson et al., 2012). Furthermore, higher L2 proficiency after training was associated with higher cortical thickness in left STG, better language recognition was associated with higher thickness in right MTG, and higher effective functional connectivity between ACC and MTG after L2 training was associated with higher thickness in left ACC (Legault et al., 2019b; Mårtensson et al., 2012).

Among young adult to middle-aged participants, increasing age was associated with lower surface area in left insula and bilateral anterior temporal lobe for monolinguals. For (bimodal) bilinguals, on the other hand, increasing age was marginally associated with higher surface area in these brain regions (L. Li et al., 2017).

### 3.5.2. *Other aspects of brain macrostructure*

Among young adult to middle-aged participants, increasing age was associated with reduced cortical folding or gyrification in widespread right frontal and parietal areas, for both bilinguals and monolinguals. However, in some brain areas – including right ACC, posterior cingulate, and entorhinal cortex – bilinguals did not show age-related reduction in gyrification (Del Maschio et al., 2019a).

Bilinguals have also shown subcortical reshaping compared to monolinguals – showing shape expansions in bilateral putamen, bilateral or right thalamus, bilateral or left globus pallidus, and right caudate – particularly for immersed bilinguals (Burgaleta et al., 2016; Pliatsikas et al., 2017). Bilinguals with limited immersion experience (less than 3 years) showed expansions and contractions in parts of bilateral caudate, compared to monolinguals (Pliatsikas et al., 2017).

In regard to anatomical asymmetry and interhemispheric organization, there was no evidence of more bilateral (less asymmetric) brain structure in bilinguals. Although, bilinguals showed higher volume in mid-anterior to central corpus callosum compared to monolinguals, which may enhance interhemispheric organization. Additionally, bilingualism may influence the direction of asymmetry, with bilinguals found to have more rightward cortical thickness asymmetry in ACC, rather than the leftward asymmetry observed in monolinguals. Furthermore, greater rightward cortical thickness asymmetry in ACC was associated with higher volume in mid-anterior to central corpus callosum (Felton et al., 2017).

Lastly, studies have examined the relationship between bilingualism and a stable neuroanatomical feature (determined in utero) – ACC sulcation pattern, that is, the presence or absence of paracingulate sulcus in left or right or both hemispheres. This early neurodevelopmental feature modulated the effects of bilingualism and the effects of age on domain-general cognitive functioning. Specifically, better interference suppression (flanker task) was associated with symmetric ACC sulcation (presence or absence of paracingulate sulcus in both hemispheres) among bilinguals, but among monolinguals better interference suppression was associated with asymmetric ACC sulcation, particularly leftward asymmetry (presence of paracingulate sulcus only in the left hemisphere; Cachia et al., 2017; Del Maschio et al., 2019b). Additionally, age-related decline in interference suppression was found to be greatest when paracingulate sulcus was absent in both hemispheres (Del Maschio et al., 2019b).

### 3.5.3. *White matter microstructure and structural connectivity*

In regard to brain structural changes relating to white matter microstructure, studies most commonly analyzed fractional anisotropy (FA), a standardized diffusivity value between 0 and 1, with 0 indicating fully isotropic diffusion of water molecules as seen in the ventricles of

**Table 2**
Results of Functional Imaging Meta-Analyses.

| Region | MNI coordinates | | | Peak ALE value | Cluster Volume (mm$^3$) |
|---|---|---|---|---|---|
| | x | y | z | | |
| *Single dataset analysis for language switching (switch > nonswitch)* | | | | | |
| R. Medial Frontal Gyrus (BA 6) | 4 | 8 | 62 | 0.025 | 3256 |
| L. Cingulate Gyrus (BA 24) | −2 | 10 | 42 | 0.025 | |
| L. Medial Frontal Gyrus (BA 6) | 0 | 0 | 66 | 0.022 | |
| L. Superior Frontal Gyrus (BA 6) | 2 | 12 | 50 | 0.020 | |
| L. Precentral Gyrus (BA 4) | −50 | −8 | 42 | 0.030 | 1192 |
| R. Lingual Gyrus | 10 | −100 | 6 | 0.022 | 1056 |
| R. Cuneus (BA 17) | 20 | −96 | 8 | 0.019 | |
| L. Inferior Frontal Gyrus (BA 9) | −50 | 18 | 20 | 0.018 | 1016 |
| L. Middle Frontal Gyrus (BA 9) | −42 | 14 | 30 | 0.015 | |
| L. Posterior Cerebellum Declive | −38 | −78 | −14 | 0.025 | 984 |
| L. Middle Temporal Gyrus (BA 21) | −58 | −24 | −10 | 0.026 | 712 |
| R. Middle Temporal Gyrus (BA 21) | 56 | −32 | −6 | 0.027 | 680 |
| L. Posterior Cerebellum Declive | −18 | −86 | −14 | 0.017 | 528 |
| L. Fusiform Gyrus (BA 19) | −26 | −80 | −12 | 0.016 | |
| R. Inferior Frontal Gyrus (BA 45) | 56 | 22 | 6 | 0.022 | 528 |
| R. Superior Temporal Gyrus | 60 | −18 | −4 | 0.021 | 512 |
| R. Superior Temporal Gyrus (BA 38) | 52 | 8 | −16 | 0.022 | 504 |
| R. Middle Frontal Gyrus (BA 9) | 54 | 20 | 22 | 0.020 | 456 |
| L. Precuneus (BA 7) | −10 | −68 | 54 | 0.016 | 360 |
| L. Caudate | −12 | 20 | 4 | 0.017 | 280 |
| L. Anterior Cerebellum Culmen | −38 | −54 | −18 | 0.015 | 264 |
| L. Fusiform Gyrus (BA 37) | −40 | −60 | −14 | 0.014 | |
| R. Fusiform Gyrus (BA 19) | 30 | −78 | −12 | 0.016 | 264 |
| L. Lingual Gyrus (BA 17) | −8 | −98 | 6 | 0.015 | 232 |
| L. Lingual Gyrus (BA 17) | −8 | −96 | 2 | 0.015 | |
| L. Superior Parietal Lobule (BA 7) | −38 | −56 | 56 | 0.016 | 232 |
| L. Medial Frontal Gyrus (BA 9) | −2 | 46 | 18 | 0.016 | 224 |
| R. Fusiform Gyrus (BA 19) | 42 | −76 | −12 | 0.016 | 160 |
| R. Precuneus (BA 7) | 4 | −68 | 42 | 0.017 | 152 |
| *Single dataset analysis for task switching (switch > nonswitch)* | | | | | |
| L. Inferior Parietal Lobule (BA 40) | −40 | −48 | 44 | 0.017 | 1048 |
| L. Angular Gyrus (BA 39) | −40 | −60 | 42 | 0.009 | |
| L. Superior Frontal Gyrus (BA 6) | −2 | 14 | 50 | 0.015 | 560 |
| R. Insula (BA 13) | 40 | 20 | 0 | 0.014 | 552 |
| L. Caudate | −10 | 10 | 6 | 0.013 | 296 |
| R. Middle Frontal Gyrus (BA 9) | 46 | 26 | 26 | 0.013 | 280 |
| L. Middle Frontal Gyrus (BA 6) | −24 | −2 | 56 | 0.010 | 232 |
| *Conjunction analysis of language and task switching* | | | | | |
| L. Superior Frontal Gyrus (BA 6) | −2 | 14 | 50 | 0.015 | 1296 |
| L. Inferior Parietal Lobule (BA 40) | −42 | −50 | 44 | 0.011 | 344 |
| L. Inferior Frontal Gyrus (BA 9) | −48 | 12 | 30 | 0.008 | 240 |
| L. Inferior Frontal Gyrus (BA 44) | −50 | 12 | 20 | 0.008 | |
| L. Posterior Cerebellum Declive | −36 | −80 | −16 | 0.008 | 216 |

Single dataset analyses were thresholded at uncorrected $p < 0.001$ and a minimum cluster size of 150 mm$^3$; conjunction analysis was thresholded at $p < .01$ and a minimum cluster size of 100 mm$^3$.

the brain, and 1 indicating fully anisotropic diffusion as seen in white matter tracts (P. Li et al., 2014). Other diffusivity metrics include axial diffusivity (AD) – rate of diffusion of water molecules along the direction of (i.e., parallel to) the axon, radial diffusivity (RD) – diffusion perpendicular to the axon, and mean diffusivity (MD) – diffusion within a voxel regardless of orientation (P. Li et al., 2014). Interpretations of changes in these metrics, however, are more complex. Fundamentally, lower FA and higher AD, RD, and MD values indicate greater displacement of water molecules, in other words decreased impediment to the movement of water molecules in white matter tracts. Therefore, they have often been interpreted as reflecting lower "white matter integrity" or "microstructural integrity". However, multiple aspects may contribute to lower anisotropy and higher diffusivity, including a) lower myelination (which may be the main motivation behind the use of the term "integrity"), b) lower packing density of axon fibers, c) larger axon diameter, d) higher membrane permeability, and e) lower coherence in axon orientation (i.e., greater range of orientations, such as from fibers fanning, branching, crossing, twisting). Current methods do not yet allow unambiguous interpretation of which aspects are the main driving forces behind changes in anisotropy and diffusivity values (Jones et al., 2013; Scholz et al., 2014). We will, therefore, avoid interpreting lower FA and higher AD, RD, or MD values as a loss of "integrity" (Jones et al., 2013).

Differences between bilinguals and monolinguals have been observed in white matter microstructural properties in a number of white matter tracts, particularly in tracts relevant for language and other higher-order cognitive functions. However, findings have been mixed, especially among healthy young adults, which may be partly due to the abovementioned multifaceted and ambiguous nature of these metrics. Some have found higher FA in bilinguals compared to monolinguals in various tracts – such as inferior fronto-occipital fasciculus (IFOF), inferior longitudinal fasciculus (ILF), superior longitudinal fasciculus (SLF), uncinate fasciculus, corona radiata, thalamic radiation, and multiple portions of the corpus callosum (Pliatsikas et al., 2015; Rossi et al., 2017). Some, however, have found lower FA in bilinguals – in IFOF, ILF, right anterior thalamic radiation, and other cerebral and cerebellar white matter tracts – together with higher MD, AD, and/or RD values (Kuhl et al., 2016; Singh et al., 2018).

Changes in white matter microstructure, as well as in structural connectivity, have been observed following relatively brief periods of L2 learning. Immediately after a training program (16 weeks), adults learners showed increased FA in white matter below right IFG pars opercularis and increased structural connectivity (using probabilistic tractography) in right opercularis-caudate and opercularis-STG/SMG pathways. These increases were correlated with increase in L2 proficiency. One year after training, however, FA and structural connectivity values decreased to pre-training levels (Hosoda et al., 2013).

