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Taxing the bilingual mind: Effects of simultaneous interpreting experience on verbal and executive mechanisms*

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Abstract

This paper reviews the neurocognitive particularities of subjects with sustained experience in simultaneous interpreting, a highly demanding form of bilingual processing. The literature converges into three broad empirical patterns. First, significant neurocognitive differences, including behavioral enhancements in verbal and executive domains, are observable after only one or two years of training. Second, such effects, both in interpreting students and/or professional interpreters, seem robust for crucial linguistic (e.g., translation) and executive (e.g., working memory) aspects of the activity, but not for more marginally relevant ones (e.g., conflict resolution) – suggesting that they are non-generalizable beyond directly taxed functions. Third, though more tentatively, some of the observed verbal and executive effects seem to be mutually independent and uninfluenced by other bilingual-experience-related factors (e.g., L2 competence), which could highlight their distinctive relation with interpreting practice. In sum, this particular model of expertise sheds novel light on the adaptive capacity of cognitive systems in bilinguals.

Introduction

Everyday cognitive processes in bilinguals are characterized by an interplay of verbal and executive systems mediating processes in, and between, two languages – often, though not always, a native and a non-native language (L1 and L2). Far from being static, such systems can exhibit significant enhancements depending on how early and competently they are put to use. Increased L2 exposure has been linked to better performance in tasks tapping linguistic (Matusevych, Alishahi & Backus, 2015) and non-linguistic (Bosma, Hoekstra, Versloot & Blom, 2017) skills, alongside plastic changes in critical brain regions (Grant, Fang & Li, 2015). Also, evidence from lexical (García, 2015a) and executive (Linck, Osthus, Koeth & Bunting, 2014) tasks shows faster and/or more accurate performance in high- than low-proficiency bilinguals. Yet, though highly informative, such evidence fails to reveal key adaptive properties of the mechanisms involved, especially when subjected to recurring exacting conditions. To further understand experience-related cognitive profiles in the bilingual population, here we review how varied domains are affected by sustained practice of simultaneous interpreting (SI), a highly demanding form of dual-language processing.

In the course of their training and throughout their careers, interpreting students (ISs) and professional simultaneous interpreters (PSIs) face more stringent processing conditions than most untrained multilinguals (UMs) – speakers of two or more languages without SI training (García, 2014). These individuals frequently mediate between one party who knows language A but not B and another one with the opposite pattern, usually in formal settings requiring topic-specific knowledge, previous documentation, and sustained communicative adequacy (e.g., appropriate register) (Chernov, 2004). In particular, during the task, they are required to comprehend oral discourse in language A and render it in language B as it unfolds, under strict time constraints (Chernov, 2004). As these subjects encounter such particular socio-communicative scenarios on a regular basis, their bilingual experience is qualitatively and phenomenologically different from that of other sub-groups within the diverse bilingual population. Indeed, the particular combination of verbal and executive demands inherent to SI sets it apart from other specialized forms of dual-language processing, such as L2 learning or teaching and consecutive interpreting (Hiltunen, Paakkonen, Vik & Krause, 2016; Stavrakaki, Megari, Kosmidis, Apostolidou & Takou, 2012).

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SI hinges on multiple processes, such as the perception, storage, recall, and transformation of verbal input (Gerver, 1976); the anticipation of upcoming utterances (Chernov, 2004); and the integration of form-level and meaning-based processes during interlingual reformulation (Paradis, 1994). On the linguistic side, successful performance depends on good auditory discrimination (for filtering out irrelevant signals in the incoming sound stream), rich word knowledge and efficient cross-language processing (to quickly activate source words and find adequate target items, irrespective of their frequency), and solid comprehension skills (to abstract key ideas and identify important conceptual subtleties in the speaker's unfolding discourse) (Chernov, 2004; Christoffels & de Groot, 2005; Padilla, Bajo & Macizo, 2005). As regards executive functions, SI requires robust short-term memory (STM) and working memory (WM) skills – for keeping information transiently active and manipulating it, respectively (Aben, Stapert & Blokland, 2012) – and effective recall despite articulatory suppression (i.e., when information cannot be rehearsed subvocally), alongside attentional and cognitive control abilities to keep track of incoming information and prevent unwarranted instances of language mixing (Christoffels & de Groot, 2005).

All these requisites tax various neurocognitive resources. Relative to other challenging tasks, such as single-language shadowing, SI involves increased activity in frontobasal and perisylvian regions, with maximal recruitment of linguistic and cognitive control hubs (e.g., superior temporal and prefrontal cortices) during parallel processing of input and output (Hervais-Adelman, Moser-Mercer, Michel & Golestani, 2014). Moreover, SI depletes WM and recall capacity significantly more than other verbal tasks (Darò & Fabbro, 1994), further highlighting the elevated cognitive load it implies.

Such demands reach their peak in conference interpreting settings, where discourse frequently surpasses the ideal rate of 95–120 words per minute (Chernov, 2004; Gerver, 1975), ear-voice spans range between 2 and 4 seconds (Gerver, 1976), and concurrent processing of input and output takes up roughly 70% of working time (Chernov, 1994). Yet, PSIs can attain outstanding propositional correspondence, largely surpassing that achieved by UMs (Barik, 1975; Dillinger, 1990; Gerver, 1975). Notably, SI performance in professionals can be predicted by a number of verbal and executive subskills, crucially including WM capacity under conditions which prevent subvocal rehearsal (Injoque-Ricle, Barreyro, Formoso & Jaichenco, 2015; Macnamara & Conway, 2016).

Briefly, specific verbal and executive systems are jointly taxed during SI. Thus, ISs and PSIs offer unique models to explore those systems' capacity for experience-driven adaptations, beyond the effects of L2 competence and exposure. Against this background, we reviewed 36 studies to understand which cognitive systems actually manifest such adaptations and how fast these emerge. Moreover, the evidence can illuminate whether potential adaptations are generalizable across cognitive domains, dependent on one another, and directly attributable to sustained practice of SI.

Our literature search was conducted on PubMed and Google Scholar via combinations of the following keywords: '(simultaneous) interpreting', 'language', 'executive functions', 'cognition', 'brain'. All relevant hits were downloaded and their reference lists were reviewed in quest of additional works. The selected studies were organized in two groups. A first subset offers direct comparisons between ISs and UMs, or between two groups of ISs at different stages of their training. The second subset focuses on PSIs[1] relative to UMs and/or ISs or other language professionals. Comparisons between any of these populations and monolinguals, or between consecutive interpreters and UMs, are excluded from the review, as they are incapable of revealing whether observed effects reflect the impact of SI practice in particular. The main patterns emerging from linguistic and executive assessments are coarsely captured in Figure 1 and Figure 2, respectively.[2] In sum, by focusing on relevant contrasts, we aim to understand how the bilingual mind reshapes itself when continually subjected to the particular demands of SI.

