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How does the bilingual experience sculpt the brain?

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Preface

The ability to speak two languages often marvels monolinguals, although bilinguals report no difficulties in achieving this feat. Here, we examine how learning and using two languages affects language acquisition and processing and various aspects of cognition. We do so by addressing three main questions. First, how do infants that are exposed to two languages acquire them without apparent difficulty? Second, how do monolingual and bilingual language processing differ in adults? Last, what are the collateral effects of bilingualism on the executive control system across the life span? Research in all three areas has not only provided some fascinating insights into bilingualism but also revealed new issues related to brain plasticity and language learning.

Introduction

The pervasive presence of bilingualism shows that humans can learn two languages without apparent difficulty. Bilingualism is, however, difficult to define, as it encompasses a broad typology of speakers. Indeed, the acquisition of two languages may occur in many different contexts. People can learn two languages from birth (such individuals are known as simultaneous bilinguals, as both languages are learned at the same time). Alternatively, they can learn a second language later in life under formal instruction, in an immersion environment as a result of immigration, or in one of many other situations (such individuals are known as successive bilinguals). Additionally, among bilinguals, individuals can show considerable variation in the proficiency levels attained in their languages: whereas some show equal proficiency in both languages, others have a clear dominance in one of their languages[1]. These differences in learning contexts and proficiency level pose methodological challenges in bilingual studies (BOX 1).

Most bilingual research has focused on adult successive bilinguals, specifically on second language processing in the brain and how it is affected by the age at which the second language is acquired and the amount of exposure an individual has to that language. However, the study of bilingualism should also examine the impact of learning a second language on the acquisition and processing of the first language (in successive bilinguals), how the simultaneous learning of two languages affects the development of these languages (in simultaneous bilinguals), and the effects of bilingualism on the mechanisms of cognitive functioning outside the language domain. These are the main topics of the present article.

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Note that we only briefly cover issues related to learning a second language and the brain representation of two languages (see Refs 2-4 for reviews of these topics and BOX 2).

In the first section of this review, we focus on the language learning challenges faced by infants who are exposed to two languages from the beginning of life (sometimes called 'bilingual first language acquisition'[2]). The studies show that although the pattern of development is not fundamentally different in bilingual versus monolingual populations, the bilingual input induces some specific learning adaptations. In the second section, we will review studies that have addressed how learning a second language affects first language comprehension and production processes. These studies have mostly focused on young adult successive bilinguals. Finally, in the third section, we will discuss the potential collateral effects of bilingualism on domain-general executive control processes. The studies discussed in this section take a life-long perspective examining the performance of simultaneous and successive bilingual infants, children, young adults and elderly.

Language development in bilingual infants

Learning a language involves acquiring knowledge about the specific properties of that language. Infants have to learn the specific phoneme repertoire of the language, the words and the sophisticated grammatical information (such as the location of articles and prepositions), among many other features. For example, infants learning Japanese have to learn that articles and prepositions come after nouns, whereas infants learning English or Spanish have to learn the opposite. The developmental trajectory of acquiring a language in a monolingual environment is relatively well described[3, 4], but much less is known about language learning in infants raised in a bilingual (or multilingual) environment. Nevertheless, as we will argue, linguistic development in monolingual and bilingual contexts is similar despite the fact that the 'bilingual experience' is associated with some specific adaptations in the learning process.

There are two main differences between acquisition of a language in a monolingual context and acquisition of two languages in a simultaneous bilingual context. The first of these is quantitative, as bilingual infants must learn two linguistic codes instead of just one (that is, two sets of phonemes, two lexicons and two grammatical systems). Furthermore, presumably learning both codes needs to be achieved in the context of a reduced exposure to each of the two languages, as there is no reason to assume that, overall, bilingual parents speak more to their children than do monolingual parents.

The second difference is qualitative and relates to bilinguals' requirement to perform specific computations that monolinguals do not have to perform. Bilingual infants need to be able to notice the existence of more than one 'type of speech' and, then, to adequately sort and parse the information corresponding to each of these objects. Thus, the learning of two (or more) language systems runs in parallel with the need to sort and properly compute the information for each language. Given these important quantitative and qualitative differences between monolingual and bilingual learning contexts, the issue is analyzing their effects on the first language(s) learning (BOX 3).

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Language discrimination

A potential challenge faced by bilingual infants is the need to discriminate the languages they are exposed to. A failure to discriminate may cause difficulties in cracking the linguistic codes of the two languages. However, language discrimination does not seem to pose a major difficulty for infants. Several studies have shown that at birth humans prenatally exposed to monolingual or bilingual inputs are able to differentiate two languages, provided they sound very different, such as Tagalog and English[5], or Dutch and Japanese[6]. This capacity to differentiate two languages is not restricted to humans. Previous studies have reported that cotton-top tamarin monkeys[7]as well as Long-Evans rats [8]can discriminate Japanese and Dutch. Thus these initial language discrimination capacities may have nothing to do with previous exposure to language.

The ability to discriminate between more-similar languages, like English and Dutch or Spanish and Italian, appears a bit later, at around 4–5 months of age, in both monolingual and bilingual infants, if they have been previously exposed to at least one of the languages in question[9-11]. Thus, it seems that infants are able to notice that there are two different language systems in their environment at an early stage, and that early exposure to a bilingual environment does not hinder this ability.

The bilingual experience does, however, seem to affect the way language discrimination is achieved. One study[9]involving bilingual and monolingual 4–5 month-olds showed that monolingual infants oriented faster to a familiar language than to an unfamiliar one, whereas bilingual infants showed the opposite pattern (Figure 1). At present, we do not have a clear understanding of the underlying mechanisms that lead to such differences.

The existence of differences between the mechanisms that underlie language discrimination in bilinguals and monolinguals is supported but other observations. Information about the properties of speech is conveyed not only by sounds but also by articulatory gestures[12, 13]. Interestingly, two studies have reported that bilinguals and monolinguals differ in their capacity to visually discriminate different languages from watching silent videos of people speaking these languages[14, 15]. One of these studies showed that French- or English-speaking monolingual infants and French and English-speaking bilingual infants (aged 4- and 6-months old) were able to discriminate people speaking French versus English from watching silent videos. Crucially, however, this ability was only retained at 8 months of age by the bilingual infants[14]. In the other study, the same silent videos were presented to 8-month old Spanish- or Catalan-speaking monolingual and Spanish-Catalan bilingual infants, that were never previously exposed to French or English. Again, only bilinguals discriminated the two languages[15]. Together, these observations suggest that bilingual infants show a specific adaptation in the attentional system that allows them to perceive and track relevant information in two different systems.

In summary, these results reveal that monolingual and bilingual infants show similar developmental trajectories in terms of language discrimination; however, the bilingual input seems to tune some of the mechanisms behind this ability.

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Establishment of the phoneme repertoire and word learning

The fact that bilingualism does not hinder the ability to discriminate languages does not necessarily imply that a bilingual experience does not affect language learning. Investigation of language learning in this context began relatively recently and has focused primarily on two crucial issues: the acquisition of the phonetic system and early word learning.

One of the best-described early stages of monolingual development is the establishment of the phoneme repertoire[3, 16]. Most phonemes become established during the second half of the first year of life, and on the approach to this milestone, infants show decreasing sensitivity to speech sounds that are not present in their environment and an increasing sensitivity to speech sounds that are associated with the language(s) they are exposed to[17]. The available evidence reveals that there are no major differences in the time required by bilinguals and monolinguals to establish their phoneme repertoires, even though bilinguals in fact learn two sets of phonemes[18-21]. The time it takes to establish the phoneme repertoire in bilinguals is remarkable given that, in monolinguals, low-frequency phonemes take longer to become established than highly frequent ones[22](note that bilingual studies have not explored the acquisition of very infrequently occurring phonemes). Indeed, one may have expected that bilingualism would induce a general delay in the acquisition of the phoneme repertoire, as presumably bilinguals receive less exposure in any one of their languages than monolinguals do in their one language.