As an interim summary for sections 3.1–3.5, Table 3 provides an outline of the main findings among healthy, younger adults, covering A) neural basis of bilingual language control, B) differences in neural responses to domain-general cognitive task, C) direct overlap in neural responses between language control and cognitive functions, and D)

**Table 3**
Summary of Findings for Healthy Younger Adults.

| **Healthy Younger Adults** |
|---|
| ***A. Bilingual Language Control*** |
| Frontoparietal-subcortical network, including dlPFC, IFG/vlPFC, pre-SMA/dACC, caudate, and parietal areas |
| - Range of language backgrounds |
| - Range of AoA |
| - Dominant in one language or relatively balanced |
| - Immersed in dominant or weaker language |
| - Young to middle-aged adults |
| - Both production and comprehension (word level), as well as morphosyntactic processing |
| Impacted by different task requirements |
| - Switch direction |
| - Dominant/L1 vs. weaker/L2 |
| - Switching vs. mixing |
| - Proactive vs. reactive control |
| - Preparation vs. execution stages |
| - Language switching with or without meaning switch |
| - Voluntary vs. cued switching |
| - Type of cue used to signal switching |
| - Cross-modal language control (spoken and signed) |
| Neuromodulation findings |
| - Causal role of right dlPFC language switching patterns in production |
| - Causal role of left IFG in language control in comprehension, specifically for switching into weaker L2 |
| ***B. Domain-General Cognitive Functions (bilinguals relative to monolinguals)*** |
| Response inhibition |
| - More efficient engagement of domain-general control areas e.g., dlPFC and ACC |
| - Less extensive engagement of posterior stimulus evaluation areas |
| - Greater reliance on language-specific control areas e.g., left IFG/vlPFC; greater engagement of these areas associated with faster conflict resolution |
| - Some found similar neural engagement |
| - Smaller N2, P3, and ERN amplitudes, earlier P3 and later N450 latencies, during tasks requiring inhibition of prepotent tendencies |
| - Larger N2 and P3 amplitudes and earlier N2 and P3 latencies on more pure response withholding i.e., nogo condition |
| - Larger N2 and P3a amplitudes for condition that require adjustment between proactive and reactive control |
| - Larger N450 amplitude on Stroop non-conflict but not Stroop conflict condition |
| Interference suppression |
| - Engagement of a wider network, including language control areas e.g., dlPFC, IFG, SMA, IPL, fusiform gyrus, basal ganglia |
| - Smaller delay in P3 latency between incongruent and congruent flanker conditions; earlier P2 latency; smaller sequential congruency effect at N2 and P3 amplitudes; larger CRN and ERN amplitudes |
| Task switching/cognitive flexibility |
| - Engagement of language control areas e.g., left IFG, left caudate and putamen, thalamus; greater engagement of these areas associated with faster performance |
| - ACC had a weaker positive influence on dlPFC and basal ganglia for bilinguals, but a stronger negative influence for monolinguals |
| - Larger N2, smaller ERN and Pe amplitudes; greater brain signal complexity (entropy) |
| Working memory updating |
| - Greater engagement of left SMG and left dlPFC |
| - Ventral ACC for spatial and right MTG for nonspatial for bilinguals, reverse pattern for monolinguals |
| - Larger P3 amplitude |
| - Larger decrease in P3 amplitude as load increased; this decrease associated with higher accuracy |
| Short-term memory |
| - Larger P3b, smaller N2b and NSW amplitudes for retrieval, marginally larger P3b amplitude for encoding |
| Orienting attention |
| - Larger Ndl and RON amplitudes |
| ***C. Direct Overlap Between Language Control and Cognitive Functions*** |
| Language control and task switching |
| - Overlap between language switching and domain-general task switching, particularly in control related brain areas e.g., right dlPFC, left IFG, pre-SMA, cingulate, caudate, bilateral parietal areas |
| - Overlap in occipital and cerebellar areas |
| - Overlap between language switching and motor sequence switching in e.g., left IFG, ACC, bilateral parietal areas |
| - Convergence in effective functional connectivity pattern between language and task switching |
| - More similar ERP responses between language and task switching for bilinguals than monolinguals |
| Language control and interference suppression |
| - Overlap between language switching and interference suppression in bilateral ACC |
| - Overlap between bilingual language processing and interference suppression in left orbital frontal and posterior cingulate areas |
| - Similar neural efficiency when facing linguistic or nonlinguistic interference |
| ***D. Brain Structure (bilinguals relative to monolinguals)*** |
| Grey matter volume/density |
| - Some found higher grey matter volume, in various frontal, cingulate, parietal, temporal, subcortical, and cerebellar areas (effect may be more pronounce for early bilinguals); some found lower; some found no differences |
| - Voxel-based grey matter volume, surface-based grey matter volume, grey matter density analyses may produce different results, even within the same participants |
| - Better response inhibition associated with higher grey matter volume in right SMG for bilinguals, but with lower volume for monolinguals |
| - Stronger relationship between better interference suppression and higher grey matter volume in ACC |
| - Higher grey matter volume among bimodal bilinguals, in both language processing and domain-general control areas e.g., bilateral frontal, left temporal, left caudate, left insula; lower in right precentral gyrus |
| - Higher grey matter volume in left caudate associated with greater activation in this area during language control for bimodal bilinguals |
| - Increasing age marginally associated with higher grey matter volume for bimodal bilinguals, but with lower volume for monolinguals, in e.g., left insula, bilateral anterior temporal lobe, left hippocampus and amygdala |
| - Higher grey matter volume even after brief periods of L2 training, in e.g., left putamen, bilateral IFG, right hippocampus |
| - Increases in grey matter volume in bilateral IFG and right hippocampus after training associated with increases in L2 proficiency |
| Cortical thickness and surface area |
| - Higher cortical thickness in e.g., right ACC, bilateral orbital frontal, temporal, and occipital areas |
| - Higher cortical thickness after brief periods of L2 training, in e.g., bilateral dlPFC, bilateral IFG, left ACC, right MTG, and left STG |
| - After training, higher cortical thickness in left STG associated with higher L2 proficiency, in right MTG associated with better language recognition, in left ACC with higher effective functional connectivity between ACC and MTG |
| - Increasing age marginally associated with higher surface area in e.g., left insula, bilateral anterior temporal lobe for bimodal bilinguals, but associated with lower surface area for monolinguals |
| Other aspects of brain macrostructure |
| - No age-related reduction in gyrification in e.g., right ACC, posterior cingulate, entorhinal cortex |
| - Subcortical shape expansions in putamen, thalamus, globus pallidus, and caudate, for immersed bilinguals; expansions and contractions in caudate for less immersed bilinguals |
| - No evidence of less asymmetric brain structure; more rightward cortical thickness asymmetry in ACC for bilinguals, leftward for monolinguals |
| - More rightward cortical thickness asymmetry in ACC associated with higher volume in portions of corpus callosum |
| - ACC sulcation pattern (determined in utero) modulated effects of bilingualism or age on interference suppression |
| White matter microstructure and structural connectivity |
| - Some found higher FA in various tracts relevant for language and other higher-order cognitive functions e.g., IFOF, ILF, SLF, uncinate fasciculus, corona radiata, thalamic radiation, and portions of corpus callosum; some found lower FA, together with higher MD, AD, and/or RD |
| - Higher FA in right sub-IFG white matter and higher structural connectivity for IFG-caudate and IFG-STG/SMG pathways immediately after brief periods of L2 training, but decreased to pre-training levels after one year |

differences in aspects of brain structure.

### *3.6. Children, older adults, and neurological disorder patients*

Besides healthy younger adults, differences between bilinguals and monolinguals have been found for other groups. Table 4 presents findings regarding A) children, B) healthy older adults, and C) neurological disorder patients. Differences between bilinguals and monolinguals in these groups have been found for brain function relating to domain-

**Table 4**
Findings for Children, Older Adults, and Neurological Disorder Patients.

| **Children, Older Adults, and Neurological Disorder Patients** | |
|---|---|
| ***A. Children (bilinguals relative to monolinguals)*** | |
| Domain-general cognitive functions | |
| - Bilinguals and L2 learners (age around 10) both more engaged language control related areas during response inhibition (Stroop and Simon tasks) e.g., right PFC, caudate, cingulate | Mohades et al., 2014 |
| - Bilinguals (age around 10) more engaged language-specific left PFC during interference suppression (flanker task), monolinguals more engaged domain-general right PFC (as imaged using fNIRS of bilateral PFC) | Arredondo et al., 2017 |
| - Larger P3 amplitude, shorter N2 and P3 latencies during response inhibition (go-nogo task), possibly contributing to bilingual performance advantage (age around 5) | Barac et al., 2016 |
| - Later occurrence of early positivity cessation and late negativity onset latencies during response inhibition (Stroop task), a more efficient motor-response pattern (age around 7) | Nayak et al., 2020 |
| - Smaller ERN amplitude in frontal and frontocentral midline regions, during cognitive flexibility (Dimensional Change Card Sort task), i.e., dampened error detection signals, suggesting greater focus on performing faster, whereas monolinguals were more invested in their accuracy (age around 4) | Nayak and Tarullo, 2020 |
| Resting-state brain function | |
| - Higher intrinsic functional connectivity within networks e.g., language, executive control, frontoparietal control, and default mode networks; lower connectivity between networks e.g., between language and default mode or ventral attention networks (age around 5) | Thieba et al., 2019 |
| - Higher connectivity between bilateral orbital IFG and left MFG associated with lower L2 performance for bilinguals, but with higher language performance for monolinguals | Thieba et al., 2019 |
| Brain structure | |
| - No differences in grey matter volume, cortical thickness, and surface area (age around 5) | Thieba et al., 2019 |
| - Higher FA in left IFOF, lower FA in portion of corpus callosum (age around 9) | Mohades et al., 2012 |
| - Greater FA increase over two years (age around 9 to 11) in these two tracts, eliminating group difference in corpus callosum | Mohades et al., 2012, 2015 |
| - Bilinguals showed change in left arcuate fasciculus/SLF over two years, monolinguals did not | Mohades et al., 2012, 2015 |
| ***B. Healthy Older Adults (bilinguals relative to monolinguals)*** | |
| Domain-general cognitive functions | |
| - Reliance on smaller set of areas or more integrated (functionally connected) network, mostly temporoparietal, during response inhibition (Simon task) | Ansaldo et al., 2015; Berroir et al., 2017 |
| - More engagement of language control areas e.g., left PFC and ACC, which was associated with better task switching | Gold et al., 2013b |
| - Smaller N2 amplitude, earlier N2 and P3 latencies, during response inhibition (Stroop and Simon tasks) like for younger adults, but larger P3 amplitude; possible better conflict monitoring, earlier conflict detection, and allocation of fewer resources | Kousaie and Phillips, 2017 |
| - Earlier N2 latency during interference suppression incongruent condition (flanker task), suggesting faster conflict monitoring, incongruent may not be more difficult than congruent | Kousaie and Phillips, 2017 |
| - Larger N2 and smaller P3b amplitudes for task switching and mixing costs, suggesting greater reliance on earlier and more automatic processing strategies, less on controlled strategies | López Zunini et al., 2019 |
| - Older bilinguals more engaged left vlPFC for alerting and right SPL for orienting compared to younger bilinguals | Dash et al., 2019 |
| Resting-state brain function | |
| - Higher intrinsic functional connectivity within and between networks relevant for language processing and cognitive control, e.g., language, executive control, frontoparietal control, and default mode networks; even for those with brief L2 learning experience (about 4 months) | Bubbico et al., 2019; de Frutos-Lucas et al., 2020; Grady et al., 2015 |
| - Greater increase in connectivity for posterior connections or anterior to posterior connections, no change or decrease in connectivity within frontal areas; in line with the notion that bilingual experience may help prevent the over-recruitment of frontal areas typically found in aging | de Frutos-Lucas et al., 2020; L. Li et al., 2015; Luk et al., 2011 |
| - Stronger negative connectivity (anticorrelation) between frontoparietal control and default mode networks associated with better response inhibition | Kousaie and Phillips, 2017 |
| - Higher connectivity in right SFG associated with less severe cognitive decline | Bubbico et al., 2019 |
| - Higher connectivity in frontoparietal control network associated with greater activation during response inhibition for bilinguals, but with lower activation for monolinguals | Grady et al., 2015 |
| - One study examined resting-state brain *activity*: Less synchronized intrinsic brain activity (lower ReHo) for middle-aged bimodal bilinguals, in spoken-language areas left STG and left rolandic operculum; lower intrinsic connectivity between dACC and these two areas; less synchronized activity associated with lower connectivity in left STG, possibly related to different levels of spoken language use between monolinguals and bimodal bilinguals | L. Li et al., 2015 |
| Brain structure | |
| - Higher grey matter volume particularly in domain-general cognitive areas e.g., bilateral ACC, PFC, IPL | Abutalebi et al., 2014; Abutalebi, Canini, et al., 2015; Abutalebi et al., 2015b; Del Maschio et al., 2018; Heim et al., 2019 |
| - Older age associated with lower grey matter volume in less distributed/ extensive brain areas, no age-related reduction cortical thickness in temporal pole for bilinguals; possible protection against neural decline in healthy aging | Abutalebi et al., 2014; Abutalebi, Canini, et al., 2015; Olsen et al., 2015 |
| - Some found diminished group difference in grey matter volume with age, suggesting a faster rate of grey matter volume decline in bilinguals | Heim et al., 2019 |
| - Some found higher grey matter volume in domain-general cognitive areas e.g., PFC, ACC, caudate, IPL to be associated with | Abutalebi et al., 2015b; Del Maschio et al., 2018 |

(continued on next page)