Evidence from interpreting students

A number of studies have compared early ISs with UMs or assessed the former at different stages of their training. Together, this evidence indicates that cognitive effects associated with interpreting experience are observable shortly after its initiation.

Neuroscientific evidence

In two imaging studies, aspiring interpreters were scanned at the beginning and end of a 15-month-long SI program, including 10 weekly hours of formal SI instruction and additional practice sessions. In both cases, the control group was composed of UMs matched for L2 proficiency. One of those studies (Hervais-Adelman, Moser-Mercer, Murray & Golestani, 2017) found that, by the second assessment, only SI trainees had developed increased cortical thickness in temporal, parietal, and dorsal premotor regions supporting phonetic, lexico-semantic, and executive functions. The other one (Hervais-Adelman, Moser-Mercer & Golestani, 2015), based on a subset of participants from the abovementioned study, analyzed fMRI recordings during a shadowing and an interpreting task. Relative to UMs, the trainees exhibited distributed patterns of functional changes between scans, with SI performance in the latter group being characterized by reduced recruitment of the right caudate nucleus, a region implicated in bilingual control (Luk, Green, Abutalebi & Grady, 2011) and word translation (García, 2013). More recently, structural and functional brain changes were reported after only nine months of training in SI (as opposed to translation), mainly in temporo-parietal, frontostriatal, and fronto-cerebellar circuits which have been previously implicated in diverse functions, including cognitive control (Van de Putte, De Baene, García-Pentón, Woumans, Dijkgraaf & Duyck 2018).

Interestingly, neuroanatomical and neurofunctional differences in many of these regions have also been reported in PSIs relative to UMs (Elmer, Hänggi & Jäncke, 2014; Elmer, Meyer & Jäncke, 2010; Elmer & Kühnis, 2016) and consecutive interpreters and translators (Becker, Schubert, Strobach, Gallinat & Kühn, 2016), even in proportion to the subjects' amount of training. Note, however, that some such findings are mixed and others have been criticized on methodological and interpretive grounds (Hervais-Adelman, Moser-Mercer & Golestani, 2018;

[1]Whereas all the subjects in the PSI groups considered were indeed SI experts, some of them also worked as professional consecutive interpreters.

[2]Note that the figures provide only a coarse overview of the main patterns detected, and that several papers include both positive and negative results from varied domains. Details on which specific task yielded each result can be found in the main body text and in the original papers.

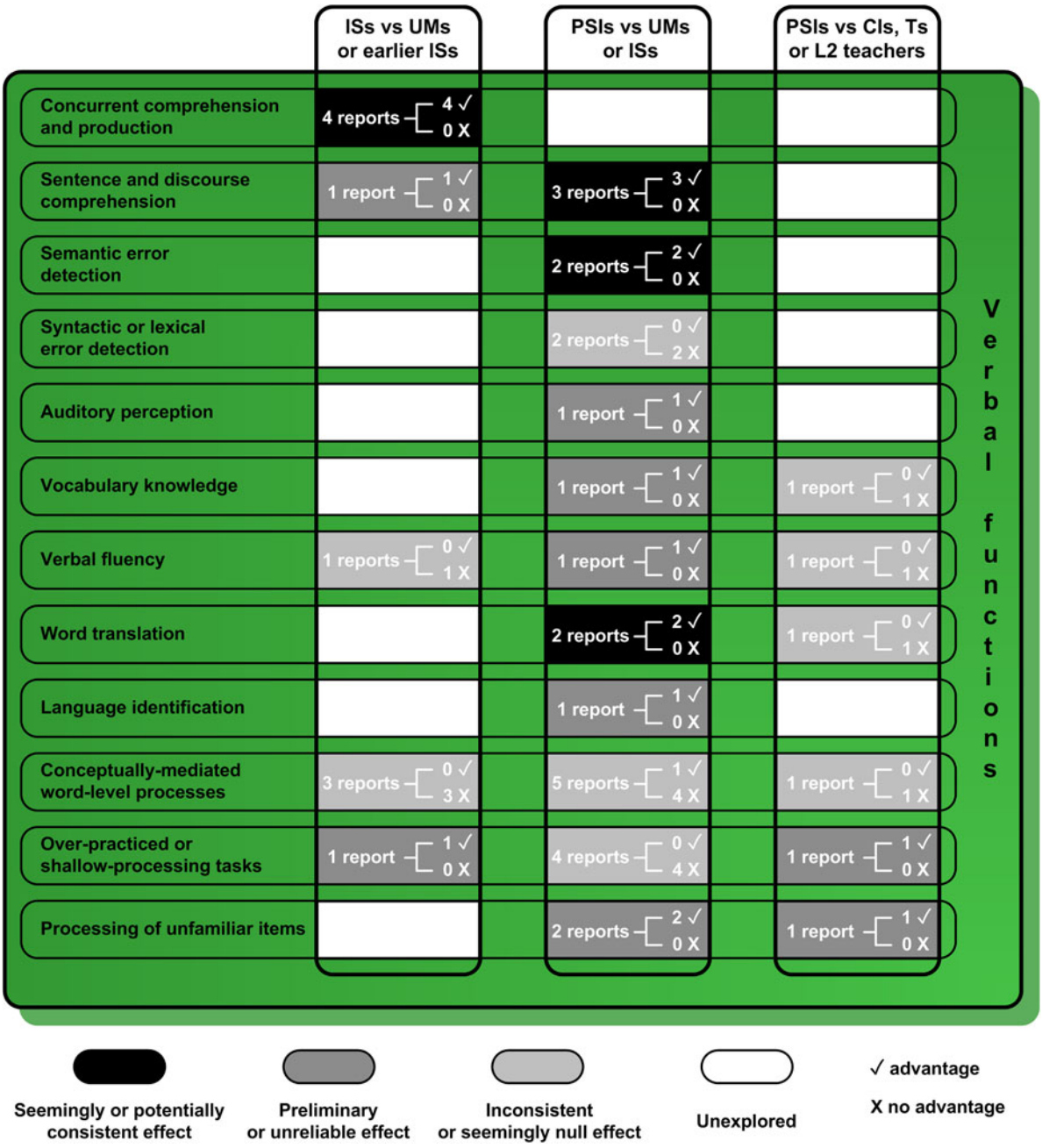

Fig. 1. (Color in Online) Key empirical patterns emerging from the results of verbal tasks. CIs: consecutive interpreters; ISs: interpreting students; L2 teachers: foreign-language teachers; PSIs: professional simultaneous interpreters; Ts: translators; UMs: untrained multilinguals.