The second major milestone in language development for which substantial data exist for monolinguals and bilinguals concerns word learning. Word learning is a complex process. In a highly simplified way it can be said that it consists in assigning a concept to a word form. As described below, a priori, the bilingual experience may affect the ability to determine word forms and assign concepts to them.

The identification of words forms in speech is heavily dependent on the computation of phonological regularity distributions in the absence of the clear word boundaries in spoken (but not written) language. One of the regularities that young monolingual and bilingual infants have to extract is combinations of phonemes that signal word endings. For example, infants learning English will eventually learn that ‘tr’ does not occur at the word end, although it can occur at the word onset. Similarly ‘rt’ can be a word offset but not a word onset. Thus, ‘putr’ would not conform to the pattern of English words, but ‘purt’ would. In the second half of the first year of life, monolingual infants start showing sensitivity to this kind of properties of the words of their first language[23]. By 9 months of age, monolingual infants discriminate sequences of sounds that occur in their native language from sequences that do not. One study compared the sensitivity to differentiate possible and impossible word endings in 10 month-old monolinguals and bilinguals[24]. Monolinguals and bilinguals showed an equivalent capacity to differentiate possible and impossible word endings in their shared language provided it was the dominant language in the bilinguals’ environment. If bilinguals were tested in their non-dominant language, then monolinguals showed a greater discrimination for possible word endings than bilinguals. These data suggest that identification of words in speech may be affected in bilinguals, but only in individuals in which there is a clear difference in the exposure time to the two languages and only then for the less prevalent language.

As mentioned above, word learning also involves linking word forms to concepts. This process may be guided by the so-called mutual exclusivity heuristic, according to which individuals hypothesize that new words correspond to new concepts[25]. In support of this principle, when presented with a known and an unknown object (the concept in this case) while listening to an unknown word, monolingual toddlers tend to look at the unknown object for a longer period than the known object[25]. The mutual exclusivity heuristic is a useful learning strategy given that objects tend to be labeled with just one word (synonyms such as 'couch' and 'sofa' are rare).

Interestingly, the outcome in the above task is different in bilingual infants: when presented with a known and an unknown object while listening to an unknown word, bilingual toddlers look at both objects for similar periods, suggesting that they are not using the mutual exclusivity heuristic [26-28]. This is probably explained by the fact that each object is likely to be linked to two labels — one in each language — rather than to just one, and thus the mutual exclusivity heuristic may not be helpful in a multilingual setting. How bilinguals compensate for the lack of utility of this principle during word learning and whether some way early vocabulary development is compromised by its absence remain unclear. However, whatever strategy is implemented, it does not seem to compromise word learning, as monolingual and bilingual toddlers know a comparable number of words (although, consequently, bilinguals know fewer words in one of their vocabularies than monolinguals know in their one vocabulary)[29, 30].

To conclude, we have argued that, based on currently available data, monolingual and bilingual infants are comparable in their capacities to discriminate languages, to learn phoneme repertoires and to learn words. Certainly, the available evidence suggests that bilingualism does not seem to compromise in any significant manner language acquisition. Nevertheless, some studies show that the bilingual input induces some specific adaptations in the mechanisms underlying such achievements. The precise nature of these adaptations and whether they represent a processing enhancement as compared to monolinguals' are still to be determined.

Language processing

In this section, we review studies that have explored how learning and using a second language may modify or interfere with first language processing in adult populations (the 'bilingual effect').

Behavioural consequences of the bilingual effect on first language processing

Bilingualism can have consequences for performance in the first language at various levels of linguistic processing (REF[31]for a review). These effects come from studies that have compared the performance in a wide range of tasks of bilingual adult speakers in their first language with that of monolingual speakers. These studies usually test successive bilinguals.

At the semantic level, the mappings from semantics to lexical items may be altered by the way the corresponding translations are mapped into semantics[32]. That is, the specific meanings of some words seem to vary depending on the meanings of the corresponding

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translation words. Therefore, word meanings in a given language may differ slightly between monolinguals and bilinguals. At the lexico-syntactic level, bilinguals retrieve and utter words slower than monolinguals and tend to suffer more tip-of-the-tongue states than monolinguals[33-35]. Also, bilinguals produce fewer words of a given semantic category in fluency tasks[36]. Together, these results show a somewhat reduced speech fluency in bilingual speakers as compared to monolinguals. Furthermore, the frequency of syntactic constructions in the second language affects bilinguals' syntactic choices in the first language[37]. At the phonological level, bilinguals' phoneme boundaries differ from monolinguals'. This reveals a shift in the phoneme space as a consequence of using second language (as has been observed in individuals who have been living in a foreign country for a long period of time). This is not to say, however, that bilinguals cannot have two phonological repertoires, one for each language [38].

Three main origins of these effects of bilingualism have been proposed.

First, some of these effects might arise because individuals who become bilingual start using their first language less often than do monolinguals. Indeed, the extent to which processing of the first language is affected might correlate with the frequency of second language usage[34, 39, 40].

Second, the effects of bilingualism on first language processing may arise because of the continuous interaction of the first and second language systems, leading to linguistic 'transfer' from the second to the first language[32]. For example, lexical and syntactic choices (use of passive or active constructions) in the first language might be modulated by the lexical and syntactic properties of the second language[37]. Interestingly, in extreme situations, linguistic transfer along with a reduced use of the first language can lead to first language attrition[41], such as in the case with international adoptions, in which the first language is often no longer (or very infrequently) used[42].

Last, the bilingual effect on first language processing might come about because of the need to control and monitor the two languages, especially in speech production tasks[43, 44]. Although language processing generally involves control and monitoring processes, bilingual language processing is more taxing on these processes because bilinguals need to ensure the right register is used in each communicative context. Furthermore, these control processes are especially important since bilinguals activate their two languages in a non-selective way[45-47]. That is, when planning to name an apple, Spanish–English bilinguals activate both 'manzana' and 'apple' (the words for apple in Spanish and English respectively). Moreover, when a bilingual hears a word in one of their languages (for example a Russian–English bilingual hearing the Russian word 'marku'), phonologically related words in both languages are activated (such as the English word 'marker'). Thus, bilinguals almost have two potential lexical candidates (one in each language) for each concept they want to express, and hence they need to continuously decide which one to utter, in accordance with the situation, and to avoid intrusions from the other language. Because of these additional demands on cognitive processes, one may expect that first language efficiency becomes affected (for example, by a decrease in speech rate).

These three explanations for the bilingual effect are not mutually exclusive and, indeed, they may all contribute to some of the observed effects. Having discussed the behavioural consequences of bilingualism for first language processing, we now turn to the issue of how bilingualism affects the neural circuitry involved in such processing.

Neural consequences of the bilingual effect on first language processing

Various studies have found potential differences in the neural correlates of language processing in monolingual and bilingual young adults. As argued below, it is difficult to determine exactly how these potential neural differences relate to the possible explanations for the effects of bilingualism on first language processing. Nevertheless, most studies have interpreted neural differences as indicators of increased language processing demands in bilinguals, resulting from either a reduced frequency of language use or a need for greater linguistic control.

According to a few studies, some brain structures show differential activity in monolinguals and bilinguals, suggesting a bilingual-specific brain activity signature. For example, the left inferior frontal cortex shows increased activity in simultaneous bilinguals compared with monolinguals during comprehension tasks[48, 49], and this differential activity has been suggested to be involved in some sort of language separation mechanism in bilinguals (see REF[50] for evidence of the involvement of the left head of caudate in bilingual language control). Moreover, individuals that learn the new orthography-to-phonology mappings of a second language begin to show increased activation of the left ventral prefrontal cortex during reading in their first language. This increase has been interpreted to mean that bilinguals have higher lexical and non-lexical demands during reading in their first language[51]. The conclusions of these studies, however, are limited by the fact they involved a bilingual experimental setting in which participants are presented with stimuli from two languages. This setting may engage certain processes (for example, identifying the language in which a given item is presented) that are not necessarily involved when bilinguals process language in just one of their languages (and that are clearly not required when monolinguals process their only language). Hence, when interpreting the evidence presented below, it is important to keep in mind whether each particular study has made used of bilingual or monolingual settings.