**Table 4** (*continued*)

| **Children, Older Adults, and Neurological Disorder Patients** | |
|---|---|
| better interference suppression (flanker task) only in monolinguals | |
| - Some found grey matter volume in dACC account for variance in interference suppression (flanker task) only in bilinguals | Borsa et al., 2018 |
| - Higher white matter volume in frontal lobe, marginally higher in temporal lobe; higher frontal lobe white matter volume associated with better response inhibition (Stroop task) | Olsen et al., 2015 |
| - Grey matter volume in bilateral caudate was associated with resting-state functional connectivity in bilateral occipital areas only for bilinguals | de Frutos-Lucas et al., 2020 |
| - Some found no differences in grey matter volume | Borsa et al., 2018; Gold et al., 2013a; 2013b |
| - Lower FA, higher RD and AD in widespread white matter tracts e.g., ILF, SLF, IFOF, fornix, and multiple portions of corpus callosum; but still better cognitive performance | Anderson et al., 2018b; Gold et al., 2013a |
| - Higher FA when matched on cognitive functioning, in e.g., corpus callosum, extending to bilateral SLF, right IFOF, and uncinate fasciculus | Luk et al., 2011 |
| ***C. Neurological Disorder Patients (bilinguals relative to monolinguals)*** | |
| *Older adults with Alzheimer's disease or mild cognitive impairment* | |
| Brain metabolic function | |
| - Lower glucose metabolism widespread brain areas e.g., bilateral frontal, temporal, parietal, subcortical, and cerebellar areas; but still equal, or even higher, performance on neuropsychological assessments, such as memory, cognitive flexibility, attention, and language production | Kowoll et al., 2016; Perani et al., 2017 |
| Brain structure | |
| - Lower parenchymal (global grey and white matter) volume, lower grey matter volume in right SMG and left lingual gyrus; no longitudinal reduction volume over 6–9-month period in some areas e.g., right cingulate, basal ganglia, hippocampus, left fusiform | Costumero et al., 2020 |
| - Greater atrophy in temporal areas (as imaged using CT) | Schweizer et al., 2012 |
| - Some found higher grey matter density in bilateral hippocampus | Duncan et al., 2018 |
| - Higher cortical thickness in right IFG, vlPFC, cerebellum; higher cortical thickness in IFG, pre-SMA, SMG, and anterior temporal lobe associated with better short-term memory only for bilinguals | Duncan et al., 2018 |
| - Higher FA, lower MD, AD, and RD in bilateral cingulum, lower RD in uncinate fasciculus, but higher MD in fornix | Marin-Marin et al., 2020 |
| *Other neurodegenerative disorder patients* | |
| Brain structure | |
| - For patients with multiple sclerosis (a non-age-related neurodegenerative disorder), short-term L2 training (8 weeks) increased grey matter volume in e.g., right hippocampus, parahippocampal gyrus, anterior putamen; for healthy controls in left insula | Ehling et al., 2019 |
| - Better L2 performance after training was associated with higher grey matter volume in right hippocampus and parahippocampal gyrus for patients with multiple sclerosis | Ehling et al., 2019 |
| *Other neurological disorder patients* | |
| Brain structure | |
| - For patients with temporal lobe epilepsy (a disorder associated with white matter pathology), bilinguals showed lower FA in uncinate fasciculus and cingulum ipsilateral to the side of seizure, compared to monolingual patients and/or bilingual or monolingual healthy controls | Reyes et al., 2018 |
| - Higher FA in these tracts was associated with better response inhibition (Stroop task) and cognitive flexibility (Trail Making Test); but despite differences in FA, bilingual and monolingual patients showed similar performance | Reyes et al., 2018 |
| *Lesion and neurosurgical patients* | |
| Bilingual language control | |
| - Intracranial single-neuron recording among pre-surgical patients: when performing language switching (during visual continuous recognition), no increased firing found in PFC and ACC (the task may not require inhibition, but need to keep both languages active to respond correctly on switch trials); switch targets increased firing in left hippocampus (more abstracted, top-down processing of semantic content), nonswitch targets in right hippocampus (more bottom-up processing of surface form), L1 switch in amygdala (words in L1/dominant language may be more tightly linked to emotional centers than translation equivalents in L2/weaker language) | Hussey et al., 2017 |
| Overlap between language control and cognitive functions | |
| - A left parietal lesion impaired both language interference control (during lexical decision) and interference suppression (flanker task) | Van der Linden et al., 2018 |
| - A left basal ganglia lesion impaired language switching (during color naming), response inhibition (Stroop task), and cognitive flexibility (Trail Making Test) | Adrover-Roig et al., 2011 |
| - Intra-operative direct electrical stimulation of left caudate impaired both language switching (during picture naming) and task switching, though with greater difficulty in language than in task switching | X. Wang et al., 2013 |
| Resting-state brain function | |
| - A left parietal lesion produced reduced connectivity between language control and language production networks; such a pattern was consistent with the patient's behavioral performance, namely impaired language processing particularly in L1 and larger cross-language interference compared to healthy controls | Van der Linden et al., 2018 |

general cognitive tasks; non-task-related brain function, including resting-state brain function and brain metabolic function (the latter only among patients); and brain structure, including grey and white matter macrostructure and white matter microstructure.

### 3.7. Individual difference factors

Findings reviewed so far have concerned differences between

**Table 5**
Findings on Individual Difference Factors.

| Factor | How Operationalized | Associated With | |
|---|---|---|---|
| ***A. Bilingual Language Control*** | | | |
| Proficiency and exposure | Early high-proficiency (more balanced) bilinguals compared to previously reported low-proficiency bilinguals | More engaged subcortical structures e.g., caudate during language switching (in naming) | Garbin et al., 2011 |
| | Higher L1 proficiency | Increased activation in bilateral putamen during L1 auditory recognition in the presence of L2 competitors | Marian et al., 2017 |
| | L2 learners in early stages of L2 vocabulary learning | Engaged areas responsible for novel word retrieval and memory formation e.g., hippocampus during L2 auditory recognition in the presence of L1 competitors | Bartolotti et al., 2017 |
| | Increased L2 exposure/proficiency over time (4–5 months of classroom learning) | Decreased number of effective functional connections within PFC inhibitory control areas (decreased involvement), increased number of connections in semantic processing areas MTG and IFG, during cross-language competition (in lexical decision) | Grant et al., 2015 |
| | Language with decreased exposure (L1 in this case) compared to more exposed language | Increased activation in domain-general control areas e.g., left caudate and ACC during language switching (in narrative listening) | Abutalebi et al., 2007 |
| Number of languages previous acquired | L2 learners compared to L3 learners, with brief exposure (2 h) to a new language | During cross-language competition (in semantic decision), the former engaged more higher-level cognitive mode of control mainly involving right PFC and caudate, the latter engaged more motor-based mode of control mainly involving phonological and articulatory processes underlay by putamen | Bradley et al., 2013 |
| Language control ability | Language switching training (via picture naming, 8 days) | Decreased activation in dACC and left caudate during language switching (in naming) | Kang et al., 2017 |
| | Smaller language switch cost (better language control) | Decreased activation in dACC during language switching (in naming) | Kang et al., 2017 |
| | Smaller language mixing cost (better language control), more symmetric language switch cost | Increased activation in parietal areas during language switching (in naming) | Y. Wang et al., 2009 |
| Codeswitch experience | Codeswitcher compared to non-codeswitcher | Greater N400 sensitivity to congruency manipulations for codeswitches in sentence comprehension | Beatty-Martínez and Dussias, 2017 |
| Language context | L1-dominant compared to L2-dominant context | Larger LPC amplitude for switching into L2, but not for switching into L1 (in naming) | Y. Zhang et al., 2019 |
| Cognitive style | Field-dependent compared to field-independent cognitive styles | Larger LPC amplitude for switching into L2 than into L1 (in naming); larger LPC and smaller N2 amplitudes for participant switch (two-person naming) | Timmer et al., 2019 |
| Domain-general cognitive abilities | Better response inhibition ability (Simon task) | Increased activation in pre-SMA for switch costs when switching into weaker L2/L3 (in naming) | de Bruin et al., 2014 |
| | Better response inhibition ability (Simon task) | Decreased activation in putamen during auditory L1 recognition with L2 competitors, decreased activation in bilateral PFC during L2 recognition with L1 competitors | Marian et al., 2017 |
| | High response inhibition ability compared to low (Simon task) | Larger LPC amplitude for L2 than L1 for both switch and nonswitch; higher theta power for switching into L2 or L3 than switching into L1 | H. Liu et al., 2014, 2016, 2017 |
| | Response inhibition training (via Simon task, 8 days) | After training, no difference between high and low ability groups in LPC amplitude for all switch and nonswitch conditions | H. Liu et al., 2016 |
| | Better interference suppression (flanker task) | Decreased activation in both frontoparietal domain-general control areas and temporal semantic processing areas during cross-language competition (in lexical decision) | Grant et al., 2015 |
| ***B. Domain-General Cognitive Functions*** | | | |
| AoA | Bilingual children (age around 10, i.e., earlier AoA) compared to L2 learners (i.e., later AoA) | Increased activation in control areas e.g., right PFC and caudate during response inhibition (Simon and Stroop tasks) | Mohades et al., 2014 |
| | Earlier AoA | Increased activation in control areas e.g., right PFC, right parietal, left cerebellum, during interference suppression (flanker task) | DeLuca et al., 2020 |
| Proficiency | Balanced bilinguals (higher L2 proficiency) compared to nonbalanced | The former more engaged phonological working memory areas during phonological working memory updating (n-back task), the latter more engaged goal-directed processing areas [but phonological working memory updating is more language-specific rather than domain-general, i.e., it may be that more engagement of phonological working memory processes produced higher L2 proficiency] | Chee et al., 2004 |
| | High-proficiency (more balanced) bilinguals compared to low-proficiency | More engaged functionally connected short-term memory networks for linguistic serial order short-term memory [but language-specific short-term memory rather than domain-general, i.e., it may be that more efficient engagement of short-term memory networks | Majerus et al., 2008 |

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**Table 5** (*continued*)

| Factor | How Operationalized | Associated With | |
|---|---|---|---|
| | | produced better verbal sequence learning and storage abilities for high-proficiency over low-proficiency bilinguals] | |
| | Lower L2 proficiency (less balanced) (older adults) | Increased activation in vlPFC for alerting to the presence of a cue, controlling education | Dash et al., 2019 |
| | Higher L2 proficiency | Larger N2 and/or P3 amplitudes during response inhibition (go-nogo and Stroop tasks) | Fernandez et al., 2013; Jiao et al., 2019 |
| | Higher L2 proficiency (more balanced) | Smaller pre-saccadic positivity (antisaccade task) | Heidlmayr et al., 2016 |
| Immersion | Longer L2 immersion | Decreased activation in control areas e.g., bilateral dlPFC, cerebellum, right parietal, thalamus, during interference suppression (flanker task) | DeLuca et al., 2020 |
| | L2-immersed compared to L1-immersed bilinguals [though the former used L1 (English) extensively, and the latter were highly proficient in L2 (English)] | Larger incongruency cost at LPC component during response inhibition (Stroop task) | Hannaway et al., 2019 |
| | Longer L2 immersion | Smaller pre-saccadic positivity (antisaccade task) | Heidlmayr et al., 2016 |
| Use | Greater extent of home use | Decreased activation in control areas e.g., right IPL, MTG, left cerebellum, during interference suppression (flanker task) | DeLuca et al., 2020 |
| | Greater extent of social use | Increased activation in control areas e.g., right dlPFC, IPL, bilateral cerebellum, ACC/PCC, during interference suppression (flanker task) | DeLuca et al., 2020 |
| Simultaneous interpretation experience | Bilinguals with more experience in simultaneous interpretation compared to those with less | Smaller P3 amplitude for incongruent, larger N1 and N2 amplitudes for both congruent and incongruent conditions, during interference suppression (flanker task) | Dong and Zhong, 2017 |
| Language control ability | Language switching training (via picture naming, 10 days) | Larger N2 amplitude during response inhibition (AX-Continuous Performance Task) | H. Zhang et al., 2015a |
| Language context | Context (manipulated via picture naming) involving a less proficient and more typologically distinct L3 (L1-L3 or L2-L3, as opposed to L1-L2) | Relied on a less integrated (functionally connected) network, with increased activation in right PFC areas, during response inhibition (Stroop task) | Yang et al., 2018 |
| | Mixed language (filler words and nonwords) compared to single language | Smaller P3 amplitude for interference suppression (flanker incongruent condition) | Y. J. Wu and Thierry, 2013 |
| ***C. Direct Overlap Between Language Control and Cognitive Functions*** | | | |
| AoA | Earlier AoA | Predicted greater activation in left ACC for response inhibition (Simon task); predicted less activation in left IFG for language control (in naming) | Vaughn et al., 2016 |
| Proficiency | High-proficiency (more balanced) bilinguals compared to low-proficiency | The former showed no activation differences between language switching (in naming) and task switching, the latter showed greater activation of left dlPFC during language switching compared to task switching | Mouthon et al., 2020 |
| | Higher L1, lower L2 proficiencies (more balanced) | Predicted greater activation in left ACC for response inhibition (Simon task); did not predict activations for language control | Vaughn et al., 2016 |
| | Higher L2 proficiency (more balanced) | Greater convergence in connectivity patterns between language and task switching | J. Wu et al., 2019 |
| General intelligence | Higher nonverbal intelligence (Raven's score) | Greater convergence in connectivity patterns between language and task switching | J. Wu et al., 2019 |
| DRD2 genotype (related to dopamine availability in the striatum) | A1 allele carrier status (fewer dopamine receptors) | Predicted smaller activation difference in bilateral ACC between task switch and nonswitch conditions; predicted greater activation in bilateral IFG for language control (in naming) | Vaughn et al., 2016 |
| ***D. Non-Task-Related Brain Function*** | | | |
| *Resting-state functional connectivity* | | | |
| AoA | Earlier AoA; or simultaneous bilinguals (AoA = 0) compared to sequential (AoA = 13.5 or 7.4) | Stronger resting-state functional connectivity in local, interhemispheric, and distributed anterior to posterior connections, particularly in language and control networks | Berken et al., 2016a; DeLuca et al., 2019a; Gullifer et al., 2018; Kousaie et al., 2017; Sulpizio et al., 2020a |
| | | Controlling amount and diversity of L2 use | Gullifer et al., 2018 |
| | | Interaction with proficiency: higher proficiency associated with higher connectivity for late bilinguals, but associated with lower connectivity for early bilinguals | Sulpizio et al., 2020a |
| | | Interaction with language use: more balanced use associated with higher connectivity for late bilinguals | Sulpizio et al., 2020a |
| | | Interaction with language switching tendency: higher tendency to switch to L2 associated with higher connectivity for late bilinguals in language network, and in executive control network for late bilinguals with more balanced use | Sulpizio et al., 2020a |
| Proficiency | High-proficiency (more balanced) bilinguals compared to low-proficiency | Lower connectivity within both cognitive flexibility and inhibition areas | Sun et al., 2019 |