Koshkin & Ossadtchi, 2017) – details can be found in a separate review within this special issue.

Evidence on verbal domains

Complementary evidence has revealed behavioral enhancements in specific verbal domains. Using a 15-minute-long SI task, Tzou, Eslami, Chen, and Vaid (2012) recorded the output of the participants, had their renditions judged in terms of two translation quality measures, and observed that second-year trainees outperformed first-year trainees and that the latter outperformed UMs. In another study (Hervais-Adelman et al., 2015), aspiring interpreters performed shadowing and interpreting tasks at the beginning and end of a 15-month-long SI program, with UMs being tested at the same time-points. Comparisons of performance between testing sessions showed that only the SIs had significantly improved their interpreting outcomes, whereas neither group exhibited changes in the shadowing condition. Taken together, these studies show that SI training is linked to a greater capacity for achieving linguistic correspondence between source and target texts.

More notably, additional evidence shows that early advantages can be tracked in specific sub-domains encompassed by SI. In an auditory shadowing experiment, Darò (1989) found that first-year ISs made significantly fewer errors than UMs. While these results should be taken with reserve due to the extremely low sample size

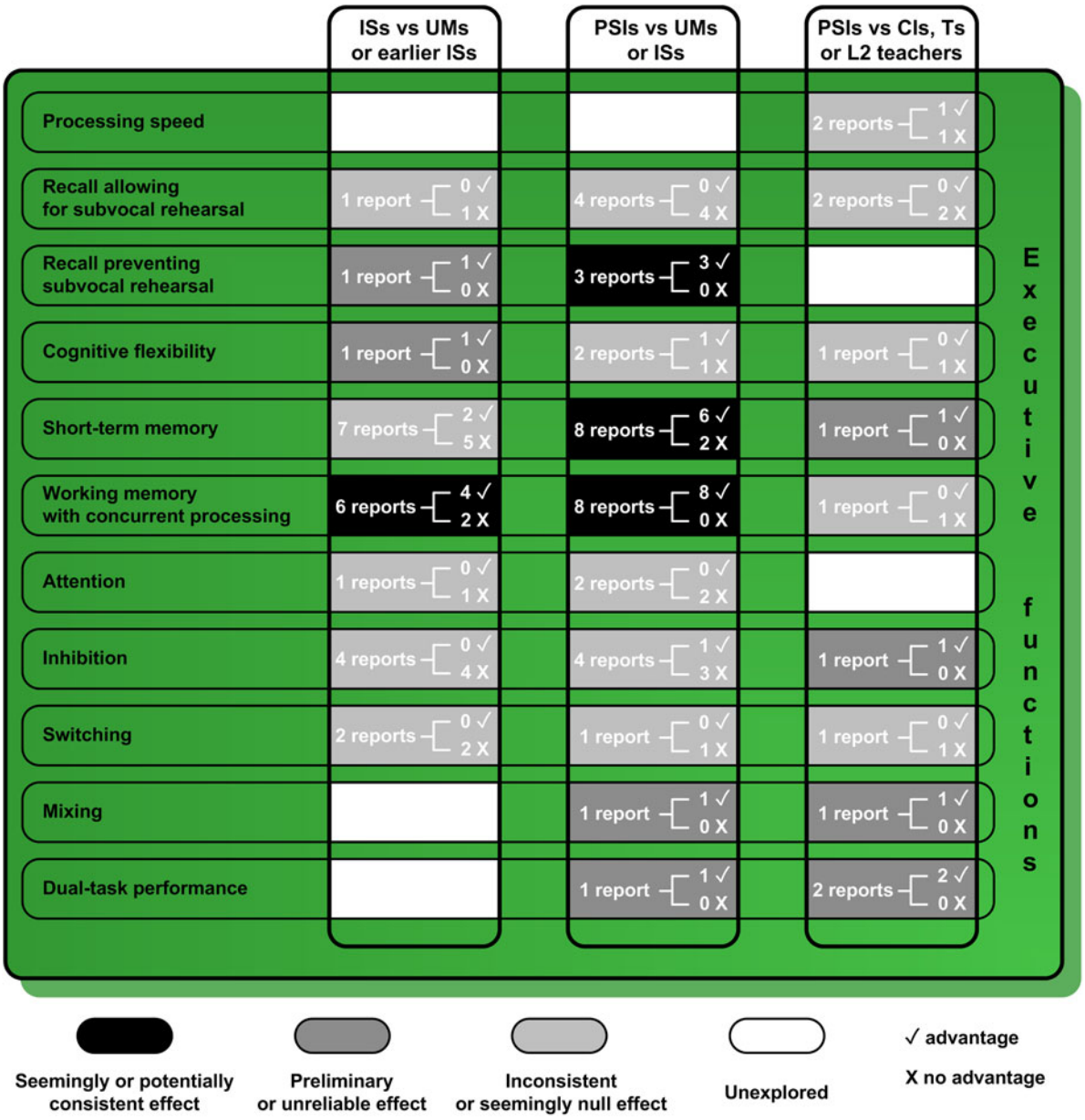

Fig. 2. (Color in Online) Key empirical patterns emerging from the results of behavioral executive tasks. CIs: consecutive interpreters; ISs: interpreting students; L2 teachers: foreign-language teachers; PSIs: professional simultaneous interpreters; Ts: translators; UMs: untrained multilinguals.

of both groups ($n \leq 5$), a more robust study found that a sample of interpreting students (combined with a few professionals) proved more precise than UMs and translators in respeaking – a form of shadowing whereby live discourse from audiovisual materials is immediately repeated into speech recognition software (Szarkowska, Krejtz, Dutka & Pilipczuk, 2018). Together, these studies suggest higher abilities in interpreting trainees for handling simultaneous comprehension and production, both inter- and intra-lingually.

For their part, Bajo, Padilla & Padilla (2000) assessed first-year ISs and UMs via semantic categorization and sentence comprehension tasks. While no between-group differences were reported in a first evaluation, the trainees were the only ones exhibiting either nearly-significant effects (trends) or significant improvements across all tasks upon retesting one year later. Still, these results should be taken with caution as they were obtained with small sample sizes ($n \leq 10$) and without a systematic assessment of potential confounds, such as L2 proficiency. Actually, not all studies have found differences between ISs and proficient bilinguals in linguistic tasks, as shown by measures of word reading speed (Chincotta & Underwood, 1998) and verbal fluency (Van de Putte et al., 2018).