Perhaps the most convincing evidence for increased language processing demands in bilinguals compared with monolinguals comes from a study[52] in which high-proficient early successive bilinguals performed several linguistic tasks in only their first language. A comparison of brain activity in these bilinguals and monolingual controls revealed that bilinguals exhibit higher activity in five left-hemisphere language-related brain areas (dorsal precentral gyrus, pars triangularis, pars opercularis, superior temporal gyrus and planum temporale). These differences were evident in tasks involving word retrieval and articulation, such as picture naming and reading aloud, but not in receptive language tasks. Interestingly, monolinguals showed increases in activity in the same five brain areas when the language processing demands in the naming and reading tasks were increased. Given these results, the authors concluded that the main difference between bilingual and monolingual processing relates to the increased processing demands faced by bilinguals

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because of the additional need to control the two languages, the requirement to resolve lexical competition, and/or the reduced frequency of articulatory rehearsal.

Consistent with the notion that bilingualism taxes control processes, several studies have shown a larger involvement of brain areas implicated in language control in bilinguals than in monolinguals. For example, Abutalebi and collaborators have convincingly argued that the head of the left caudate and the left anterior cingulate cortex are preferentially recruited during bilingual language processing in high-proficient early bilinguals[53-56]. Furthermore, these authors suggest that both structures are involved in keeping the two languages apart during language processing, at least in contexts in which both languages are engaged (see REF[57] for similar evidence with bimodal bilinguals — individuals who can sign and speak the same language). It must be mentioned, however, that the increase in processing demands associated with bilingualism can also lead to some processing benefits. For example, early high-proficient bilinguals show enhanced subcortical representation of linguistic sounds, as revealed by a larger electrical brain response in the range of sounds fundamental frequency, suggesting that bilinguals have more efficient and flexible auditory processing[58].

An exciting recent discovery in this context is the fact that bilingualism also seems to affect the structure of certain brain areas. For example, early and late high-proficient bilinguals, on average, show increased grey matter in areas involved in verbal fluency tasks (left inferior parietal structures[59]), articulatory and phonological processes (left putamen[60]) and auditory processing (Heschl Gyrus[61]). Furthermore, changes in white matter tracts have also been reported associated to bilingualism[62]. A study of older successive high-proficient bilingual adults (70 years-old) reported higher white matter integrity in the corpus callosum in bilinguals than in monolinguals[63]. Some of these structural changes are also sensitive to the proficiency level in the second language, further suggesting that they are indeed related to the use of a second language rather than to other potentially uncontrolled variables[59]. Thus, although it is difficult to give a complete and coherent picture of the relationships between some of these structural changes and their functional roles, it seems that the learning and continuous use of two languages have pervasive effects on the functional and structural properties of various cortical and subcortical structures.

The current evidence is sufficiently consistent to suggest that bilingualism does indeed have behavioural and neural functional consequences for language processing even in a bilingual's first and dominant language. This is not to say, however, that such an experience leads to fundamental differences in the way that the first language is processed, unless extensive exposure to a second language causes first language attrition.

Beyond language

As we have discussed, bilingualism affects the brain activity related to language processing, probably as a result of an increase in language processing demands. Given that exchanging linguistic information is one of the most frequent cognitive activities that humans perform, the question arises as to whether bilingualism affects other cognitive processes. Research on this issue is perhaps the topic in the field that is receiving the most attention from both the scientific community and the general public at the moment. In this section, we first review the current evidence regarding the behavioural consequences of bilingualism in relation to the efficiency with which executive control processes work, and then we turn to the issue of how bilingualism affects the neural circuitry sustaining the executive control system across the life-span.

Behavioural consequences of the bilingual effect on executive control processes

The multifactorial executive control system involves processes such as inhibition, flexible switching between tasks, working memory and monitoring[64, 65], which may be assigned to any given behavioural task to facilitate its completion. It has been hypothesized that these domain general executive control mechanisms are recruited in a more taxing manner during bilingual than during monolingual language processing. Hence, continuous recruitment of these mechanisms during bilingual language processing may therefore affect the development and efficiency of the multifactorial executive control system[43, 55, 66].

Some behavioural evidence supports this hypothesis: bilinguals experience less interference in conflict resolution tasks than do monolinguals[66-70] (see Ref[31] for an excellent review of the scope of the bilingual effect on cognitive control) and, in some contexts, bilinguals seem to be more flexible when switching between non-linguistic tasks[71, 72]. These effects of bilingualism on the executive control system have been observed in a wide range of tasks with little or no linguistic content, such as Stroop-like tasks[66-68, 73]. Furthermore, these effects seem to be present not only in simultaneous bilinguals but also in successive ones, and across the life span; that is, from infancy to elderhood[66, 74].

Nevertheless, there are certain difficulties when interpreting the results outlined above. First, serious concerns have been raised about the robustness and reliability of the reported cognitive effects of bilingualism— especially in young adults — and in particular about which of the different control processes engaged by bilingual language processing actually generates these advantages[75-78]. Second, our current knowledge about the nature of the different components of the executive control system and their interactions with each other is rather limited, making it difficult to relate them to the processes involved in bilingual language control. Often, our understating of the cross-talk between the two systems seems to depend on the use of relatively underspecified terms such as ‘inhibition’ and ‘monitoring’. Third, it is not immediately obvious which (and how many) aspects of bilingualism might enhance executive control processes. The bilingual effect on the executive control system may come about because of the need to decide which language to use for each particular interlocutor, to prevent interference from the language that is not in use, to update working memory continuously, and/or to attend to the relevant linguistic features of each language (for example, the different phonological repertoires) when learning the two languages. However, the link between the processes engaged during bilingual language production and comprehension and their potential effects on each of these executive components is poorly understood[79, 80].

Further complicating this picture is the observation that the cognitive effects of bilingualism are already present in infants. Seven-month-old simultaneous bilingual infants are able to switch their attention more efficiently than monolingual infants in non-linguistic tasks[74], and at 18 months, they appear to have more developed memory generalization processes[81].

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These observations suggest that an explanation of the bilingual effect only in terms of the need to control their two languages during speech production is not tenable anymore, given that these infants do not yet engage in speech production.

The reviewed evidence strongly suggests that bilingualism has behavioral consequences for the mechanisms involved in executive control processes. Given these behavioral observations, it is important to understand the way in which bilingualism alters the neural circuitry that sustains executive control processes.

The effects of bilingualism on executive control circuits

The study of how bilingualism affects the neural basis of executive control processes has only recently commenced. Nevertheless, these early studies clearly indicate that early bilingualism not only alters the functional involvement of certain brain areas in the performance of executive control tasks[82-84]but also induces experience-related changes in brain structure[63, 83]. For example, when performing non-linguistic switching tasks, early bilinguals recruit larger proportions of the left hemisphere brain areas related to language control, such as the left striatum and the left inferior frontal lobe, than do monolinguals[82]. Moreover, early bilinguals seem to recruit fewer brain resources in conflict monitoring tasks, as revealed by a reduction in brain activity in the anterior cingulate cortex[83]. Indeed, the anterior cingulate cortex seems to be specially tuned by bilingualism, given that its gray matter density (volume) is greater in early bilinguals than in monolinguals[83]. Thus, neuroimaging studies convincingly show that bilingualism does have effects on brain structures involved in executive control processes. These observations nicely complement the behavioral effects of bilingualism on the executive control system reviewed above (see also[31]).