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Table 5 (*continued*)

| Factor | How Operationalized | Associated With | |
|---|---|---|---|
| | Higher L2 proficiency (more balanced) | Higher local efficiency (greater local integration) in executive control network | Sulpizio et al., 2020a |
| | | Interaction with language use: higher proficiency associated with higher connectivity for those with more balanced use | Sulpizio et al., 2020a |
| Use | Greater social diversity of language use | Higher connectivity between proactive control (basal ganglia) and conflict monitoring (ACC) areas, controlling AoA and amount of L2 use | Gullifer et al., 2018 |
| | Higher language switching frequency | Lower connectivity between cognitive flexibility (left ACC) and inhibition (right dlPFC) areas | Sun et al., 2019 |
| Simultaneous interpretation experience | Simultaneous interpreters compared to non-interpreter bilinguals | Higher connectivity in frontal areas and between frontal and temporal areas | M. Becker et al., 2016a; Klein et al., 2018 |
| | Simultaneous interpreters compared to non-interpreter bilinguals | Higher degree (greater connectivity with other nodes) and global efficiency (greater global integration) in left frontal pole | M. Becker et al., 2016a |
| *Brain metabolic function (Huntington's disease patients)* | | | |
| Use | More balanced use | Higher metabolic function in frontotemporal areas | Martínez-Horta et al., 2019 |
| ***E. Brain Structure*** | | | |
| *Volume, thickness, and surface area* | | | |
| AoA | Earlier AoA, or simultaneous/early bilinguals (AoA = 0 or 5.19) compared to sequential/late (AoA = 13.5 or 13.84) | Higher grey matter volume or density (voxel-based) in right frontal, left subcortical, insula, parietal, bilateral occipital, cerebellar areas; higher volume (surface-based) in left MTG controlling L2 proficiency | Berken et al., 2016b; Claussenius-Kalman et al., 2020; Deluca et al., 2019a, 2019b; Legault et al., 2019b; Mechelli et al., 2004 |
| | Earlier AoA | Higher grey matter (both voxel-based and surface-based), white matter, and total volumes in right parietal areas, mainly angular gyrus extending to SPL, controlling proficiency and exposure | Wei et al., 2015 |
| | Simultaneous/early bilinguals (AoA = 0 or 5.19) compared to sequential/late (AoA = 13.5 or 13.84) | Lower grey matter density in bilateral PFC, premotor, right temporal, parietal areas; lower in right IFG controlling L2 proficiency | Berken et al., 2016b; Claussenius-Kalman et al., 2020 |
| | Earlier AoA, higher proficiency, and higher exposure jointly | Higher grey matter, white matter, and total volumes in right orbital IFG (none predicted volume in this area independently) | Wei et al., 2015 |
| Proficiency (either jointly or interacting with AoA) | Greater multilingual experience (weighted sum of AoA and proficiency across languages, larger weights for earlier AoA and higher proficiency) | Higher subcortical volume in bilateral caudate, controlling age and total intracranial volume, relationship stronger for proficiency than for AoA | Hervais-Adelman et al., 2018 |
| | Higher proficiency in L2 pronunciation (within late bilinguals, AoA = 13.5) | Higher grey matter density in left putamen | Berken et al., 2016b |
| | Better L2 performance during training (within adult L2 learners i.e., late AoA) | Higher grey matter volume in left IPL | Legault et al., 2019a |
| Proficiency | Higher L2 proficiency (more balanced) | Higher grey matter volume or density in bilateral IFG, caudate, STG/SMG, ACC, left IPL | Hosoda et al., 2013; Mechelli et al., 2004 |
| | Higher L2 performance during L2 training | Higher cortical thickness in left ACC, left IFG, right IPL | Legault et al., 2019a |
| | Higher L2 proficiency (more balanced) (middle-aged to older adults) | Higher grey matter volume in left temporal pole, controlling L1 proficiency and AoA | Abutalebi et al., 2014 |
| | Higher L2 proficiency (more balanced) (middle-aged to older adults) | Higher grey matter volume in left IPL, particularly for those whose languages are more similar (e.g., Cantonese-Mandarin), rather than more distinct (e.g., Cantonese-English) | Abutalebi et al., 2015a |
| | Higher proficiency in dominant language (older adults with Alzheimer's disease) | Higher cortical thickness in left entorhinal cortex and MTG, controlling age and education | Smirnov et al., 2019 |
| | Higher proficiency in weaker language (more balanced) (older adults with Alzheimer's disease) | Higher cortical thickness in left ACC | Smirnov et al., 2019 |
| Exposure | Higher L2 exposure (middle-aged to older adults) | Higher grey matter volume in right IPL | Abutalebi et al., 2015a |
| Use | More balanced use (Huntington's disease patients) | Marginally higher (uncorrected) grey matter volume in right IFG | Martínez-Horta et al., 2019 |
| | Greater bilingual language use (adolescents, age over 12) | Higher total cortical surface area, higher surface area in ACC; controlling gender, genetic ancestry factor, scanner type | Brito and Noble, 2018 |
| | | Interaction with SES: lower SES associated with stronger relationship between language use and total cortical surface area; controlling gender, genetic ancestry factor, scanner type | Brito and Noble, 2018 |
| | Greater dominant language use (listening) (less balanced use) | Higher grey matter volume in left MTG | Burgaleta et al., 2016 |
| Immersion | After 3 years of continued immersion | Higher grey matter volume in cerebellum | Deluca et al., 2019a, 2019b |
| Simultaneous interpretation experience | Simultaneous interpreters compared to non-interpreter bilinguals | Higher grey matter volume in left frontal pole | M. Becker et al., 2016a |
| | | | Elmer et al., 2014 |

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**Table 5** (*continued*)

| Factor | How Operationalized | Associated With | |
|---|---|---|---|
| | Simultaneous interpreters compared to non-interpreter multilinguals [also differed in age, the former were in 30 s–40 s, the latter in 20 s–30 s] | Lower grey matter volume in left cingulate, bilateral IFG, insula, SMG, caudate | |
| | Higher cumulative hours of interpretation practice | Lower grey matter volume in left cingulate, bilateral IFG, caudate | Elmer et al., 2014 |
| | Simultaneous interpreters compared to non-interpreter multilinguals | The former showed increased cortical thickness (over 1 year), the latter showed decreased, in left posterior STG, right SFG, bilateral parietal, planum temporale in lateral fissure | Hervais-Adelman et al., 2017 |
| L2 training | Post-training compared to pre-training (10 weeks) | higher grey matter volume in right hippocampus and left occipital; longer study time and better short-term memory associated with greater increase in right hippocampus grey matter volume | Bellander et al., 2016 |
| SES | Higher SES (children and adolescents, mean age 13.5) | Higher total cortical surface area, higher surface area in left IFG and ACC; controlling age, gender, genetic ancestry factor, scanner type | Brito and Noble, 2018 |
| *Other aspects of macrostructure* | | | |
| AoA | Early bilinguals (AoA before 6) compared to later (AoA after 9) | Higher macromolecular tissue volume (qMRI) in areas crucial for resolving cross-language lexical competition e.g., left anterior IFG and fusiform gyrus | Luo et al., 2019 |
| | Earlier AoA | Expansions in left nucleus accumbens and bilateral thalamus | DeLuca et al., 2019a |
| AoA and proficiency jointly | Greater multilingual experience (weighted sum of AoA and proficiency across languages, larger weights for earlier AoA and higher proficiency) | Greater shape expansion in left anterior and dorsomedial caudate, controlling age and total intracranial volume | Hervais-Adelman et al., 2018 |
| Proficiency | Higher L2 proficiency | Greater gyrification in right posterior cingulate | Del Maschio et al., 2019a |
| Immersion | Longer L2 immersion | Expansion and contraction in right posterior caudate, expansion in right putamen and globus pallidus, contractions in bilateral thalamus and nucleus accumbens | DeLuca et al., 2019a; Pliatsikas et al., 2017 |
| | After 3 years of continued immersion | Contraction in left caudate, amygdala, bilateral hippocampus, expansion in right hippocampus | Deluca et al., 2019a, 2019b |
| Use | Greater L2 use in social settings | Expansions in left caudate, left nucleus accumbens, right thalamus | DeLuca et al., 2019a |
| | Longer duration of active L2 use | Expansion in left nucleus accumbens | Deluca et al., 2019a |
| | Longer duration of active L2 use in immersive setting | Expansion and contractions in right caudate, contraction in right nucleus accumbens | Deluca et al., 2019a |
| | Greater dominant language use (speaking and listening) (less balanced use) | Lower shape expansion in left thalamus and right caudate respectively | Burgaleta et al., 2016 |
| *White matter microstructure and structural connectivity* | | | |
| AoA | Earlier AoA | Higher FA in various white matter tracts e.g., ILF, IFOF, corona radiata, thalamic radiation | Rossi et al., 2017 |
| | Earlier AoA | Lower FA in corpus callosum, left ILF, and AF | Deluca et al., 2019a; Nichols and Joanisse, 2016 |
| | Simultaneous bilinguals (AoA = 0) compared to sequential (AoA after 3) (children 9−11) | Higher FA in left IFOF; however, the latter showed greater longitudinal change over two years, resulting in no group difference at Time 2 | Mohades et al., 2012, 2015 |
| Proficiency | Higher L2 proficiency (more balanced) | Higher FA in right ILF, right AF, and forceps minor; higher RD in right SLF | Nichols and Joanisse, 2016; Singh et al., 2018 |
| | Higher L2 vocabulary | Higher FA in right sub-IFGop whiter matter, ILF, and AF | Hosoda et al., 2013 |
| | Higher L2 vocabulary | Stronger connectivity for right IFGop-CN and IFGop-STG/SMG | Hosoda et al., 2013 |
| Immersion | Longer L2 immersion | Higher FA in left cerebral tracts; lower AD, RD, and MD in bilateral cerebral and cerebellar tracts | Kuhl et al., 2016 |
| | After 3 years of continued immersion | Higher MD in left forceps minor | Deluca et al., 2019a, 2019b |
| L2 training | During immersion course (total 16 days) compared to after course or no course | Higher FA and lower RD in SLF | Mamiya et al., 2016 |
| COMT genotype | Met/Val and Val/Val genotypes compared to Met/Met | Relationship between number of days in L2 immersion course with higher FA and lower RD values in SLF | Mamiya et al., 2016 |
| Simultaneous interpretation experience | Simultaneous interpreters compared to translators (following their respective training programs, about 9 months) | Greater increase in connectivity in two subnetworks, one involving basal ganglia and interconnected frontal areas, one involving SMA and cerebellum as key areas | Van de Putte et al., 2018 |

bilingual and monolingual groups. Studies have also found variations in brain function or brain structure within bilingual groups, as functions of individual difference factors. Table 5 presents findings regarding various individual difference factors and their relationships with A) neural basis for bilingual language control; B) neural responses for domain-general cognitive tasks; C) the extent of neural overlap between language control and domain-general cognitive functions; D) non-task-related brain function, including resting-state functional connectivity and brain metabolic function; and E) aspects of brain structure. Individual difference factors implicated mainly concern bilingual language experience factors – such as AoA, proficiency, immersion, use, exposure, and so on – but also include others such as SES and general intelligence. Some influences of individual difference factors were found independently of other factors, and some were found to have joint or interacting effects.