Briefly, SI training seems to confer verbal processing advantages in some but not all domains examined so far. Suggestively, the same seems to be true of executive functions, as discussed next.

Evidence on executive domains

Linguistic processes in the bilingual mind constantly interact with (domain-general) executive mechanisms, including STM, WM, cognitive coordination, inhibitory control, mental-set shifting, self-monitoring, and attentional skills (Miyake & Friedman,

2012). Notably, performance in relevant tasks seems to increase in proportion to the subjects' bilingual abilities (Linck et al., 2014). Given that many executive domains are markedly taxed during SI training, at least some of them might be honed in ISs.

Beginner ISs have shown advantages over UMs in free-recall tasks, but only under articulatory suppression (Köpke & Nespoulous, 2006). Moreover, results from WM tasks requiring concurrent sentential processing systematically indicate better performance in both languages for ISs than UMs at the end (Tzou et al., 2012) and even at early stages (Köpke & Nespoulous, 2006) of their training. This WM advantage was corroborated in longitudinal studies testing ISs before and after five (Antonova Ünlü & Sağın Şimşek, 2018) and four (Chmiel, 2016) semesters of practice. However, only the first of these investigations was able to show the specificity of this effect – by testing UMs at the same time-points and finding no comparable results. Interestingly, this robust pattern does not emerge when intervening cognitive tasks involve non-verbal materials (Babcock, Capizzi, Arbula & Vallesi, 2017), highlighting its specificity for language-mediated operations. Neither does it seem to hold for sign-language ISs (Macnamara & Conway, 2014), arguably because of particularities of bimodal interpreting, such as sensorimotor differences between input-output interfaces for oral and signed languages. Nevertheless, these subjects do seem to exhibit training-related gains in WM coordination and transformation functions after four semesters, probably due to enhancements in managing joint comprehension and production of two languages (Macnamara & Conway, 2014).

STM assessments (via simple span tasks) have also yielded mixed results, likely reflecting discrepancies in the stimuli used and particularities of the samples tested in each study. While Tzou et al. (2012) reported better digit span for second-year ISs than UMs, the latter group was undifferentiated from beginner (Köpke & Nespoulous, 2006; Tzou et al., 2012) and advanced (Antonova Ünlü & Sağın Şimşek, 2018; Chincotta & Underwoord, 1998) ISs in various STM measures. Moreover, longitudinal evidence indicates that interpreting training can trigger improvements in STM for letters but not for digits or spatial locations (Babcock et al., 2017; Antonova Ünlü & Sağın Şimşek, 2018). Therefore, interpreting training does not seem to induce systematic STM advantages in the course of pre-professional preparation. Nevertheless, the great heterogeneity in the tasks and procedures used precludes any firm conclusions and calls for replication studies including all reported experimental approaches.

Inconclusive results have also been documented for different aspects of cognitive control. On the one hand, mental-set shifting skills seem to be enhanced in first-year ISs relative to UMs, and even more so in second-year trainees (Dong & Xie, 2014). On the other, assessments of attentional (Babcock et al., 2017), inhibitory (Dong & Xie, 2014; Köpke & Nespoulous, 2006; Van de Putte et al., 2018), and switching (Babcock et al., 2017; Van de Putte et al., 2018) skills do not point to any coherent behavioral advantage for ISs after one or even two years of training. As will be argued below, the absence of effects in these domains could reflect their marginal relevance for successful performance of SI (see "Discussion").

Roughly speaking, then, approximately 12 months of SI training seems enough to induce significant neurocognitive changes. Beyond neuroimaging outcomes, the most robust findings reveal improvements in SI proper as well as recall (especially under articulatory suppression), set-shifting and, above all, WM skills. However, assessments of STM, attention, inhibition, and switching have yielded mixed or consistently null results. Although the evidence for some of these patterns is limited, inconsistent, or based on unevenly reliable paradigms, it would thus seem only specific functions, directly taxed in the exercise of SI, benefit from sustained practice of this activity. Importantly, neuroanatomical, hemodynamic, and behavioral findings from pre/post-training experiments show that these changes are directly triggered by SI practice, thus ruling out their prior existence in prospective interpreters. Remarkably, at least some of those changes prove independent of other experience-related factors, such as L2 proficiency. An integrative treatment of these patterns will be offered in the "Discussion" section, after we consider additional empirical constraints from research on PSIs, as detailed below.

Evidence from professional interpreters

A second set of studies illuminates the issue by focusing on PSIs. This empirical corpus includes several experiments on verbal and executive functions, which we address separately in the following sections.

Evidence on verbal domains

Interpreting expertise has been linked to enhanced auditory perception. Elmer, Klein, Kuhnis, Liem, Meyer and Jäncke (2014) tested PSIs, professional musicians, and non-expert controls in a sound categorization task involving music-to-noise, speech-to-noise, and speech-to-music continua. PSIs were the only ones exhibiting a bias towards linguistic stimuli in the speech-to-music condition, and they also showed enhanced skills for categorizing musical items. Though very tentatively due to the study's modest sample sizes and reduced stimulus set, this pattern might reflect the development of enhanced, multifaceted echoic memory representations, arguably because successful SI hinges on efficient extraction and recognition of diverse auditory signals.

As regards linguistic processes proper, some reports have compared PSIs and UMs via sentence- and discourse-level tasks. Preliminary evidence from a self-paced reading paradigm (Bajo et al., 2000) suggested better sentence comprehension in the former population. A similar finding was reported by Yudes, Macizo, Morales and Bajo (2013), who found that PSIs outperformed UMs with similar L2 proficiency in answering open-ended questions after a text-reading task. Compatibly, in a small-scale study with reduced sample sizes, Dillinger (1990) compared PSIs and UMs in interpreting and recalling measures, and found that the former exhibited greater correspondence between the propositions of the source and target texts. Together, these studies suggest that experts in SI possess an elevated capacity to understand unfolding texts – another competence that is markedly taxed in the profession. Still, a better control of L2-related confounds would be necessary to assess the specificity of this pattern (see "Discussion" section).

Other studies have focused on error detection skills. In a dichotic listening test (Fabbro, Gran & Gran, 1991), PSIs recognized more semantic inaccuracies than ISs in translated sentence pairs, but the opposite was true for syntactic errors. Similarly, using a text-based task, Yudes et al. (2013) found that PSIs outperformed UMs in detecting semantic (but not lexical or syntactic) mistakes. Plausibly, the need to properly comprehend input could

involve greater sensitivity to semantic features across unfolding pieces of discourse.