The effects of long-life bilingualism on neural circuitry have been shown to promote cognitive reserve in elderly people[66]. Elderly bilinguals outperform monolinguals in executive control tasks[66, 85], even though bilinguals recruit certain brain areas, such as the left lateral frontal cortex and cingulate cortex, to a lesser extent than monolinguals[86]. Also, bilingualism promotes the maintenance of white matter integrity of the corpus callosum in elderly people[63], a finding that has further helped to understand the basis of cognitive reserve (BOX 4).

In this context, a striking observation that has deservedly captured media attention is that bilingualism seems to delay the behavioral symptoms associated with neurodegenerative disorders such as Alzheimer’s disease[87-89]. The estimated age of onset of the disease and the age of the first medical appointment related to cognitive symptoms associated with dementia are about 4–5 years later in proficient bilinguals than in monolinguals. This is not to say that bilingualism protects against the development of neurodegenerative diseases. Rather, the symptoms associated with such diseases may be delayed in bilinguals because of the presence of greater cognitive reserve caused by the bilingual experience. However, caution needs to be exercised when trying to generalize these latter sets of results, since other studies have either failed to find this protective effect of bilingualism or have identified a weakly protective effect[90-93].

In summary, there seems to be sufficient experimental evidence supporting the notion that bilingualism has an impact on cognition beyond language processing, especially on those processes involved in executive control and their corresponding brain structures. However, why, how and to what extent bilingualism affects these cognitive processes and the corresponding brain structures is far from being fully understood.

Conclusions

We have described how becoming bilingual affects first language processing and executive control processes. We have argued that the main differences between monolinguals and bilinguals in terms of language acquisition and processing are rooted in two factors. First, bilinguals receive less exposure to and make less use of each of their languages than monolinguals do in their only language. Second, bilinguals need to monitor their language systems in a more demanding way than monolinguals, requiring the involvement of cognitive control structures. These two features increase the processing demands during bilingual language acquisition and processing. Thus, while the neural networks involved in first language processing seem to be fundamentally the same for monolinguals and bilinguals, the latter group faces higher processing demands that lead to an increase in brain activity. Furthermore, a boost in executive control abilities results from coping with this increase in processing demands, which starts in infancy and continues throughout the life span, possibly enhancing cognitive reserve in the elderly.

These conclusions, however, must be interpreted with some caution when designing linguistic educational policies and offering parental advice. This is because a comparable level of competence between bilinguals and monolinguals may only be possible if the linguistic input in any language (and particularly the first one) is frequent, varied and socially useful[94]. If these conditions are not met, one finds situations of switched language dominance in which the second language of the bilingual becomes the dominant language[95, 96]. This is frequently the case in minority and immigrant populations[97]. A more balanced use of the two (or more) languages of a bilingual individual should warrant a full development of the first language and possibly of the collateral advantages in cognitive processes[80].

Importantly, other than a handful of studies investigating international adoptions, very few studies have explored the neural changes associated with switched language dominance. A closer inspection of this issue could help to better understand fundamental issues about brain plasticity across the lifespan. At the same time, a more complete description of how the age of acquisition of the second language affects first language processing and executive control will be fundamental to understanding the origin of the reported bilingual effect both at the behavioral and neural levels.

From the neural perspective, an outstanding issue for further research refers to the development of the brain networks in monolingual and bilingual children. For a long time it has been assumed that the complex language network supporting language processing in adulthood was the outcome of a temporally protracted interaction between maturation and language exposure. Increasing functional left-lateralization and increasing involvement of frontal structures was, and still is, considered the normal developmental course of language neural specialization. However, recent findings indicate that such networks (both in terms of left specialization and in the involvement of its frontal structures) may already be functional at birth[98], even in premature infants[99]. We are just starting to understand how brain networks develop in monolingual infants. This information will be crucial to better understand the origin of the neural effects that bilingualism induces in adults just reviewed.

Finally, it is important to keep in mind that advancing our knowledge of how bilingualism sculpts the brain is a socially relevant issue. Such knowledge will help debunk some misconceptions and 'neuromyths' associated with bilingualism, such as the belief that infants exposed simultaneously to two languages suffer incomplete language acquisition or that bilinguals are smarter than monolinguals[100]. This is fundamental given the controversial nature of the subject, which is frequently discussed in the context of socially sensitive issues such as immigration, civil rights or education[101].

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GLOSSARY

Successive bilinguals: The term refers to bilinguals who are exposed to the second language after they have started to acquire their first language. There is no general consensus on how much of the first language needs to be acquired before second language learning commences for someone to be a labeled a successive bilingual. Still, researchers often used the terms 'early' and 'late' bilingualism to refer to speakers that have acquired the second language before or after the critical period (see Box 3), respectively.

Simultaneous bilinguals: The term refers to bilinguals who are exposed to both languages from birth, although occasionally the term is also used to refer to individuals who acquire the second language within the first 2-3 years of life. Such individuals also called first-language bilinguals.

First language: This term refers to the first language(s) an individual learns. In the case of bilingual exposure there is more than one first language. An equivalent term is 'native language'. A related concept is dominant language, which refers to the language individuals feel more comfortable or fluent with. It is not uncommon that bilinguals change language dominance due to immigration, for instance. Unless specified, in the present review the term first language is used to refer

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	to the language(s) that are learned in the first place and that has remained the dominant one.
Word form	This term refers to those speech units that listeners can segment and recognize in the speech signal but for which they may not have a meaning.
Phonological regularity distributions	This term refers to the fact that combinations of speech sounds present specific patterns in a language. They may represent specific combinations of phonemes (see main text for a specific example) or other types of speech information. For instance, in English, most nouns are stressed on the first syllable (or they are monosyllables), therefore, syllable stress constitutes a useful cue to segment nouns in this language.
Conflict between the two linguistic systems	This term refers to the potential competition that the different representations of the two languages of a bilingual may lead to. Given the parallel activation of the two languages and the consequent activation of the two linguistic systems, bilingual speakers need to choose the representations of the target language while ignoring those of the non-intended one. This sorting out process is what we refer with conflict between the two linguistic systems.
The mutual exclusivity heuristic	This term refers to a strategy that humans (adults and infants) have at their disposal to learn new names of objects. The principle is based on the assumption that humans think that objects should only have one category label. In a basic experimental setup two objects are presented: one for which the individual knows the name and another whose name is unknown. Upon hearing a new word, humans tend to assign the new word to the nameless object.
Phoneme repertoire or phoneme space	These terms refer to the set of phonemes spoken in a specific language.
Shift in the phoneme space	As a consequence of exposure to a different phonological system, such as in the case of a second language, bilinguals tend to adapt their phoneme space of their first language. This results in bilinguals being accented when speaking their first language. This shift occurs more often when the first language is less used than the L2.
Lexical retrieval failures	This term refers to those speaking instances in which individuals make an error when producing a word. This error may involve saying a semantically related word instead of the target one (‘apple’ instead of ‘peach’), saying a phonologically related word (‘reach’ instead of ‘peach’), or having difficulties to come up with the intended word in the absence of any intrusion. This latter type of error, often referred with the term “tip of the tongue state” appears to be more prevalent in

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	bilinguals than in monolinguals, even if bilinguals try to retrieve the word in any of their two languages.
Orthography-to-phonology mappings	This term refers to the correspondence between letters and sounds. This mapping can be different across languages leading sometimes to inconsistencies across them. For example, the letter ‘p’ maps into the sound /p/ in English and into /r/ in Russian.
Convergence hypothesis	This hypothesis states that the neural networks involved in language acquisition and processing are similar for the first and second language. This is not to say, however, that some additional neural resources need to be at play when learning and using a second language, as compared to monolingual contexts, as for example, the recruitment of certain language control neural structures.
Inhibition	A cognitive control mechanism to tune out stimuli that are irrelevant to the task at hand – i.e., it suppresses irrelevant information so that only what is relevant for the current context becomes available for selection. In bilingual conversations, it prevents the speaker from producing utterances in the undesired language by keeping its lexical nodes under the threshold for selection.
Monitoring	The process of evaluating the need to apply cognitive control mechanisms (e.g. inhibition) in response to the current context - i.e., it detects what stimuli are irrelevant for the task at hand and their occurrence so as to apply cognitive control mechanisms with an optimal strength. In bilingual conversations, it detects what language to speak to whom and, therefore, the need to apply cognitive control mechanisms leading to switch or keep the same language.
Cognitive reserve	This term refers to the resistance of certain aspects of cognition to brain damage. That is, it is often the case that similar brain damage, due for example to neurodegenerative diseases, affects the cognitive abilities of different individuals to a different degree, suggesting that the cognitive abilities of some individuals are more resistant to brain damage. Cognitive reserve appears to be related, among others, with environmental factors such as lifestyle and education.