## 4. Discussion

The present systematic review aimed to comprehensively examine the relationship between bilingualism and domain-general cognitive functions at the neural level, bringing together findings from relevant neural studies (covering electrophysiology, magnetophysiology, functional, structural, and diffusion imaging, multimodal, neuromodulation, metabolic imaging, and lesion studies). Findings reviewed pertain to mechanisms underlying bilingual language control, the effects of bilingualism on domain-general cognitive functions, and direct overlap between language control and cognitive functions. Additionally, findings regarding the effects of bilingualism on non-task-related brain function and on brain structure were also uncovered, both of which may contribute to differences in various mental functions.

### *4.1. Neural basis for bilingual language control*

Findings largely indicate shared neural mechanisms between bilingual language control and domain-general cognitive functions. Namely, a common network of frontoparietal and subcortical areas has been observed, including dlPFC, IFG, SMA, cingulate, basal ganglia (particularly caudate), and inferior parietal areas (e.g., Branzi et al., 2016; de Bruin et al., 2014; Hernandez, 2009; Hernandez et al., 2000, 2001; Marian et al., 2014, 2017; Sierpowska et al., 2013, 2018) Khateb et al., 2007). In addition, ERP and oscillatory responses associated with domain-general top-down processing have also been observed, including larger P2, N2, and LPC/P3b ERP amplitudes, and increased power in alpha and theta oscillation bands (e.g., C. B. Fernandez et al., 2019; Guo et al., 2013; Leinonen et al., 2007; Litcofsky and Van Hell, 2017; Massa et al., 2020; E. M. Moreno et al., 2002; Naylor et al., 2012; Yi et al., 2018). However, distinct mechanisms may also be involved during bilingual language control, namely engagement of language-specific brain areas, such as left IFG, dACC, and left STG/MTG (e.g., Abutalebi et al., 2008, 2013; Crinion et al., 2006; Marian et al., 2017; Sierpowska et al., 2013, 2018), and an N400 ERP response (e.g., Chen et al., 2017; Christoffels et al., 2013; Liao and Chan, 2016; Moreno et al., 2002; Yi et al., 2018). See Fig. 4 for an overview. These findings come from studies assessing the mechanisms involved during bilingual language control (see section 3.1), from studies directly assessing the overlap between domain-general cognitive functions and language control among the same groups of participants (see section 3.3), and from our meta-analyses (see section 3.4).

Some have suggested that the engagement of domain-general cognitive control for managing two languages may be more critical in the earlier stages of L2 acquisition or learning, relying more on frontal areas. With increased exposure and proficiency in L2, bilingual language control may shift to more language-specific – particularly semantic – processing, relying more on posterior and subcortical areas (de Frutos-Lucas et al., 2020; Grant et al., 2015). In another regard, the involvement of domain-general cognitive functions in bilingual language control are independent of the modality of language processing. That is, language control during both production and comprehension require similar mechanisms (e.g., Abutalebi et al., 2007; Branzi et al., 2016; Peeters et al., 2019; Stasenko et al., 2020). Research on bilingual language control have often focused on language production, and it was believed that control processes are more involved in managing two languages during production than during comprehension. A recent study, however, showed that bilinguals may need to exercise domain-general cognitive control and corresponding brain areas to a greater extent that previously assumed, that is, during both production and comprehension, rather than only during production (Stasenko et al., 2020). Although, there may also be distinct control mechanisms involved in comprehension versus production. For example, one study found a dissociation within domain-general control areas, where bilateral dlPFC was more involved in language switching during production, and left ACC was more involved in language switching during comprehension (Blanco-Elorrieta and Pylkkänen, 2016).

The mechanisms for bilingual language control may depend on other task conditions, such as switch direction, voluntary or cued switching, cross-modal (i.e., spoken and signed) language control, and so on. In regard to switch direction, some have found greater involvement of frontoparietal control areas when switching into a weaker L2 (de Bruin et al., 2014; Y. Wang et al., 2007), whereas some have found the opposite (Y. Zhang et al., 2014). This difference may have been due to a difference in the paradigm used to assess language switching, where the former studies used single-word language switching (picture naming) and the latter examined language switching in a sentence context. That is, greater effort may be required to process contexts in a weaker L2 for sentences that involve a switch into a dominant L1. Additionally, differences in the nonswitch baselines used may also contribute, where, for single-word switches, trials switching to L1 are contrasted with nonswitch naming trials in L1; but for switching in sentence context, trials switching to L1 from an L2 context are contrasted with nonswitch sentences in L2, to match the processing of the predominant context.

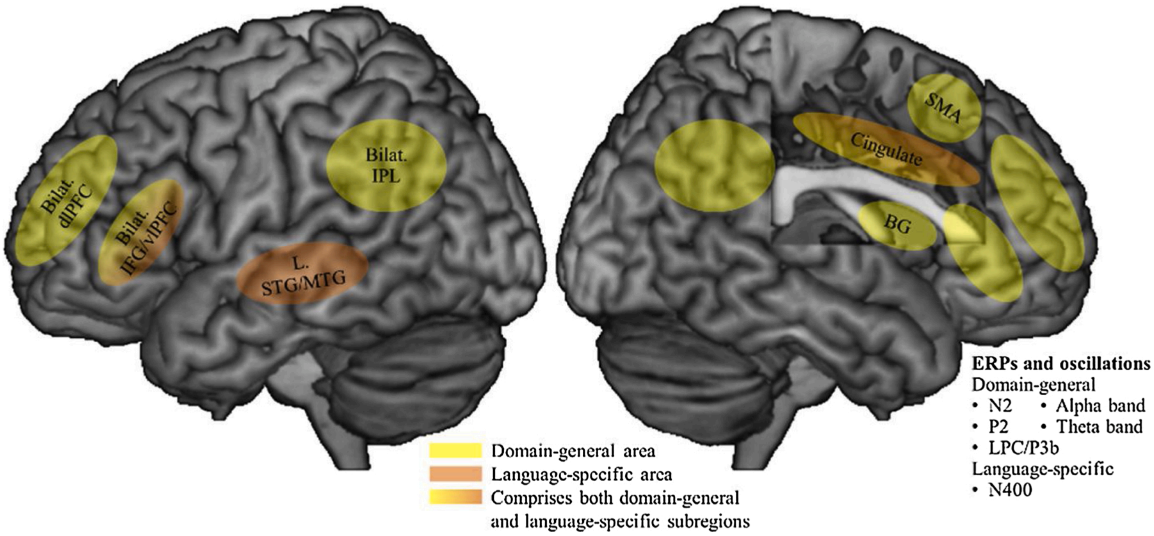


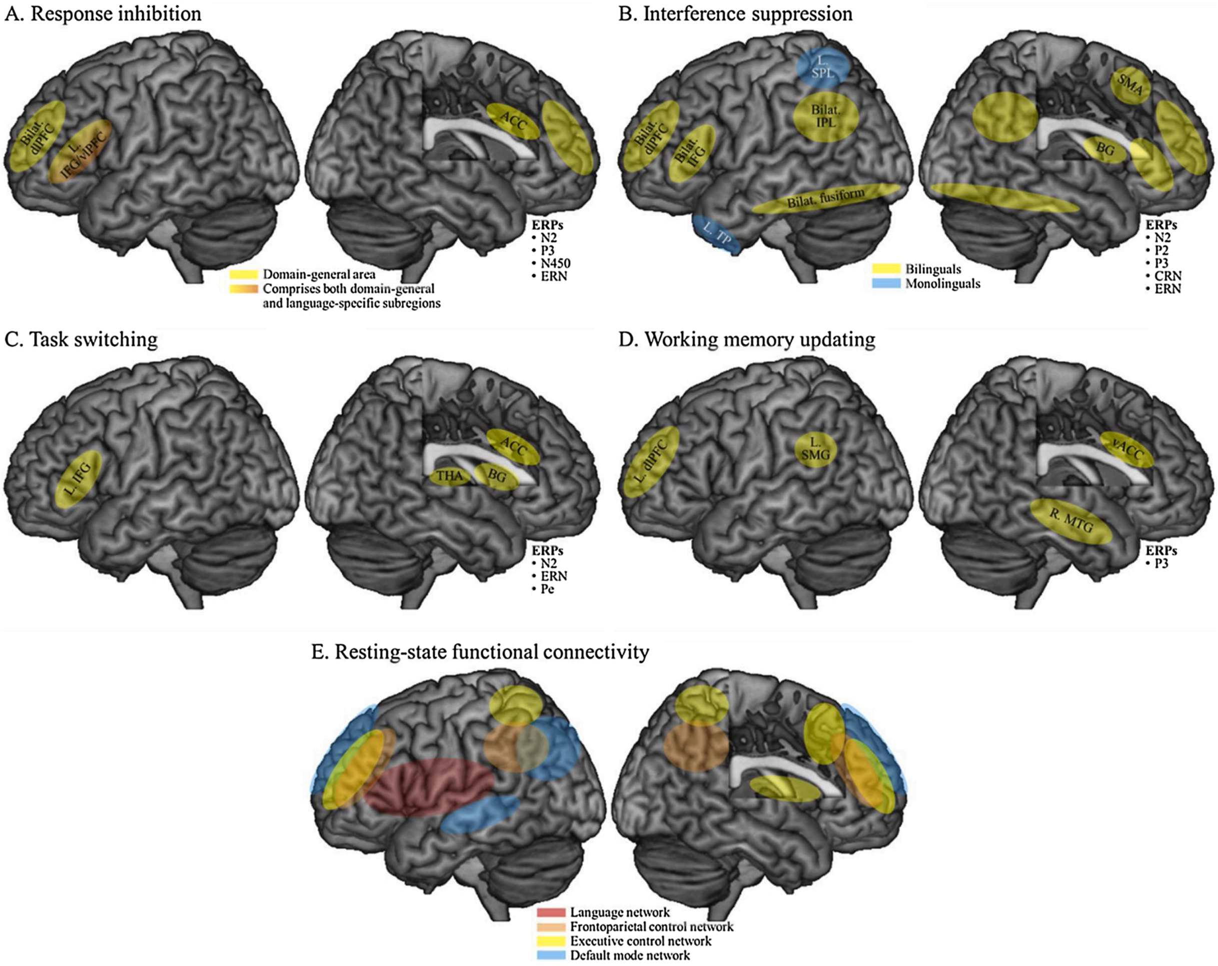
**Fig. 4.** Overview of neural responses (activations and neuroelectric responses) during bilingual language control. dlPFC = dorsolateral prefrontal cortex; IFG/vlPFC = inferior frontal gyrus/ventrolateral prefrontal cortex; IPL = inferior parietal lobule; STG/MTG = superior/middle temporal gyrus; SMA = supplementary motor area; BG = basal ganglia; LPC = late positive complex.

However, other findings from single-word switching paradigms, such as findings from functional connectivity (e.g., Tabassi Mofrad and Schiller, 2019), ERP responses (e.g., Yi et al., 2018), and behavioral performance, have indicated that switching into a dominant L1 may be more cognitively demanding than the reverse. In regard to other task conditions, voluntary switching have been shown to involve more bottom-up mechanisms, whereas cued switching involves more inhibitory control processes (Blanco-Elorrieta and Pylkkänen, 2017; H. Liu et al., 2020b). For bimodal bilinguals, studies have suggested that cross-modal language control may not incur additional neural cost compared to single-language contexts, because the pressure to “finalize” language selection at the articulatory-motor level, which requires more effortful domain-general top-down control, is reduced (Blanco-Elorrieta et al., 2018; Kovelman et al., 2009).