Beyond such results, most evidence comes from lexical paradigms. A pivotal finding is that PSIs know more words than bilingual university students, but they present no differences relative to L2 teachers with similar amounts of professional experience (Christoffels, de Groot & Kroll, 2006). The same seems true of phonological and semantic fluency tasks. These have revealed better vocabulary-search skills in PSIs relative to UMs (Santilli, Gonzalez, Mikulan, Martorell, Muñoz, Sedeño & García, 2018) but not as compared to L2 teachers (Stavrakaki et al., 2012). Therefore, interpreting expertise may be related to greater word knowledge and fluency, but such an effect can also emerge through other sustained practices taxing bilingual verbal skills. Importantly, however, since both groups in Santilli et al. (2018) were matched in key L2-related variables (competence, age of acquisition, years of study, weekly exposure), that effect seems directly – though non-exclusively– related to interpreting expertise, arguably due to the continual need to retrieve specific words under pressing time constraints (Chernov, 2004).

Moreover, two studies indicate that PSIs also present advantages in word translation. First, Christoffels et al. (2006) reported that PSIs were faster than UMs in both L2-L1 and L1-L2 translation, but their performance was similar to that of L2 teachers. While the authors attributed the latter pattern to high L2 proficiency in both professional groups, more recent evidence suggests otherwise. Indeed, Santilli et al. (2018) found that PSIs had shorter response times than UMs in both translation directions despite being matched in L2 competence, age of acquisition, years of study, and weekly exposure. Also, PSIs proved more accurate and faster than UMs with similar language proficiency at detecting whether serially presented words belonged to their L1 or L2 (Aparicio, Heidlmayr & Isel, 2017). Thus, sustained engagement in interlingual reformulation by PSIs may optimize cross-linguistic processing and language identification skills, even beyond the impact of L2 proficiency.

However, other operations within bilingual memory do not seem boosted in interpreters. Indeed, two separate experiments reported non-significant differences between PSIs and UMs or L2 teachers in picture naming (Christoffels et al., 2006; Santilli et al., 2018). Neither are PSIs characterized by consistent enhancements in other conceptually-mediated word-level processes. Semantic congruency judgment tasks involving pairs of (real) words have yielded mixed results, with one study showing interpreter advantages relative to L2-matched UMs (Elmer & Kühnis, 2016) and another one yielding non-significant behavioral differences and distinct neurophysiological responses in only one out of four conditions (Elmer et al., 2010). Null effects of interpreting experience were also observed for semantic categorization of real words (Bajo et al., 2000). However, the latter study showed that PSIs did outperform UMs in categorizing NON-TYPICAL exemplars (Bajo et al., 2000). Though undermined by its relatively low sample size and small number of trials, this result might suggest that the effects of SI experience on conceptual mechanisms may be confined to unfamiliar lexical fields.

Interestingly, a similar pattern seems true of lower-order language skills. Widely experienced PSIs and UMs of comparable L2 proficiency have similar outcomes in over-practiced or shallow-processing tasks, such as repeatedly counting from one to ten (Signorelli, Haarmann & Obler, 2012), performing lexical decisions on real words (Bajo et al., 2000), reading such items in L1 or L2 (Santilli et al., 2018), or repeating them, even under distractive conditions (Hiltunen et al., 2016). Conversely, PSIs do outperform UMs when asked to recognize (Bajo et al., 2000) or repeat (Signorelli et al., 2012) NON-words, and they also surpass L2 teachers when asked to recall such stimuli (Stavrakaki et al., 2012). Accordingly, PSIs' enhancements in form-level processing may be evident only for unfamiliar, non-rotely-learned items – which are arguably highly recurrent in professional SI settings.

In sum, ONLY SOME bilingual verbal skills are behaviorally enhanced in PSIs. Relative to UMs, these experts would appear to possess superior skills for auditory perception, discourse comprehension, and semantic-error detection. Moreover, although their wide vocabulary may not exceed that of other language professionals, they seem characterized by greater efficiency for time-constrained lexical search, word translation, and processing of unfamiliar items. Nevertheless, they possess no clear advantages in conceptually-mediated word-level processes. Finally, their expertise seems to have no influence on lexical- and syntactic-error detection or shallow-processing tasks. Therefore, linguistic enhancements in this population seem confined to those mechanisms directly taxed in professional settings (see "Discussion" below).

Evidence on executive domains

Additional results have been reported for executive domains. Numerous studies assessing STM[3] and WM have consistently revealed advantages for PSIs over UMs. Although digit-span tasks have yielded significant (Bajo et al., 2000), marginal (Stavrakaki et al., 2012), and null (Köpke & Nespoulous, 2006; Santilli et al., 2018) effects, STM advantages have been found for letters (Babcock & Vallesi, 2017), spatial locations in visual matrices (Babcock & Vallesi, 2017), non-words (Stavrakaki et al., 2012), and words in L1 and L2 (Christoffels et al., 2006). Compatibly, PSIs outperformed translators in a letter memory task (Henrard & Van Daele, 2017). Considering that STM effects prove much less systematic in ISs (see above), this might suggest that gains in these domains tend to consolidate once expert standards are attained (see "Discussion").

Superior memory performance has also been shown in span tasks involving concurrent cognitive operations, such as reading ever-larger groups of phrases (Bajo et al., 2000; Christoffels et al., 2006), uttering written sentences (Signorelli et al., 2012; Yudes, Macizo & Bajo, 2011; Yudes et al., 2013), producing spontaneous statements (Christoffels et al., 2006), judging sentence sensibility (Chmiel, 2016), and performing mathematical operations (Babcock & Vallesi, 2017). Therefore, PSIs seem characterized by increased ability to transiently store information while performing additional tasks, a critical requisite for successful SI. However, results from a listening span task showed no differences between PSIs and L2 teachers (Stavrakaki et al., 2012), suggesting that other forms of expert bilingual training may also involve WM gains. Therefore, in line with evidence of enhanced WM in consecutive interpreters (Dong & Liu, 2016), it would seem that one and the same executive domain may significantly benefit from different professional activities taxing dual-language mechanisms.