References

1. Grosjean, F. What bilingualism is NOT. 2010.
2. Genesee F. Bilingual first language acquisition: Exploring the limits of the language faculty. Annual Review of Applied Linguistics. 2001:153–158.
3. Gervain J, Mehler J. Speech Perception and Language Acquisition in the First Year of Life. Annu. Rev. Psychol. 2010; 61:191–218. [PubMed: 19575623]
4. Kuhl PK. Brain Mechanisms in Early Language Acquisition. Neuron. 2010; 67:713–727. [PubMed: 20826304]
5. Byers-Heinlein K, Burns TC, Werker JF. The Roots of Bilingualism in Newborns. Psychological Science. 2010; 21:343–348. [PubMed: 20424066]

6. Nazzi T, Bertoncini J, Mehler J. Language discrimination by newborns: Toward an understanding of the role of rhythm. Journal of Experimental Psychology-Human Perception and Performance. 1998; 24:756–766. [PubMed: 9627414]
7. Ramus F, Hauser M, Miller C, Morris D, Mehler J. Language discrimination by human newborns and by cotton-top tamarin monkeys. Science. 2000; 288:349–351. [PubMed: 10764650]
8. Toro J, Trobalon J, Sebastian-Galles N. The use of prosodic cues in language discrimination tasks by rats. Animal Cognition. 2003; 6:131–136. [PubMed: 12728358]
9. Bosch L, Sebastian-Galles N. Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. Cognition. 1997; 65:33–69. [PubMed: 9455170]
10. Bosch L, Sebastian-Galles N. Evidence of early language discrimination abilities in infants from bilingual environments. Infancy. 2001; 2:29–49.
11. Nazzi T, Jusczyk PW, Johnson EK. Language Discrimination by English-Learning 5-Month-Olds: Effects of Rhythm and Familiarity. Journal of Memory and Language. 2000; 43:1–19.
12. Calvert GA, et al. Activation of auditory cortex during silent lipreading. Science. 1997; 276:593–596. [PubMed: 9110978]
13. van Wassenhove V, Grant KW, Poeppel D. Visual speech speeds up the neural processing of auditory speech. Proc. Natl. Acad. Sci. U. S. A. 2005; 102:1181–1186. [PubMed: 15647358]
14. Weikum WM, et al. Visual language discrimination in infancy. Science. 2007; 316:1159–1159. [PubMed: 17525331]
15. Sebastian-Galles N, Albareda-Castellot B, Weikum WM, Werker JF. A Bilingual Advantage in Visual Language Discrimination in Infancy. Psychological Science. 2012; 23:994–999. [PubMed: 22810164]
16. Kuhl PK. Early language acquisition: cracking the speech code. Nat. Rev. Neurosci. 2004; 5:831–843. [PubMed: 15496861]
17. Kuhl PK, et al. Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. Dev. Sci. 2006; 9:F13–F21. [PubMed: 16472309]
18. Albareda-Castellot B, Pons F, Sebastian-Galles N. The acquisition of phonetic categories in bilingual infants: new data from an anticipatory eye movement paradigm. Dev. Sci. 2011; 14:395–401. [PubMed: 22213908]
19. Burns TC, Yoshida KA, Hill K, Werker JF. The development of phonetic representation in bilingual and monolingual infants. Appl. Psycholing. 2007; 28:455–474.
20. Sundara M, Polka L, Molnar M. Development of coronal stop perception: Bilingual infants keep pace with their monolingual peers. Cognition. 2008; 108:232–242. [PubMed: 18281027]
21. Petitto LA, et al. The “Perceptual Wedge Hypothesis” as the basis for bilingual babies’ phonetic processing advantage: New insights from fNIRS brain imaging. Brain Lang. 2012; 121:130–143. [PubMed: 21724244]
22. Anderson JL, Morgan JL, White KS. A statistical basis for speech sound discrimination. Lang. Speech. 2003; 46:155–182. [PubMed: 14748443]
23. Jusczyk PW, Friederici AD, Wessels J, Svenkerud VY, Jusczyk AM. Infants’ sensitivy to the sound patterns of native language words. Journal of Memory and Language. 1993; 32:402–420.
24. Sebastian-Galles N, Bosch L. Building phonotactic knowledge in bilinguals: role of early exposure. J. Exp. Psychol. Hum. Percept. Perform. 2002; 28:974–989. [PubMed: 12190262]
25. Markman E, Wachtel G. Childrens use of Mutual Exclusivity to Constrain the Meanings of Words. Cognit. Psychol. 1988; 20:121–157. [PubMed: 3365937]
26. Byers-Heinlein K, Werker J. Monolingual, bilingual, trilingual: infants’ language experience influences the development of a word-learning heuristic. Developmental Science. 2009; 12:815–823. [PubMed: 19702772]
27. Byers-Heinlein K, Werker JF. Lexicon Structure and the Disambiguation of Novel Words: Evidence from Bilingual Infants. Cognition. 2013; 128 407-407-416.
28. Houston-Price C, Caloghiris Z, Raviglione E. Language Experience Shapes the Development of the Mutual Exclusivity Bias. Infancy. 2010; 15:125–150.
29. Hoff E, et al. Dual language exposure and early bilingual development. J. Child Lang. 2012; 39:1. [PubMed: 21418730]

30. Core C, Hoff E, Rumiche R, Señor M. Total and conceptual vocabulary in spanish-english bilinguals from 22 to 30 months: implications for assessment. J. Speech Lang. Hear. Res. 2013; 56:1637–1649. [PubMed: 24023382]

31. Bialystok E, Craik FIM, Luk G. Bilingualism: consequences for mind and brain. Trends Cogn. Sci. 2012; 16:240–250. [PubMed: 22464592]

32. Pavlenko A, Malt BC. Kitchen Russian: Cross-linguistic differences and first-language object naming by Russian-English bilinguals. Bilingualism-Language and Cognition. 2011; 14:19–45.

33. Gollan T, Acenas L. What is a TOT? Cognate and translation effects on tip-of-the-tongue states in Spanish-English and Tagalog-English bilinguals. Journal of Experimental Psychology-Learning Memory and Cognition. 2004; 30:246–269.

34. Ivanova I, Costa A. Does bilingualism hamper lexical access in speech production? Acta Psychol. 2008; 127:277–288.

35. Sadat J, Martin CD, Alario FX, Costa A. Characterizing the Bilingual Disadvantage in Noun Phrase Production. J. Psycholinguist. Res. 2012; 41:159–179. [PubMed: 21997516]

36. Gollan T, Montoya R, Werner G. Semantic and letter fluency in Spanish-English bilinguals. Neuropsychology. 2002; 16:562–576. [PubMed: 12382994]

37. Runnqvist E, Gollan TH, Costa A, Ferreira VS. A disadvantage in bilingual sentence production modulated by syntactic frequency and similarity across languages. Cognition. 2013; 129:256–263. [PubMed: 23948209]

38. García-Sierra A, Ramírez-Esparza N, Silva-Pereyra J, Siard J, Champlin CA. Assessing the double phonemic representation in bilingual speakers of Spanish and English: An electrophysiological study. Brain Lang. 2012; 121:194–205. [PubMed: 22534571]

39. Gollan TH, Montoya RI, Cera C, Sandoval TC. More use almost always means a smaller frequency effect: Aging, bilingualism, and the weaker links hypothesis. Journal of Memory and Language. 2008; 58:787–814. [PubMed: 19343088]

40. Baus C, Costa A, Carreiras M. On the effects of second language immersion on first language production. Acta Psychol. 2013; 142:402–409.