Findings reviewed generally support theoretical frameworks on bilingual language control. It appears that some top-down cognitive control processes are required, at least in some conditions, in order to a) produce items in the target language, in line with the IC model and later variants; and b) suppress competing items to achieve correct comprehension, in line with the BIA model and variants. Findings also support, more specifically, neurocognitive and computational models. In line with the Language Control model (an extension of the IC model; Abutalebi and Green, 2007), domain-general cognitive processes may be required to a greater extent to suppress the more dominant language, when using a weaker language (e.g., de Bruin et al., 2014; Wang et al., 2007). Greater resources may then also be required when needing to disinhibit and re-engage the dominant language (e.g., Abutalebi et al., 2013; Branzi et al., 2016; Tabassi Mofrad and Schiller, 2019; Y. Zhang et al., 2014). The Adaptive Control model (another variant of the IC model; Abutalebi and Green, 2016; Green and Abutalebi, 2013), further stipulates a role for the interactional context. A few studies have found that interactional contexts modulate language control processes, such as by adaptive changes in areas and circuits associated with certain control processes (e.g., Abou-Ghazaleh et al., 2020; Peeters et al., 2019; Yang et al., 2018). Furthermore, individual experiences relating to interactional context may have an impact. For example, greater L2 use in home and social settings was associated with more effective handling of increased demands for mixing and control (DeLuca et al., 2020), and with relevant brain network organization (Gullifer et al., 2018). Lastly, in line with the computational Conditional Routing Model (Stocco et al., 2014), the basal ganglia have been shown to play a crucial role in bilingual language control, where the management of two languages relies on domain-general signal routing mechanisms via this subcortical structure (Yamasaki et al., 2019).

### 4.2. *Effects of bilingualism on brain function*

Aside from language, bilingual experiences may influence neural



A. Response inhibition

B. Interference suppression

C. Task switching

D. Working memory updating

E. Resting-state functional connectivity

**Fig. 5.** Overview of the effects of bilingualism (differences between bilinguals and monolinguals) on brain function. A)-D) differences in task-related brain function (activations and neuroelectric responses). E) differences in resting-state functional connectivity (higher connectivity within and between these networks found for bilinguals). dlPFC = dorsolateral prefrontal cortex; IFG/vlPFC = inferior frontal gyrus/ventrolateral prefrontal cortex; vACC = ventral anterior cingulate cortex; SPL = superior parietal lobule; IPL = inferior parietal lobule; TP = temporal pole; SMA = supplementary motor area; BG = basal ganglia; THA = thalamus; SMG = supramarginal gyrus; MTG = middle temporal gyrus; ERN = error related negativity; CRN = correct related negativity; Pe = error positivity.

responses relating to other cognitive capacities, as well as non-task-related brain function. See Fig. 5 for an overview.

### 4.2.1. *Task-related brain function*

Many studies have suggested that differences between bilinguals and monolinguals in cognitive functions, often not detected behaviorally, may be more readily observed at the neural level, both via functional activations and via electrophysiology (see section 3.2). For example, bilinguals and monolinguals have shown similar levels of behavioral performance on various cognitive tasks, but such performance may be achieved via different brain networks or different patterns of neural engagement (e.g., Ansaldo et al., 2015; Arredondo et al., 2017; Berroir et al., 2017; Costumero et al., 2015; Luk et al., 2010; Rodríguez-Pujadas et al., 2013; Waldie et al., 2009), and may produce different ERP responses (e.g., Fernandez et al., 2013, 2014; Grundy et al., 2017a; Grundy, Chung-Fat-Yim, et al., 2017; Grundy and Bialystok, 2018; Heidlmayr et al., 2016; Kousaie and Phillips, 2012, 2017; Moreno et al., 2014; Morrison et al., 2019a; 2019b; Nayak et al., 2020; Rämä et al., 2018; Sullivan et al., 2014; Y. J. Wu et al., 2016). Some have suggested that bilinguals recruit neural resources more efficiently or more flexibly compared to monolinguals, such as by recruiting more task-specific resources rather than more general, all-purpose resources (e.g., Alain et al., 2018; Anderson et al., 2018a; Gold et al., 2013b; Stocco and Prat, 2014; Waldie et al., 2009). Studies have also found that mechanisms to resolve competition in nonlinguistic domains may be similar to those recruited to resolve competition among language representations, or may be shaped by bilingual experience in linguistic conflict resolution (e.g., T. M. Becker et al., 2016b; Costumero et al., 2015; Rodríguez-Pujadas et al., 2013, 2014). This involvement of language control mechanisms in domain-general cognition echoes the involvement of domain-general mechanisms in bilingual language control, further indicating overlap or collaboration across the two domains.

The differences in task-related brain function between bilinguals and monolinguals have often been observed when cognitive and brain functions are at their peak, that is, during young adulthood. There may also be developmental and aging differences between the two language groups. Bilingual experiences may influence the developmental course as well as the outcome of language control and cognitive control brain areas, particularly in bilateral prefrontal regions (Arredondo et al., 2017; Mohades et al., 2014). Furthermore, the differences were observed in later childhood (around age 10), but not during early childhood (around age 4), suggesting that neural differences between bilinguals and monolinguals may become more apparent with maturation (Arredondo et al., 2017; Mohades et al., 2014; Moriguchi and Lertladaluck, 2019). Correspondingly, bilingual experiences may impact behavioral and neural responses for domain-general cognitive functions particularly later in life, for example, by protecting against age-related brain changes such as over-recruitment of frontal areas (Dash et al., 2019; de Frutos-Lucas et al., 2020; Luk et al., 2011).

### 4.2.2. *Non-task-related brain function*

Resting-state studies have found influences of bilingual experiences on intrinsic brain function, particularly among children, older adults, and patients (see section 3.6). In particular, bilinguals have often shown enhanced intrinsic functional connectivity, within and between a number of brain networks relevant for language and cognitive functions (e.g., Bubbico et al., 2019; de Frutos-Lucas et al., 2020; Grady et al., 2015; Thieba et al., 2019). Bilingual experiences may also impact intrinsic brain activity, where bimodal bilinguals showed less synchronized activity (lower regional homogeneity) – particularly in spoken language areas – relative to monolinguals. This reduced synchronized activity was further associated with reduced functional connectivity within a spoken language area. These findings are likely to be related to differences in the amount of spoken language use, and may not generalize to unimodal bilinguals. (L. Li et al., 2015). Nonetheless, these results illustrate that experiences relating to bilingualism can impact intrinsic brain activity.

In addition to the spatial dynamics of intrinsic brain activity typically examined using resting-state fMRI, recent research (beyond the cutoff for the present review) has begun to examine its temporal dynamics using resting-state EEG. For example, compared to monolinguals, bilinguals showed greater power and coherence in alpha and beta frequency bands at certain electrode sites, and lower theta power and coherence at certain sites. Further, higher alpha power was associated with higher L2 use and earlier AoA, and higher power in all three bands examined was associated with higher L1 proficiency (Bice et al., 2020). Alpha activity has been implicated in domain-general cognitive control and supports bilingual language control, beta activity has been implicated in dual-language success, and theta in learning and memory. Future research may carry out further work to examine in greater depth resting-state temporal dynamics relating to bilingualism.

Lastly, studies have found influences of bilingual experiences on changes in brain metabolic function in neurodegeneration. Bilingual patients have shown reduced metabolic function in widespread brain areas, compared to disease-matched monolinguals, but still showed similar or even higher cognitive performance (Kowoll et al., 2016; Perani et al., 2017). Differences in resting-state brain function and in brain metabolic function have both been associated with various mental functions (e.g., Berken et al., 2016a; Bubbico et al., 2019; Grady et al., 2015; Gullifer et al., 2018; Kousaie et al., 2017; Martínez-Horta et al., 2019; Sun et al., 2019; Thieba et al., 2019; Van der Linden et al., 2018).

## 4.3. *Effects of bilingualism on brain structure*

Bilingual experiences may also influence aspects of brain structure, which may in turn impact various mental functions. See Fig. 6 for an overview. Both macrostructural and microstructural changes can have cognitive or behavioral consequences. For example, brain atrophy in different areas produces dysfunction in different cognitive capacities (e.g., Ibarretxe-Bilbao et al., 2011). Changes in white matter microstructure have also been associated with variations in cognitive abilities (see Scholz et al., 2014, for a review). Moreover, aspects of brain structure can be strengthened through certain activities (e.g., physical exercise, intellectual learning, social interaction, and so on), which have then been associated with corresponding cognitive benefits (e.g., Hötting and Röder, 2013; Vance et al., 2010). Experience in more than one language is plausibly one such activity that can produce cognitive benefits by strengthening aspects of brain structure.

For brain macrostructure (structural imaging), the majority of studies reviewed have examined grey and white matter volume or density, with a few studies examining cortical thickness, surface area, cortical folding, subcortical reshaping and so on (see section 3.5). Findings indicate that bilingual experiences can lead to structural neuroplastic changes among healthy young adults, in both language and cognitive processing brain regions, likely as a result of the additional demands for linguistic and cognitive control required for managing two languages (e.g., Berken et al., 2016b; Hervais-Adelman et al., 2018; Legault et al., 2019a; 2019b; L. Li et al., 2017; Mechelli et al., 2004; Zou et al., 2012). Furthermore, brain structural changes can occur relatively quickly, namely within a matter weeks or months of L2 learning (Bellander et al., 2016; Ehling et al., 2019; Hosoda et al., 2013; Legault et al., 2019a; 2019b; Mårtensson et al., 2012). Bilingualism may also influence interhemispheric organization, with differences between bilinguals and monolinguals observed in the structural conduit for interhemispheric communication – the corpus callosum, and in the direction of structural asymmetry – particularly in ACC, an area crucial for cognitive control (Felton et al., 2017). Changes in brain macrostructure may depend on the modality of languages. Some have observed structural differences among bimodal bilinguals compared to monolinguals (L. Li et al., 2017; Zou et al., 2012), whereas some have found no differences between these two groups (Olulade et al., 2016). Higher brain volumes (grey matter volume or macromolecular tissue volume) have been associated

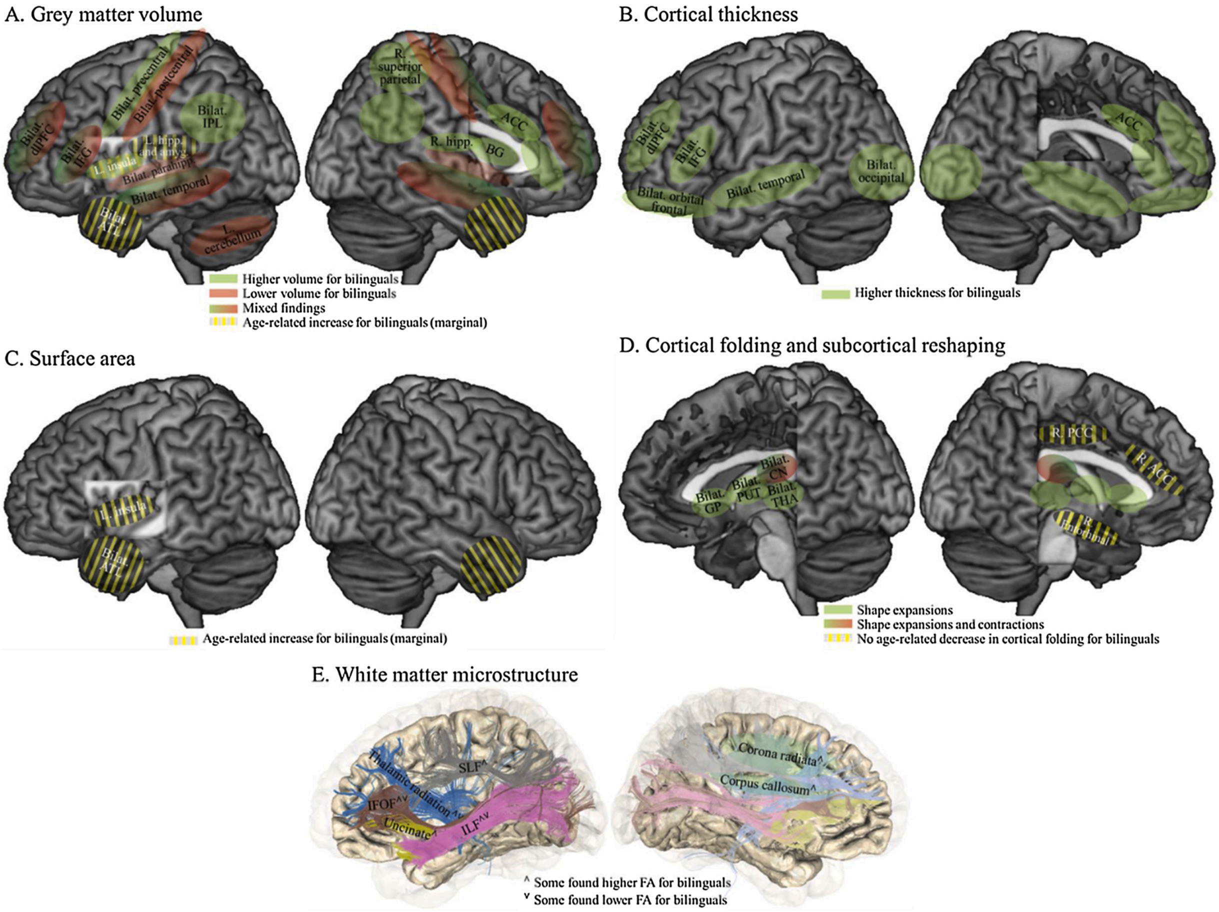


**Fig. 6.** Overview of the effects of bilingualism (differences between bilinguals and monolinguals) on brain structure. A)-D) differences in aspects of grey matter macrostructure. E) differences in white matter microstructure (fibers visualized using AFQ-Browser, Yeatman et al., 2018). dlPFC = dorsolateral prefrontal cortex; IFG = inferior frontal gyrus; IPL = inferior parietal lobule; ATL = anterior temporal lobe; BG = basal ganglia; ACC = anterior cingulate cortex; PCC = posterior cingulate cortex; CN = caudate; GP = globus pallidus, PUT = putamen; THA = thalamus; IFOF = inferior fronto-occipital fasciculus; ILF = inferior longitudinal fasciculus; SLF = superior longitudinal fasciculus; FA = fractional anisotropy.

with better domain-general cognitive functions (response inhibition or task switching/cognitive flexibility; M. Becker et al., 2016a; Luo et al., 2019; Martínez-Horta et al., 2019).