Evidence from free- and cued-recall paradigms reinforces the view that mnesic advantages in PSIs are related to the particular demands they encounter in professional settings. When participants must simply recall as many words as possible from a

[3]Note that most of the studies including simple and/or complex span tasks discuss them both by reference to WM. However, only the latter tap on such a domain, whereas the former actually measure STM –for a detailed treatment, see Aben et al. (2012).

given list, no differences emerge between PSIs and UMs (Bajo et al., 2000; Köpke & Nespoulous, 2006; Signorelli et al., 2012; Stavrakaki et al., 2012). The same is true in comparisons with L2 teachers or consecutive interpreters, both for word lists (Hiltunen et al., 2016) and prose passages (Hiltunen & Vik, 2017). Conversely, when the task involves articulatory suppression (by repeating a predefined syllable during encoding), PSIs exhibit significantly better outcomes than UMs (Bajo et al., 2000; Köpke & Nespoulous, 2006). In fact, they even outperform advanced ISs in complex (though not in standard) suppression conditions (Yudes, Macizo & Bajo, 2012). Therefore, recall efficiency in this population only seems significantly greater when subvocal rehearsal is impeded – i.e., in scenarios that replicate the processing conditions of actual SI. In fact, whereas interpreting performance correlates with WM under articulatory suppression, no such association emerges when subvocal rehearsal is allowed (Injoque-Ricle et al., 2015).

Likewise, PSIs seem better than UMs and other language professionals (translators and consecutive interpreters) at handling specific cognitive control functions. They were observed to perform faster on a dual task requiring joint identification of tones and shapes (Becker et al., 2016; Strobach, Becker, Schubert & Kühn, 2015) and in a dual (visual-auditory) version of the *n*-back-task – where participants had to identify any item that matched stimuli presented one, two, or three trials earlier (Morales, Padilla, Gomez-Ariza & Bajo, 2015). Therefore, expertise in SI would seem related to better coordinating functions, a critical component of successful SI (Chernov, 1994, 2004; García, 2014; Gerver, 1976). In particular, this skill would be needed to manage joint input and output demands while refreshing critical information in memory segment after segment.

However, research on other executive functions has produced inconclusive findings. Comparisons of overall processing speed between PSIs and other language professionals have yielded both significant and null results (Christoffels et al., 2006; Henrard & Van Daele, 2017). Also, whereas the PSIs assessed by Yudes et al. (2011) proved more efficient and precise than UMs (matched for L2 proficiency) at the Wisconsin Card-Sorting Test (a classical measure of mental-set shifting skills), no between-group differences were observed by Santilli et al. (2018) on the same task. While this discrepancy might be partly related to the analysis of only one outcome measure (number of correctly inferred categories) in the latter study, further evidence attests to the unsystematic impact of SI expertise on cognitive control. Indeed, when both groups are asked to switch between two tasks (color and shape discrimination), PSIs exhibit smaller mixing costs but not smaller switching costs (Babcock & Vallesi, 2017), even when compared with translators and consecutive interpreters (Becker et al., 2016). Interestingly, the former measure is negatively associated with grey matter density in the left frontal pole, a region implicated in cognitive control (Becker et al., 2016). Neither did PSIs differ from translators in a plus-minus task assessing flexibility (Henrard & Van Daele, 2017). This pattern is consistent with the demands of professional SI, where intrusions must be minimized during a single dual-language activity, without a need to alternate between tasks involving different modalities.

Moreover, it seems that PSIs possess no advantages in tasks assessing aspects of attention and inhibition. Research on alerting and orienting functions shows that attentional domains are not particularly honed in these subjects, either in terms of efficacy (accuracy) or efficiency (reaction times) (Babcock & Vallesi, 2017; Morales et al., 2015). Similarly, no interpreter advantages have emerged in conflict-resolution experiments that assessed the capacity to suppress the effects of lexical (Babcock & Vallesi, 2017; Köpke & Nespoulous, 2006) and locational (Yudes et al., 2011) information on perceptually-driven processes – but see Henrard and Van Daele (2017) for different results. In fact, evidence from a Stroop task shows that PSIs respond faster but significantly less accurately than UMs (Aparicio et al., 2017). Though based on varyingly robust tasks, these null and negative results might reflect the fact that successful practice of SI does not require active suppression of interference among linguistic, spatial, and perceptual modalities.

Overall, as is the case with verbal domains, ONLY SOME executive mechanisms seem enhanced in PSIs. Although the evidence is not fully consistent, these experts appear to possess elevated STM and WM skills, higher recall capacity under articulatory suppression, and greater abilities to perform simultaneous tasks and prevent mixing between alternating processes. However, results concerning task-switching, attentional, and inhibitory functions indicate null effects of interpreting experience. Once again, among all executive domains, only those distinctively taxed during SI appear to be boosted in interpreters (see "Discussion" below).

Discussion: On the adaptability of neurocognitive systems in bilinguals

Beyond its relevance for understanding the distinguishing traits of ISs and PSIs, the evidence above sheds light on the adaptive capacity of cognitive systems in bilinguals. In particular, it suggests that (at least some of) the verbal and executive advantages observed in these populations may be (i) specifically attributable to the practice of SI, (ii) traceable shortly after the onset of field-specific training, (iii) non-generalizable beyond directly taxed functions, (iv) mutually independent, and (v) uninfluenced by other bilingual-experience-related factors.

Admittedly, most of the studies reviewed are moot on the "self-selection issue," as they cannot ascertain whether it is accruing SI expertise that boosts putative domains or if subjects who thrive in the profession are those possessing previous advantages in relevant skills (Christoffels & de Groot, 2005). However, some results seem compatible with the former alternative, albeit preliminarily. First, a study on executive functions (including STM and updating tasks) revealed no differences between UMs and aspiring interpreters about to start their training (Rosiers, Woumans, Duyck & Eyckmans, 2019). Second, as seen above, longitudinal research comparing ISs before and after periods of intensive practice (and UMs at the same time points) has shown increased performance for the trainees in key SI-related functions, such as WM (Antonova Ünlü & Sağın Şimşek, 2018), in addition to structural (Hervais-Adelman et al., 2017) and functional (Hervais-Adelman et al., 2015) brain changes in critical hubs. Complementarily, various neurocognitive effects in PSIs are significantly associated with their hours of practice (Elmer, Hänggi & Jäncke, 2014) and their years of professional experience (Santilli et al., 2018), indicating that the longer the experience in SI, the greater its effects on particular cognitive systems. In principle, then, sustained exposure to extreme processing demands may constitute a specific (albeit partial) determinant of the particular patterns reviewed above. Note, however, that causal evidence is markedly limited in the field and that some of the effects observed in our target populations have also been reported in UMs. Therefore, more research is urgently needed to establish the extent to

which these distinctive features of ISs and PSIs are causally and specifically related to SI experience.