41. Schmid MS. Languages at play: The relevance of L1 attrition to the study of bilingualism. Bilingualism-Language and Cognition. 2010; 13:1–7.

42. Pallier C, et al. Brain imaging of language plasticity in adopted adults: can a second language replace the first? Cereb. Cortex. 2003; 13:155–161. [PubMed: 12507946]

43. Green DW. Mental control of the bilingual lexico-semantic system. Biling. Lang. Cogn. 1998; 1:67–81.

44. Kroll JF, Bobb SC, Misra M, Guo T. Language selection in bilingual speech: Evidence for inhibitory processes. Acta Psychol. 2008; 128:416–430.

45. Colome A. Lexical activation in bilinguals' speech production: Language-specific or language-independent? Journal of Memory and Language. 2001; 45:721–736.

46. Thierry G, Wu YJ. Brain potentials reveal unconscious translation during foreign-language comprehension. Proc. Natl. Acad. Sci. U. S. A. 2007; 104:12530–12535. [PubMed: 17630288]

47. Spivey MJ, Marian V. Cross talk between native and second languages: Partial activaction of an irrelevant lexicon. Psychological Science. 1999; 10:281–284.

48. Kovelman I, Baker SA, Petitto L. Bilingual and monolingual brains compared: A functional magnetic resonance imaging investigation of syntactic processing and a possible "neural signature" of bilingualis. J. Cogn. Neurosci. 2008; 20:153–169. [PubMed: 17919083]

49. Kovelman I, Shalinsky MH, Berens MS, Petitto L. Shining new light on the brain's "bilingual signature": A functional Near Infrared Spectroscopy investigation of semantic processing. Neuroimage. 2008; 39:1457–1471. [PubMed: 18054251]

50. Crinion J, et al. Language control in the bilingual brain. Science. 2006; 312:1537–1540. [PubMed: 16763154]

51. Nosarti C, Mechelli A, Green DW, Price CJ. The Impact of Second Language Learning on Semantic and Nonsemantic First Language Reading. Cerebral Cortex. 2010; 20:315–327. [PubMed: 19478033]

Europe PMC Funders Author Manuscripts

52. Parker Jones O, et al. Where, When and Why Brain Activation Differs for Bilinguals and Monolinguals during Picture Naming and Reading Aloud. Cerebral Cortex. 2012; 22:892–902. [PubMed: 21705392]
53. Abutalebi J. Neural aspects of second language representation and language control. Acta Psychol. 2008; 128:466–478.
54. Abutalebi J, et al. Language control and lexical competition in bilinguals: An event-related fMRI study. Cerebral Cortex. 2008; 18:1496–1505. [PubMed: 17947346]
55. Abutalebi J, Green D. Bilingual language production: The neurocognition of language representation and control. Journal of Neurolinguistics. 2007; 20:242–275.
56. Garbin G, et al. Neural bases of language switching in high and early proficient bilinguals. Brain Lang. 2011; 119:129–135. [PubMed: 21550652]
57. Zou L, Ding G, Abutalebi J, Shu H, Peng D. Structural plasticity of the left caudate in bimodal bilinguals. Cortex. 2012; 48:1197–1206. [PubMed: 21741636]
58. Krizman J, Marian V, Shook A, Skoe E, Kraus N. Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. Proc. Natl. Acad. Sci. U. S. A. 2012; 109:7877–7881. [PubMed: 22547804]
59. Mechelli A, et al. Structural plasticity in the bilingual brain. Nature. 2004; 431:757. [PubMed: 15483594]
60. Abutalebi J, et al. The role of the left putamen in multilingual language production. Brain Lang. 2013; 125:307–315. [PubMed: 22538086]
61. Ressel V, et al. An effect of bilingualism on the auditory cortex. J. Neurosci. 2012; 32:16597–16601. [PubMed: 23175815]
62. García-Pentón L, Pérez Fernández A, Iturria-Medina Y, Gillon-Dowens M, Carreiras M. Anatomical connectivity changes in the bilingual brain. Neuroimage. 2014; 84:495–504. [PubMed: 24018306]
63. Luk G, Bialystok E, Craik FIM, Grady CL. Lifelong Bilingualism Maintains White Matter Integrity in Older Adults. Journal of Neuroscience. 2011; 31:16808–16813. [PubMed: 22090506]
64. Miyake A, et al. The Unity and Diversity of Executive Functions and Their Contributions to Complex “Frontal Lobe” Tasks: A Latent Variable Analysis. Cognit. Psychol. 2000; 41:49–100. [PubMed: 10945922]
65. Shallice T, Burgess P. The domain of supervisory processes and temporal organization of behaviour. Philosophical Transactions of the Royal Society B-Biological Sciences. 1996; 351:1405–1411.
66. Bialystok E, Craik FIM, Klein R, Viswanathan M. Bilingualism, aging, and cognitive control: Evidence from the Simon task. Psychol. Aging. 2004; 19:290–303. [PubMed: 15222822]
67. Costa A, Hernandez M, Sebastian-Galles N. Bilingualism aids conflict resolution: Evidence from the ANT task. Cognition. 2008; 106:59–86. [PubMed: 17275801]
68. Costa A, Hernandez M, Costa-Faidella J, Sebastian-Galles N. On the bilingual advantage in conflict processing: now you see it, now you don’t. Cognition. 2009; 113:135–149. [PubMed: 19729156]
69. Bialystok E, Martin MM. Attention and inhibition in bilingual children: evidence from the dimensional change card sort task. Developmental Science. 2004; 7:325–339. [PubMed: 15595373]
70. Martin-Rhee MM, Bialystok E. The development of two types of inhibitory control in monolingual and bilingual children. Biling. -Lang. Cogn. 2008; 11:81–93.
71. Prior A, MacWhinney B. A bilingual advantage in task switching. Bilingualism-Language and Cognition. 2010; 13:253–262.
72. Hernández M, Martin CD, Barceló F, Costa A. Where is the bilingual advantage in task-switching? Journal of Memory and Language. 2013; 69:257–276.
73. Stroop JR. Studies of interference in serial verbal reactions. J. Exp. Psychol. 1935; 18:643–662.
74. Kovacs AM, Mehler J. Cognitive gains in 7-month-old bilingual infants. Proc. Natl. Acad. Sci. U. S. A. 2009; 106:6556–6560. [PubMed: 19365071]