Bilinguals and monolinguals have also shown differences in brain structure in older age. Aging is typically associated with brain atrophy, such as reductions in grey matter volume, cortical thickness, surface area, and cortical folding. Bilinguals, however, sometimes do not show such reductions with age (e.g., Abutalebi et al., 2014; Abutalebi, Canini, et al., 2015; Del Maschio et al., 2019a; 2019b; Olsen et al., 2015). Middle-aged and older adult bilinguals have even shown higher grey matter volume and cortical thickness compared to monolingual peers, particularly in areas related to domain-general cognitive functions (e.g., Abutalebi et al., 2014; Abutalebi, Canini, et al., 2015; Abutalebi et al., 2015b; Del Maschio et al., 2018; Duncan et al., 2018; Heim et al., 2019). Even over a relatively brief period of time (6−9 months), older adult monolinguals with dementia showed a reduction in brain volume, whereas bilingual patients did not (Costumero et al., 2020). Among middle-aged adults, older age has even been marginally associated with higher grey matter volume and surface area among bilinguals, whereas monolinguals peers showed the typical negative trends (L. Li et al., 2017). These findings indicate a more extensive and faster rate of brain atrophy among monolinguals relative to bilinguals. On the other hand, some have found that brain structural differences between bilinguals and monolinguals may diminish with age, indicating a faster rate of decline among bilinguals (Heim et al., 2019). Additionally, among older adult dementia patients, bilinguals have shown greater brain atrophy compared to monolinguals, but despite that still showed similar levels of cognitive performance (Costumero et al., 2020; Schweizer et al., 2012). Nevertheless, bilingual experiences appear to offer some protection against brain structural decline, in both healthy aging and in neurodegenerative disorders. Such protection may be due to either enhancing regional brain structure throughout the lifespan, or attenuating age-related declines in older age (Olsen et al., 2015; Zou et al., 2012).

Studies have also examined the influences of bilingual experiences on white matter microstructure (diffusion imaging). Like for brain macrostructure, bilingual experiences may contribute to microstructural neuroplasticity among healthy young adults – in various white matter tracts, including those related to language processing and cognitive functions – again, likely as a result of the increased linguistic and cognitive load for bilingual language use relative to monolinguals (e.g., Kuhl et al., 2016; Pliatsikas et al., 2015; Reyes et al., 2018; Rossi et al., 2017; Singh et al., 2018). Like for macrostructural changes, changes in white matter microstructure has also been observed following relatively brief periods (weeks to months) of L2 learning (Hosoda et al., 2013). Such changes may also manifest in the early years of cognitive and neural development. For example, compared to monolingual peers, bilingual children showed differences in white matter microstructure, and also showed greater longitudinal change over a two year period (around age 9−11; Mohades et al., 2012, 2015). At the other end of the age scale, for both healthy aging and dementia, lifelong bilingual experiences have been associated with differences in white matter microstructure, which may in turn protect against neurodegenerative and cognitive function decline (Anderson et al., 2018b; Gold et al., 2013a; Luk et al., 2011; Marin-Marin et al., 2020). Among patients with a neurological disorder that affects white matter microstructure (temporal lobe epilepsy), bilingualism has also been found to protect against possible changes in cognitive functioning, despite changes in relevant white matter tracts (Reyes et al., 2018).

### 4.4. *Neuroplasticity and reserve*

Based on the current body of findings, it appears that bilingual experiences influence both task- and non-task-related brain function, as well as aspects of brain structure. Such changes may appear in childhood, with effects on intrinsic brain function detected in early childhood, whereas effects on task-related brain function and brain structure may manifest in later childhood or adolescence (e.g., Arredondo et al., 2017; Mohades et al., 2012, 2014, 2015; Moriguchi and Lertladaluck, 2019; Thieba et al., 2019). Through functional and structural neuroplastic changes, bilingual experiences may provide benefits in terms of domain-general cognitive functions, which may be particularly evident later in life. That is, such benefits may be sustained across the lifespan, protecting against neural and cognitive decline, in healthy aging and in the presence of neurodegenerative disorders (e.g., Abutalebi et al., 2014, 2015a; 2015b; Anderson et al., 2018b; Costumero et al., 2020; Del Maschio et al., 2018; Gold et al., 2013a; Heim et al., 2019; Luk et al., 2011; Martínez-Horta et al., 2019; Olsen et al., 2015).

The benefits of bilingualism on cognitive functioning can occur through two possible pathways, cognitive reserve and neural reserve (see Fig. 7). As discussed, bilingual experiences throughout the lifespan may lead to both functional and structural neuroplastic changes. These changes then contribute to cognitive and neural reserves. In older age, contributions to cognitive reserve may manifest as benefits by protecting against loss of cognitive functions – even when there are similar, or even more severe, levels of neural decline compared to monolingual peers. Such benefits may occur, for example, through enhancements in various functional networks, or through flexible use of alternative functional networks to compensate for neural atrophy (e.g., Anderson et al., 2018b; Del Maschio et al., 2018). Contributions to neural reserve may manifest as benefits by protecting against neural decline itself, which in turn protects against loss of cognitive functions (e.g., Abutalebi et al., 2015b; Anderson et al., 2018b; Duncan et al., 2018). At the same time, however, the compensatory mechanism protecting against cognitive decline, in the face of more severe neural decline, may work against bilinguals. Neurodegenerative disorders, such as dementia, are often detected through neuropsychological assessments. With less severe loss of cognitive functions, such disorders may not be detected via cognitive clinical assessments until later stages of neural decline, delaying the implementation of interventions (Kowoll et al., 2016; Perani et al., 2017; Schweizer et al., 2012).

### 4.5. *Unresolved issues and directions for future research*

#### 4.5.1. *The issue of functional specificity*

Studies examining the neural mechanisms underlying bilingual language control have often found involvement of neural components associated with domain-general cognitive functions. The majority of these studies, however, did not directly examine neural responses when performing domain-general tasks, but only examined response to language control tasks. These studies, therefore, generally rely on reverse inferencing to conclude that bilingual language control entails domain-general cognitive processes, namely on the basis that the neural responses observed have previously been found to be involved in domain-general cognitive processing. However, reverse inference can be a fallacy, due to a) activation specificity – many different processes can activate the same brain areas (Poldrack, 2006), and b) cognitive degeneracy – multiple neural systems may be involved for the same cognitive process (Price and Friston, 2002). To overcome this fallacy, inferences regarding neural responses need to be conditioned by the relevant task setting (Hutzler, 2014). Furthermore, patterns of brain activations in response to the same tasks differ widely across individuals. Thus, to more reliably infer that bilingual language control involves domain-general cognitive processes, studies should assess both language control and the cognitive function hypothesized to be involved within the same group of participants. So far only a relatively small number of studies have directly assessed the neural overlap between bilingual language control and domain-general cognitive functions, by assessing both processes within the same participant samples. Moreover, the majority of these studies examined overlap between task switching and language control; only two studies examined overlap with interference

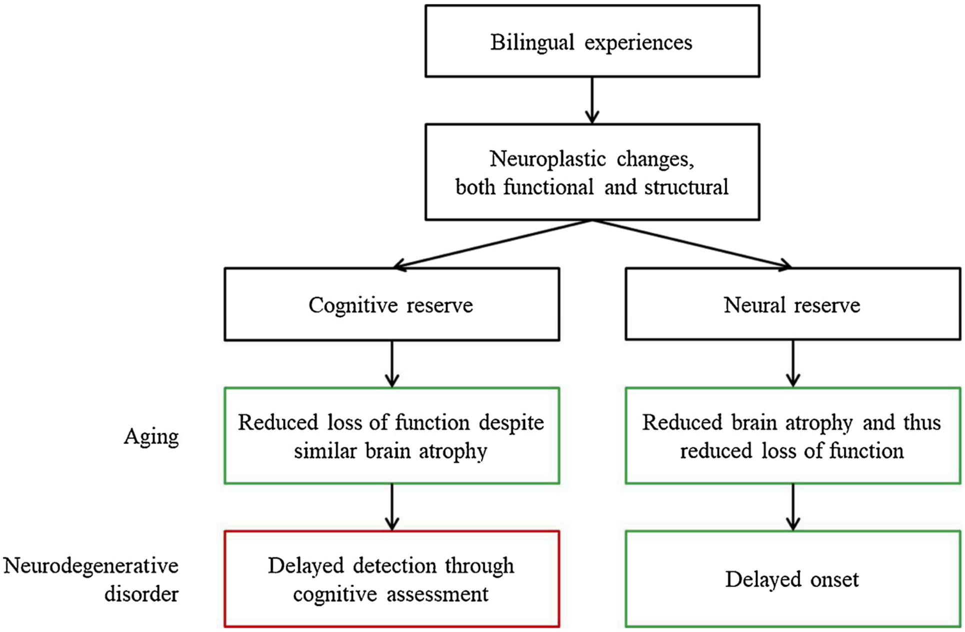


**Fig. 7.** Bilingual experiences may protect against neural decline and/or cognitive decline, via neuroplasticity and contributions to cognitive and neural reserves; but may, at the same time, delay the detection of neurodegenerative disease through neuropsychological assessment.

suppression, and none examined other key domain-general cognitive functions such as response inhibition and working memory updating. On the other hand, research has often suggested that bilingual language control entails inhibitory control processes, or that bilingual experiences impact neural responses during response inhibition tasks. Therefore, more research is needed to assess the direct overlap – that is, within the same group of participants – between bilingual language control and domain-general cognitive functions, particularly response inhibition.

A further issue is that of underestimating functional specificity in neuroimaging studies. Analyses of imaging data typically rely on aggregation of activation across participants based on spatial overlap, and use spatial smoothing to compensate for inter-subject brain variability. Findings of multifunctionality of a region may, thus, be an artifact of averaging across adjacent but functionally distinct brain regions (Fedorenko et al., 2010). Therefore, overlapping activations found across language control and cognitive control tasks may not actually indicate that the same brain regions were involved for both processes, but it may be that the two tasks entailed closely neighboring though non-overlapping regions. Relevant to language and cognitive processing, non-overlapping and functionally distinct subregions have been distinguished within left IFG, with minimal correspondence to anatomical subdivisions (e.g., pars opercularis, pars triangularis, BA 44, 45). One subregion has been shown to be more for language-specific processing, and another to be more involved in domain-general processing (e.g., Chein et al., 2002; Fedorenko et al., 2012; Fedorenko and Blank, 2020; Tao et al., 2020). Similarly, in the domain of visual processing, portions of the fusiform gyrus have been functionally distinguished to be face-selective, rather than the whole fusiform gyrus being one multifunctional unit (e.g., Chang and Tsao, 2017; Kanwisher et al., 1997). Future research on overlapping neural mechanisms across domains may explore methods to improve functional resolution. One such approach may be to use whole-brain voxel-based analysis methods such as a *subjectict-specific* functional ROI. Such a method requires multiple runs of data or use of a functional localizer. Data from the separate run is then used to create a subject-specific mask to limit the aggregation of activation to only those voxels within the mask. That is, instead of using spatial smoothing, subject-specific functional localization is used to compensate for inter-subject variability when averaging across participants in group analyses (Nieto-Castañón and Fedorenko, 2012).