Moreover, relevant cognitive systems seem to be RAPIDLY RESPONSIVE to such stringent conditions. Significant neural and behavioral enhancements can be observed in subjects who completed as little as two semesters of SI training, with the most striking evidence coming from pre/post designs (e.g., Antonova Ünlü & Sağın Şimşek, 2018; Hervais-Adelman et al., 2015, 2017; Van de Putte et al., 2018). Therefore, when subjected to high demands, cognitive systems in bilinguals do not remain unaffected until expert standards are reached; rather, they exhibit swift adaptations visible in the short term, even in adult subjects. This observation extends previous evidence of dynamic cognitive effects in bilinguals across the lifespan (Malt, Li, Pavlenko, Pavlenkou & Ameel, 2015), showing that specific, highly demanding experiences may trigger such changes at a fast pace.

Still, some particular domains might require longer periods of SI practice to exhibit significant enhancements. For example, verbal fluency advantages have been observed in PSIs (Santilli et al., 2018) but not in ISs (Van de Putte et al., 2018) relative to balanced UMs. Similarly, whereas WM skills are systematically boosted both in PSIs and ISs, advantages in STM would seem to be more consistent in the former population. If these effects indeed appear only in the course of professional, as opposed to formative, stages of these subjects' careers, it might be that specific cognitive systems in bilinguals feature distinct adaptive time-courses – a hypothesis with great potential for future investigation.

Be that as it may, a number of relatively clear patterns can be identified in the evidence from PSIs. As suggested above, behavioral improvements in this population are observed only in putative functions that are distinctly taxed during SI – e.g., discourse comprehension, word translation, time-constrained lexical search, STM, WM, dual-task processing, and recall under articulatory suppression (Chernov, 2004; Christoffels et al., 2006; Pöchhacker, 2004). Instead, the domains yielding null effects do not seem to undergo elevated demands in this translation modality. For example, SI does not rely on a high capacity for retrieving the names of visual stimuli (as critical information is almost exclusively conveyed aurally) or performing shallow, context-free tasks (Santilli et al., 2018). This might account for the non-significant results observed in picture-naming and word-naming paradigms. Neither does SI seem to distinctively tax inhibitory or task-switching mechanisms. In fact, these domains appear to be only marginally relevant for such an activity, which requires both languages to be constantly active rather than alternately inhibited (Dong & Xie, 2014; Yudes et al., 2011), without a need to unexpectedly shift between disparate processing modalities (e.g., visual, acoustic, linguistic). Likewise, although the relationship between SI and DIVIDED ATTENTION is well established (Pöchhacker, 2004), the specific strategies developed in the course of training (Cowan, 2000) might arguably enable PSIs to circumvent high demands on the more focal and sustained attentional resources assessed so far in the field. However, more exhaustive assessments of multiple attentional domains would be needed to reach a definite conclusion.

Therefore, although myriad verbal and executive mechanisms constantly interact during SI, their expertise-related effects seem to retain DEMAND-BASED DOMAIN-SPECIFICITY. In other words, enhancements in a specific linguistic or executive subfunction (e.g., verbal fluency or WM) do not necessarily percolate to the entirety of its overarching cognitive system, even if the latter encompasses highly interrelated mechanisms. Of note, similar patterns have been reported in other experts, such as mnemonists evincing better performance in WM and verbal memory but not in visual memory tasks (Maguire, Valentine, Wilding & Kapur, 2002). Even more relevantly, a study on consecutive interpreting students showed that, as opposed to WM, updating efficiency was specifically enhanced by field-specific training and represented a more robust predictor of post-training performance, suggesting that cognitive gains were predominant for those domains that are more robustly correlated with interpreting outcomes (Dong, Liu & Cai, 2018). In the same vein, despite contradictory results (Lehtonen, Soveri, Laine, Järvenpää, de Bruin & Antfolk, 2018), the demands of lifelong bilingualism have been claimed to be associated with advantages in ONLY SOME executive domains (Bialystok, Craik & Luk, 2012), and even in ONLY SOME dimensions within circumscribed functions, such as WM (Calvo, Ibáñez & García, 2016). Compatibly, particular operations in bilinguals are subserved by relatively independent neural substrates (Chee, Soon & Lee, 2003; Klein, Zatorre, Chen, Milner, Crane, Belin & Bouffard, 2006) which can be dissociated by brain lesions (García, 2015b) or cortical stimulation (Lucas, McKhann & Ojemann, 2004), further attesting to their partial functional autonomy. In combination, these findings align with the view that when heavy demands are placed on specific cognitive functions, associated boosts are characterized by restricted (if not altogether null) cross-domain generalizability.

In line with the above claim, note that some of the reported VERBAL AND EXECUTIVE EFFECTS SEEM TO BE POTENTIALLY INDEPENDENT FROM EACH OTHER. Although linguistic and executive operations interact profusely during SI (Christoffels, de Groot & Waldorp, 2003), advantages for PSIs do not emerge to the same level in verbal and STM tasks (Christoffels et al., 2006) and they emerge in subjects with low and high WM capacity (Yudes et al., 2013). Moreover, lexical processing enhancements remain significant even when PSIs are matched with UMs for overall executive abilities (Santilli et al., 2018). In fact, findings from graphical modeling highlight translation efficiency and STM capacity as independent subdomains which play non-co-dependent roles in SI performance (Christoffels et al., 2003). Taken together, these preliminary findings might also speak to the relative adaptive autonomy of linguistic and executive mechanisms in bilinguals – although additional evidence would be necessary to more solidly assess the robustness of this pattern.

Interestingly, too, verbal and executive domains seem to be differently affected by the bilingual experience, in general, and SI experience, in particular. The development of bilingual skills has been linked to advantages in certain executive domains – e.g., non-verbal WM (Calvo et al., 2016)– and disadvantages in certain linguistic domains – e.g., verbal fluency (Bialystok et al., 2012). However, increased dual-language processing demands associated with SI experience do not uniformly augment these effects; rather, while they seem to extend some executive advantages – e.g., in WM (Antonova Ünlü & Sağın Şimşek, 2018) – , they appear to attenuate or reverse linguistic disadvantages – e.g., in verbal fluency (Santilli et al., 2018). Therefore, the sustained demands associated with SI experience seem to involve particular trajectories of linguistic and executive adjustments which cannot be fully reduced to extensions of general bilingualism-related effects.