Europe PMC Funders Author Manuscripts

75. Hilchey MD, Klein RM. Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. Psychon. Bull. Rev. 2011; 18:625–658. [PubMed: 21674283]
76. Paap KR, Greenberg ZI. There is no coherent evidence for a bilingual advantage in executive processing. Cognit. Psychol. 2013; 66:232–258. [PubMed: 23370226]
77. Kousaie S, Phillips NA. Conflict monitoring and resolution: are two languages better than one? Evidence from reaction time and event-related brain potentials. Brain Res. 2012; 1446:71–90. [PubMed: 22356886]
78. Dunabeitia JA, et al. The Inhibitory Advantage in Bilingual Children Revisited. Exp. Psychol. 2013:1–18.
79. Calabria M, Hernandez M, Branzi FM, Costa A. Qualitative differences between bilingual language control and executive control:Evidence from task-switching. Frontiers in Psychology. 2012; 2:1–10.
80. Prior A, Gollan TH. Good Language-Switchers are Good Task-Switchers: Evidence from Spanish-English and Mandarin-English Bilinguals. Journal of the International Neuropsychological Society. 2011; 17:682–691. [PubMed: 22882810]
81. Brito N, Barr R. Influence of bilingualism on memory generalization during infancy. Dev. Sci. 2012; 15:812–816. [PubMed: 23106735]
82. Garbin G, et al. Bridging language and attention: Brain basis of the impact of bilingualism on cognitive control. Neuroimage. 2010; 53:1272–1278. [PubMed: 20558314]
83. Abutalebi J, et al. Bilingualism Tunes the Anterior Cingulate Cortex for Conflict Monitoring. Cerebral Cortex. 2012; 22:2076–2086. [PubMed: 22038906]
84. Rodriguez-Pujadas A, et al. Bilinguals use language-contro. brain areas more than monolinguals to perform non-linguistic switching tasks. PLoS ONE. Sep 13.2013 8(9):e73028. [PubMed: 24058456]
85. Kave G, Eyal N, Shorek A, Cohen-Mansfield J. Multilingualism and cognitive state in the oldest old. Psychol. Aging. 2008; 23:70–78. [PubMed: 18361656]
86. Gold BT, Kim C, Johnson NF, Kryscio RJ, Smith CD. Lifelong Bilingualism Maintains Neural Efficiency for Cognitive Control in Aging. Journal of Neuroscience. 2013; 33:387–396. [PubMed: 23303919]
87. Bialystok E, Craik FIM, Freedman M. Bilingualism as a protection against the onset of symptoms of dementia. Neuropsychologia. 2007; 45:459–464. [PubMed: 17125807]
88. Craik FIM, Bialystok E, Freedman M. Delaying the onset of Alzheimer disease Bilingualism as a form of cognitive reserve. Neurology. 2010; 75:1726–1729. [PubMed: 21060095]
89. Schweizer TA, Ware J, Fischer CE, Craik FIM, Bialystok E. Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer's disease. Cortex. 2012; 48:991–996. [PubMed: 21596373]
90. Chertkow H, et al. Multilingualism (But Not Always Bilingualism) Delays the Onset of Alzheimer Disease: Evidence From a Bilingual Community. Alzheimer Disease & Associated Disorders. 2010; 24:118–125. [PubMed: 20505429]
91. Crane PK, et al. Use of Spoken and Written Japanese Did Not Protect Japanese-American Men From Cognitive Decline in Late Life. Journals of Gerontology Series B-Psychological Sciences and Social Sciences. 2010; 65:654–666.
92. Gollan TH, Salmon DP, Montoya RI, Galasko DR. Degree of bilingualism predicts age of diagnosis of Alzheimer's disease in low-education but not in highly educated Hispanics. Neuropsychologia. 2011; 49:3826–3830. [PubMed: 22001315]
93. Sanders AE, Hall CB, Katz MJ, Lipton RB. Non-Native Language Use and Risk of Incident Dementia in the Elderly. Journal of Alzheimers Disease. 2012; 29:99–108.
94. Schmid, MS. Language attrition. Theoretical perspectives. Köpke, B.; Schmid, MS.; Keijzer, M.; Dostert, S., editors. John Benjamins; Amsterdam/Philadelphia: 2007. p. 135-153.
95. Dewaele, JM.
First Language Attrition: Interdisciplinary Perspectives on Methodological Issues. Schmid, MS.; Köpke, B.; Keijzer, M.; Weilemar, L., editors. John Benjamins; Amsterdam/Philadelphia: 2004. p. 81-104.

96. Schmid MS, Dusseldorp E. Quantitative analyses in a multivariate study of language attrition: The impact of extralinguistic factors. Second Language Research. 2010; 26 125-125-160.
97. Schmid, MS. Language attrition. Cambridge University Press; Cambridge: 2011.
98. Leroy F, et al. Early Maturation of the Linguistic Dorsal Pathway in Human Infants. J Neurosci. 2011; 31:987. 1500-1500-1506.
99. Mahmoudzadeh M, et al. Syllabic discrimination in premature human infants prior to complete formation of cortical layers. Proc. Natl. Acad. Sci. U. S. A. 2013; 110:4846–4851. [PubMed: 23440196]
100. Bhattacharjee Y. Why bilinguals are smarter. The New York Times. 2012:SR12.
101. Wiese A, Garcia E. The Bilingual Education Act: Language Minority Students and US Federal Education Policy. International Journal of Bilingual Education and Bilingualism. 2010; 4 229-229-248.
102. Li P. Computational modeling of bilingualism: How can models tell us more about the bilingual mind? INTRODUCTION. *Bilingualism-Language and Cognition*. 2013; 16:241–245.
103. Dijkstra T, van Heuven WJB. Modeling bilingual word recognition: Past, present and future RESPONSE. Bilingualism-Language and Cognition. 2002; 5:219–224.
104. Diaz B, Baus C, Escera C, Costa A, Sebastian-Galles N. Brain potentials to native phoneme discrimination reveal the origin of individual differences in learning the sounds of a second language. Proc. Natl. Acad. Sci. U. S. A. 2008; 105:16083–16088. [PubMed: 18852470]
105. Ventura-Campos N, et al. Spontaneous Brain Activity Predicts Learning Ability of Foreign Sounds. J. Neurosci. 2013; 33:9295–9305. [PubMed: 23719798]
106. Tversky A, Kahneman DK. Belief in Law of Small Numbers. Psychol. Bull. 1971; 76:105–&.
107. Button KS, et al. Power failure: why small sample size undermines the reliability of neuroscience. Nature Reviews Neuroscience. 2013; 14:365–376.
108. Chiswick BR. Are Immigrants Favorably Self-Selected? Am. Econ. Rev. 1999; 89:181–185.
109. Hartsuiker RJ, Pickering MJ, Veltkamp E. Is Syntax Separate or Shared Between Languages?: Cross-Linguistic Syntactic Priming in Spanish-English Bilinguals. Psychological Science. 2004; 15:409–414. [PubMed: 15147495]
110. Dijkstra, A.; Van Heuven, WJB. Localist connectionist approaches to human cognition. Grainger, J.; Jacobs, A., editors. Lawrence Erlbaum Associates; Hillsdale, NJ: 1998. p. 189-225.
111. Kroll JF, Bobb SC, Wodniecka Z. Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. Bilingualism-Language and Cognition. 2006; 9:119–135.
112. Klein D, Zatorre RJ, Milner B, Meyer e. Evans AC. Left putaminal activation when speaking a second language: evidence from PET. Neuroreport. 1994; 5:2295–2297. [PubMed: 7881049]
113. Chee MW. Dissociating language and word meaning in the bilingual brain. Trends Cogn. Sci. 2006; 10:527–529. [PubMed: 17049907]
114. Chee MW, Soon CS, Lee HL. Common and segregated neuronal networks for different languages revealed using functional magnetic resonance adaptation. J. Cogn. Neurosci. 2003; 15:85–97. [PubMed: 12590845]
115. Perani D, et al. The bilingual brain - Proficiency and age of acquisition of the second language. Brain. 1998; 121:1841–1852. [PubMed: 9798741]
116. Green, DW. The interface between syntax and the lexicon in second language acquisition. van Hout, R.; Hulk, A.; Kuiken, F.; Towell, R., editors. John Benjamins; Amsterdam: 2003. p. 197-217.
117. Kotz SA. A critical review of ERP and fMRI evidence on L2 syntactic processing. Brain Lang. 2009; 109:68–74. [PubMed: 18657314]
118. Willms JL, et al. Language-invariant verb processing regions in Spanish-English bilinguals. Neuroimage. 2011; 57:251–261. [PubMed: 21515387]
119. Golestani N, et al. Syntax production in bilinguals. Neuropsychologia. 2006; 44:1029–1040. [PubMed: 16427099]

Europe PMC Funders Author Manuscripts

120. Luk G, Green DW, Abutalebi J, Grady C. Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. Language and Cognitive Processes. 2012; 27:1479–1488. [PubMed: 24795491]

121. Hensch TK. Critical period plasticity in local cortical circuits. Nature Review Neuroscience. 2005; 6:877–888.

122. Epstein S, Flynn S, Martohardjono G. Second language acquisition: Theoretical and experimental issues in contemporary research. Behav. Brain Sci. 1996; 19:677–&.