### 4.5.2. *Inferring mental processes from neural activities*

An ongoing issue in cognitive neuroscience is whether neuroimaging and other noninvasive neurorecording methods actually allow researchers to measure mental functions in the brain – that is, can a set of brain activities unequivocally correspond to a specific mental process (see e.g., Aue et al., 2009; De-Wit et al., 2016; op de Beeck et al., 2001; Page, 2006; Poeppel, 2012, for discussions on this topic). Although there is not yet an ultimate solution to this problem, there are ways to help estimate the extent to which brain activities predict specific mental processes, for example by using multivariate analysis methods. Neural studies on language and cognitive control, like in other fields, have traditionally used mass-univariate analysis methods, which entails performing a separate statistical test (e.g., between two conditions) at every point in space or time. Multivariate methods, in contrast, make use of patterns of brain activity over multiple measurements (e.g., voxels, electrodes or time points). Classifiers based on machine learning methods are then used to "decode" mental processes from these patterns. Multivariate classifiers help to quantify the degree to which a pattern of brain activity predicts a specific mental process, providing insights on how cognitive representations are encoded in brain signals (see e.g., Haxby et al., 2014; Haynes, 2015; Kragel et al., 2018; Poldrack, 2011, for reviews and perspectives). In addition to decoding from brain activation, studies have also decoded mental processes from patterns of functional connectivity, which may be more discriminatory in classification, at least for some processes (e.g., C. Liu et al., 2020a; Pantazatos et al., 2012; Shirer et al., 2012).

### 4.5.3. *How does brain structure enable function?*

Mental functions are inherently informed and constrained by brain structure, though at present it is less clear in which cases and to what extents structure determines function (Honey et al., 2010). Bilingual experiences have already been associated with brain structural differences (see section 4.3). One avenue for further research on the relationship between bilingualism and domain-general cognitive functions is to determine the causal involvement of brain regions in various mental functions. In this regard, lesion patients with damage to particular brain areas have provided insights (e.g., Adrover-Roig et al., 2011; Van der Linden et al., 2018, in the present review). Lesion patients, however, are not often accessible. Furthermore, pre-lesion behavioral and neural responses are often not available, but can only compare post-lesion responses to that of healthy controls. Therefore, pre-existing individual differences may contribute to changes observed among lesion patients, rather than purely caused by the lesion itself. In the absence of suitable lesion patients, brain function can be temporarily altered using neuromodulation methods, which also allow for comparison with pre-modulation behavioral and neural responses (e.g., B. Li et al., 2018; H. Liu et al., 2020b, 2020c; Nakamura et al., 2010, in the present review). In particular, TMS produces a temporary "virtual lesion" in the targeted brain area, allowing researchers to examine whether the targeted region is casually involved in the mental function assessed. For example, TMS to left posterior IFG has been found to affect single-language naming, and to affect naming in the two native languages of simultaneous bilinguals differently (Hämäläinen et al., 2018; Sakreida et al., 2018). TMS with online EEG recording have shown that pIFG and pSTG/STS were involved during sentence comprehension at different times following target stimulus onset (Kroczek et al., 2019). Furthermore, TMS to left IFG versus medial frontal cortex (medial BA 8) dissociated language and deductive reasoning. More specifically, suppression of neural activity at the former site reduced accuracy on a language task but not on a matched logic task, whereas TMS at the latter site produced the opposite pattern (Coetzee et al., 2019).

Aside from macroscopic cortical and subcortical regions, white matter tracts may also constrain functions. White matter fiber tracts provide essential anatomical links between spatially separated brain regions, enabling higher-order functions that require integration of neural activities across multiple regions. Indeed, inter-subject variations in white matter microstructural properties have been found to be behaviorally relevant (see Scholz et al., 2014, for a review). However, precise relationships between mental functions and tracts are yet to be fully identified. One study dissociated distinct sets of white matter tract regions, corresponding to three components of attention (i.e., alerting, orienting, and executive control), indicating that there are functionally and anatomically separable networks among white matter fiber tracts, and that variations in white matter microstructure may modulate functions in specific ways (Niogi et al., 2010). A recent study further examined functional responses within white matter tracts. Specifically, grey matter clusters activated during a Stroop task were first identified using fMRI; diffusion imaging data were then used to identify and reconstruct white matter tracts between each pair of activated clusters; task-specific hemodynamic response functions (HRFs) were then characterized for the white matter tracts (M. Li et al., 2019). Future research may explore specific involvement of white matter tracts in mental functions of interest, to better understand the functional role of these fibers.

Relationships between structure and function have also been observed in terms of connectivity, but the full picture is yet to be uncovered. It has been found, for example, that functionally connected regions tended to be structurally connected as well (see Honey et al., 2010, for a review). Moreover, models for effective functional connectivity for lexical and spatial tasks were improved when informed by structural connectivity data (Stephan et al., 2009). On the other hand, functional connectivities were not highly predictive of structural ones, indicating that strong functional connectivity can exist between regions that are not anatomically linked. The correspondence between functional and structural connectivities may also depend on spatial resolution and time scales (Honey et al., 2010). More research is needed, therefore, to explore links between functional and structural connectivities, to better understand how structural networks enable neural activities. Integrative analyses linking structural and effective functional connectivity have so far helped provide converging evidence in other fields of study, such as neural pathways involved in fear recognition (McFadyen et al., 2019) and in biological motion detection (Sokolov et al., 2018).

#### 4.5.4. *Direction of influence between bilingualism and domain-general cognitive functions*

Research has mostly suggested influences of bilingualism on domain-general cognitive functions, rather than influences of domain-general cognitive functions on bilingualism. However, most of the available evidence to date do not allow inferences regarding the causal direction – that bilingualism caused changes in cognitive processing, in brain function, or in brain structure. It is possible in some cases that pre-existing differences in cognitive capacities, brain function, or brain structure led to some individuals being more likely to gain proficiency in more than one language. For example, better response inhibition ability and better phonological memory have been shown to be associated with better post-training L2 performance (Bartolotti et al., 2017). On the other hand, some have reported no influences of domain-general cognitive functions – including inhibition, switching, working memory updating, working memory capacity, visual attention, nonverbal intelligence – on L2 learning rate (Prat et al., 2016). This latter study, however, found that pre-training resting-state brain function (as measured by qEEG, particularly in the low-beta frequency band) predicted L2 learning rate over the course of eight weeks, but not post-training L2 comprehension performance (Prat et al., 2016).

A small number of studies have examined the effects of training using pretest-posttest designs (Bellander et al., 2016; Ehling et al., 2019; Grant et al., 2015; Hosoda et al., 2013; Kang et al., 2017; Legault et al., 2019a; 2019b; H. Liu et al., 2016; Mamiya et al., 2016; Mårtensson et al., 2012; Sullivan et al., 2014; Van de Putte et al., 2018), or examined changes over a period of maturation (Costumero et al., 2020; Deluca et al., 2019a, 2019b; Hervais-Adelman et al., 2017; Mohades et al., 2015), which may provide valuable insights into development trajectories and causal relationships among variables. However, these studies have been relatively short-term, from a single experimental session up to a few months of training, or up to three years of maturation. Furthermore, the majority of training and maturation studies involved young adults; only one longitudinal study examined children, but only during later childhood. Therefore, a) differences observed at posttest may not be fully consolidated changes; b) there may be other pre-existing differences that play a role, for example, differences in a genetic trait (Vaughn et al., 2016) and differences in a neuroanatomical trait determined in utero (Cachia et al., 2017; Del Maschio et al., 2019b) have been found to modulate cognitive functions. If resources allow, researchers can explore extended longitudinal designs, beginning at the early stages of development and tracking across the lifespan.

#### 4.5.5. *Independent and joint influences of individual difference factors*

Lastly, studies investigating the effects of bilingualism have traditionally compared bilinguals with monolinguals. Bilinguals, however, are not one homogeneous group. The heterogeneity of bilingual populations is part of the difficulty in conducting research on bilingualism, contributing to the many varied findings. Increasingly, researchers are investigating bilingualism as a continuum or multiple continua of experiences, examining the influences of various individual difference factors within bilingual groups (e.g., Berken et al., 2016a; DeLuca et al., 2019a, 2020; Deluca et al., 2019a, 2019b; Kousaie et al., 2017; Mohades et al., 2014; Moriguchi and Lertladaluck, 2019; Mouthon et al., 2020; Nichols and Joanisse, 2016; Sulpizio et al., 2020a; Sun et al., 2019; Vaughn et al., 2016; Wei et al., 2015).

Bilingual experience factors – such as AoA, proficiency, language use, immersion context – have been found to influence neural responses when performing language control tasks, responses when performing domain-general cognitive tasks, the extent of neural overlap between the two domains, non-task-related brain function including resting-state functional connectivity and brain metabolic function, and aspects of brain structure (see section 3.7). However, there have been mixed findings and mixed methods. For example, some divided bilinguals into subgroups (e.g., early vs. late acquisition, high- vs. low-proficiency), and some examined these factors as continuous variables. Furthermore, there are some factors that may play a role that have so far received little attention. For example, linguistic distance – that is, the extent to which languages differ from each other – may modulate language control mechanisms and, in turn, the effects of bilingualism on domain-general cognitive functions. Although linguistic distance is difficult to measure, there have been attempts to quantify it (e.g., Chiswick and Miller, 2005; Isphording and Otten, 2013). Another potential influencing factor is cultural background, for example, some cultures plausibly emphasize performance outcomes more than others, producing cognitive differences. Individual differences in linguistic distance and cultural background have been found to be behaviorally relevant (e.g., Feniger and Lefstein, 2014; Samuel et al., 2018; Tao et al., 2011, 2015, 2019; Tomoschuk et al., 2019), which could then be reflected at the neural level, influencing brain function and/or structure. For example, one study in the present review found that the effects of L2 proficiency on grey matter volume were observed more for bilinguals whose two languages are more similar than those with more distinct languages (Abutalebi et al., 2015a).

More research is needed to systematically tease apart the independent, joint, and interactional influences of the complex spectrum of bilingual experience factors, including (and not limited to) AoA, proficiency in each language and relative balance between languages, immersion environment, amount of use and exposure, context of use and exposure, linguistic distance between languages, cultural differences, and so on. Additionally, individual differences not relating to bilingual experiences have been found to play a role, including sociodemographic characteristics such as age and SES, mental capacities such as general intelligence, and pre-existing biological traits such as genetics (e.g., genotypes for DRD2 and COMT genes) and stable neuroanatomical features (e.g., ACC sulcation pattern). Studies involving bilingual groups need to carefully consider the characteristics of participants, both language-related and non-language-related.

### 4.6. *Conclusion*

The present paper reviewed the relationship between bilingualism and domain-general cognitive functions from a neural perspective. Findings uncovered pertain tuncovered pertain to the neural mechanisms underlying bilingual language control, and the effects of bilingualism on function, and the effects of biligualism on brain structure.

The accumulated evidence indicates that a) bilingual language control likely entails neural mechanisms (both neural activations and electrophysiological responses) responsible for domain-general cognitive functions, but also involves language-specific processes; b) bilingual experiences impact neural responses to domain-general cognitive functions, further supporting a close relationship between the two domains; and c) bilingual experiences impact non-task-related brain function (both resting-state and metabolic function) and aspects of brain structure (both macrostructure and microstructure), each of which may in turn impact mental processes, including domain-general cognitive functions. Changes in aspects of brain structure can manifest after brief periods of L2 learning (weeks to months), and can provide protection against age-related decline.

The functional and structural neuroplasticity associated with bilingual experiences may contribute to both cognitive reserve and neural reserve, providing benefits across the lifespan, particularly protecting against cognitive and neural decline in aging (either through enhancement throughout the lifespan or attenuation of decline in aging). For example, bilinguals may show similar cognitive performance to monolinguals, despite more severe neural decline. However, delayed loss of functions can lead to delayed detection of neurodegenerative disorders via cognitive assessments, leading to delayed implementation of interventions.

Future research can explore the many issues that are yet to be resolved, including the issue of functional specificity of brain regions, the issue of inferring mental processes from neural activities, the relationship between brain structure (including macro- and microscopic structure and structural connectivities) with brain function, the direction of influence between bilingualism and domain-general cognitive functions, and the influences of the spectrum of individual difference factors (both language- and non-language-related).

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## Declaration of Competing Interest

The authors report no declarations of interest.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.neubiorev.2021.02.029.

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