Finally, as argued at the outset, diverse processes in bilinguals are susceptible to the impact of experience-related factors, such as age of L2 acquisition or the degree of exposure and attained

proficiency in that language (e.g., Bosma et al., 2017; Grant et al., 2015). The present review indicates that, in addition to how early or how proficiently an L2 was acquired, another critical determinant in the sustained development of bilingual systems is the INTENSITY OF THE DEMANDS placed on them. Admittedly, some studies have failed to report whether their IS or PSI samples were matched for L2 proficiency/experience with UMs (e.g., Bajo et al., 2000; Darò, 1989; Fabbro et al., 1991; Hiltunen et al., 2016; Szarkowska et al., 2018; Tzou et al., 2012). Although interpreter advantages in those cases may well be reflecting the impact of higher language competence, most reports have effectively ruled out this confound (e.g., Aparicio et al., 2017; Babcock & Vallesi, 2017; Elmer & Kühnis, 2016; Hervais-Adelman et al., 2015, 2017; Morales et al., 2015; Santilli et al., 2018; Signorelli et al., 2012; Van de Putte et al., 2018; Yudes et al., 2011, 2013), suggesting that such effects could actually be specifically driven by experience in this particular activity.

That being said, note that other populations characterized by different intense forms of bilingual training/practice (e.g., translators, consecutive interpreters or L2 teachers) have sometimes been shown to possess performance levels similar to those obtained by ISs or PSIs. This has been observed for specific domains, such as vocabulary knowledge, word translation, picture naming (Christoffels et al., 2006), verbal fluency (Stavrakaki et al., 2012), WM (Stavrakaki et al., 2012), cognitive flexibility (Henrard & Van Daele, 2017), and recall without articulatory suppression (Hiltunen et al., 2016; Hiltunen & Vik, 2017). Although such patterns suggest that SI experience is not the only factor that could lead to (some of) the reported effects, they do not invalidate the claim that SI experience is directly associated with the reported enhancements; as it were, a relationship between factors A and Z is not falsified by evidence that Z is also related to B. Still, establishing which, if any, of the observed effects are actually specific to this particular trade opens major avenues for future research, especially in light of evidence showing that PSIs can actually outperform L2 teachers, translators, and/or consecutive interpreters in measures of dual-task performance and processing speed (Becker et al., 2016; Henrard & Van Daele, 2017; Strobach et al., 2015). Be that as it may, the evidence does indicate that particular language use patterns, especially when characterized by sustained elevated demands, should be factored in as an important variable modulating cognitive function in bilinguals (García, Ibáñez, Huepe, Houck, Michon, Gelormini & Rivera-Rei, 2014).

Limitations, challenges, and avenues for further research

Despite its richness and expansion, this research area faces important limitations and challenges. First, except for the studies signaled out as featuring low sample sizes, most findings comes from groups of 15 to 25 subjects. While such numbers are common practice in cognitive science at large, they were rarely established through power estimations or other objective approaches, which may compromise the reliability of reported results (Button, Ioannidis, Mokrysz, Nosek, Flint, Robinson & Munafò, 2013). Therefore, a future challenge lies in testing whether the patterns emerging so far can be robustly replicated with larger groups.

Also, different studies often refer to different cognitive domains under the same label (see footnote 2 for the case of STM vs. WM). It would thus be greatly useful for a consensus group to form and provide unifying terminological criteria for the field, thus simplifying the joint analysis of studies based on target functions – as done in the present review.

Moreover, only some of the assessed domains have been consistently examined across studies through validated tasks. Although ad hoc instruments and stimulus sets created exclusively for a particular experiment are invaluable and often indispensable to address specific research questions, some of the available studies are sub-optimal in terms of the number of trials for a given experimental condition or the handling of confounds between allegedly comparable stimulus sets. In this sense, the field could benefit from a more systematic application of standardized instruments, when available, and the public sharing of scripts for strictly controlled paradigms.

An additional issue concerns the sensitivity of the dependent variables considered so far in the literature. For example, as noted earlier, measures of accuracy and/or reaction time have yielded no evidence of enhanced inhibitory skills in either ISs (Dong & Xie, 2014; Köpke & Nespoulous, 2006; Van de Putte et al., 2018) or PSIs (Babcock & Vallesi, 2017; Köpke & Nespoulous, 2006; Yudes et al., 2011). However, electrophysiological results suggest that training in at least one interpreting modality (consecutive interpreting) may distinctively modulate event-related potentials underlying monitoring and inhibitory functions (Dong & Zhong, 2017). Insofar as neural signatures may reveal processing advantages despite null behavioral differences, specific effects of SI experience on inhibitory processing and other seemingly unaffected domains might also be tracked through methods which prove sensitive to earlier (pre-response) processing windows. More research would be needed to test this conjecture.

Finally, available studies vary greatly in the amount and quality of information they provide on the participants. Most reports offer few or no details about the subjects' years of experience, type and length of training, hours of weekly practice, preferred interpreting direction, and other generalities of their language history. The incorporation of standardized questionnaires, as those developed for general assessments of bilingualism (e.g., Li, Zhang, Tsai & Puls, 2014), would represent a major asset for the sustained growth of the field.

Looking forward, continued research on the relationship between SI expertise and bilingualism could illuminate several important questions. First, what determines whether expertise-related effects manifest similarly in both languages (e.g., Santilli et al., 2018) or only in one of them (e.g., Elmer et al., 2010)? Second, given that challenging cognitive activities, including bilingual processing, have been associated with increased cognitive reserve (Calvo, García, Manoiloff & Ibáñez, 2015), might sustained practice of SI constitute another protective factor for age-related cognitive decline, or even a component in intervention programs for bilingual patients with STM impairments, as proposed by Stavrakaki et al. (2012)? Third, which of the reported effects are specific to SI and which ones might also be associated to other oral translation modalities, such as consecutive interpreting (Dong & Liu, 2016)? Fourth, given that some subjects in the PSI samples considered also possessed experience in consecutive interpreting, future studies could examine the extent to which the reported effects are influenced by cumulative experience in both interpreting modalities. Finally, as previously stated, further pre/post experiments are needed to better understand which, if any, of the observed patterns are causally attributable to this particular activity.

Conclusion

Research on prospective and professional simultaneous interpreters offers a unique testing ground to characterize the adaptive potential of cognitive systems in bilinguals. When continually faced with the extreme demands of SI, bilinguals appear to exhibit cognitive changes that are relatively fast in their emergence, restricted to distinctly taxed functions, and independently operative in verbal and executive domains. Moreover, SI practice might play a specific role in such findings, even beyond the contributions of other experience-related factors, such as L2 proficiency or age of acquisition. In future years, additional research on this population will be crucial to better understand the bilingual mind and its capacity for usage-driven changes.

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