123. Li P. Lexical Organization and Competition in First and Second Languages: Computational and Neural Mechanisms. Cognitive Science. 2009; 33:629–664. [PubMed: 21585481]

124. Werker J, Tees R. Speech perception as a window for understanding plasticity and commitment in language systems of the brain. Dev. Psychobiol. 2005; 46:233–251. [PubMed: 15772961]

125. Juffs A. Second language acquisition. Wiley Interdisciplinary Reviews-Cognitive Science. 2011; 2:277–286.

126. Hu W. Parents Take Language Class Into Their Own Hands. New York Times. 2006

127. Hickok G, Poeppel D. The cortical organization of speech processing. Nat. Rev. Neurosci. 2007; 8:393–402. [PubMed: 17431404]

128. Huttenlocher PR, Dabholkar AS. Regional differences in synaptogenesis in human cerebral cortex. J. Comp. Neurol. 1997; 387:167–178. [PubMed: 9336221]

129. Huttenlocher PR. Dendritic and synaptic development in human cerebral cortex: Time course and critical periods. Journal of Developmental Neuropsychology. 1999; 16:347–349.

130. Pujol J, et al. Myelination of language-related areas in the developing brain. Neurology. 2006; 66 339-339-343.

131. Garcia-Sierra A, et al. Bilingual language learning: An ERP study relating early brain responses to speech, language input, and later word production. Journal of Phonetics. 2011; 39:546–557.

132. Bartoletti A, Medini P, Berardi N, Maffei L. Environmental enrichment prevents effects of dark-rearing in the rat visual cortex. Nat. Neurosci. 2004; 7:215–216. [PubMed: 14966527]

133. Pitres A. Étude sur l'aphasie chez les polyglottes. Revue de médecine. 1895; 15:873–899.

134. Pearce JMS. A note on aphasia in bilingual patients: Pitres' and Ribot's laws. Eur. Neurol. 2005; 54:127–131. [PubMed: 16244484]

135. Paradis, M. Handbook of neuropsychology. Berndt, RS., editor. Elsevier Science; Amsterdam: 2001. p. 69-91.

136. Abutalebi J, Rosa PAD, Tettamanti M, Green DW, Cappa SF. Bilingual aphasia and language control: A follow-up fMRI and intrinsic connectivity study. Brain Lang. 2009; 109:141–156. [PubMed: 19427522]

137. Green DW, Abutalebi J. Understanding the link between bilingual aphasia and language control. Journal of Neurolinguistics. 2008; 21:558–576.

138. Faroqi-Shah Y, Frymark T, Mullen R, Wang B. Effect of treatment for bilingual individuals with aphasia: A systematic review of the evidence. Journal of Neurolinguistics. 2010; 23:319–341.

139. Green, DW. Handbook of bilingualism: Psycholinguistic perspectives. Kroll, JF.; de Groot, AMB., editors. Oxford University Press; New York: 2005. p. 516-530.

140. Kiran S, Grasemann U, Sandberg C, Miikkulainen R. A computational account of bilingual aphasia rehabilitation. Bilingualism-Language and Cognition. 2013; 16:325–342.

141. Costa A, et al. On the parallel deterioration of lexico-semantic processes in the bilinguals' two languages: Evidence from Alzheimer's disease. Neuropsychologia. 2012; 50:740–753. [PubMed: 22261401]

142. Gollan TH, Salmon DP, Montoya RI, da Pena E. Accessibility of the nondominant language in picture naming: A counterintuitive effect of dementia on bilingual language production. Neuropsychologia. 2010; 48:1356–1366. [PubMed: 20036679]

143. Zanini S, et al. Greater syntactic impairments in native language in bilingual Parkinsonian patients. Journal of Neurology Neurosurgery and Psychiatry. 2004; 75:1678–1681.

144. Zanini S, Tavano A, Fabbro F. Spontaneous language production in bilingual Parkinson's disease patients: Evidence of greater phonological, morphological and syntactic impairments in native language. Brain Lang. 2010; 113:84–89. [PubMed: 20188407]

145. de Souza LC, Lehericy S, Dubois B, Stella F, Sarazin M. Neuroimaging in dementias. Curr. Opin. Psychiatr. 2012; 25:473–479.

146. Ferreira LK, Diniz BS, Forlenza OV, Busatto GF, Zanetti MV. Neurostructural predictors of Alzheimer's disease: A meta-analysis of VBM studies. Neurobiol. Aging. 2011; 32:1733–1741. [PubMed: 20005012]

147. Pavese N. PET studies in Parkinson's disease motor and cognitive dysfunction. Parkinsonism Relat. Disord. 2012; 18(Supplement 1):S96–S99. [PubMed: 22166468]

148. Ray NJ, Strafella AP. The neurobiology and neural circuitry of cognitive changes in Parkinson's disease revealed by functional neuroimaging. Mov. Disord. 2012; 27:1484–1492. [PubMed: 23038645]

149. Wang X, Wang Y, Jiang T, Wang Y, Wu C. Direct evidence of the left caudate's role in bilingual control: An intra-operative electrical stimulation study. Neurocase. 2012:1–8.

150. Dehaene-Lambertz G, Houston D. Faster orientation latencies toward native language in two-month old infants. Lang. Speech. 1998; 41:21–43.

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BOX 1

Methodological considerations in bilingualism research

In contrast to learning a first language, the acquisition of a second language comes in several different forms: second language learners vary along some fundamental dimensions such as age of acquisition, amount of exposure, motivation, type of learning experience, and also the degree of similarity between their two languages. This natural variation affords the opportunity to test relevant issues about learning and brain plasticity, such as the presence of critical periods, but it also causes crucial methodological problems, such as finding homogeneous study groups of with individuals sharing equivalent linguistic experiences. In this regard, computational models might be a promising tool to help identify the relevant variables affecting second language processing while controlling for potential confounds (see[102, 103])

The inherent variability of second language learning also leads to difficulty when trying to understand the origin of the individual differences in second language proficiency, given that such differences could be understood as the result or the cause of the brain changes associated with it. Some individuals seem to be more “talented” than others when learning a new language[104, 105]. These issues are particularly relevant for neuroimaging studies that typically explore relatively small samples, and thus can be more affected by heterogeneous sampling[106, 107]. Studies investigating neurological patients (originated either from brain injury or neurodegenerative conditions) are also especially affected by this variability, since premorbid performance is often unavailable in these cases.

Furthermore, monolinguals and bilinguals often differ in fundamental variables such as socioeconomic status and/or emigration. For example, in the US, bilingualism is often associated with low socioeconomic status, as can be appreciated by the fact that legislation referring to bilingual education is included in a Federal program for disadvantaged students[101]. The correlation between emigration and bilingualism may be influenced involve self-selection, as individuals who emigrate may be more capable or ambitious than others who do not (to make the comparison even more complex, there are differences between emigrants who move to improve economic opportunities and refugees who are forced to emigrate[108]).

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BOX 2

The neural representation of two languages

How bilinguals represent and manage their two linguistic systems is a core issue in bilingualism. The received wisdom is that certain linguistic representations and processes seem to be shared across languages and that the two languages are active in parallel in most contexts[109-114]. Indeed, similar brain structures are involved when bilinguals use either of their two languages[115]. Consistent with the ‘convergence hypothesis’[116], the degree of neural overlap between the two languages depends primarily on second language proficiency and to some extent on age of acquisition of the second language. Also, it appears that the linguistic principles governing the organization of the two languages are the same[117, 118]. However, there is also evidence suggesting that some language control brain areas are differentially recruited in the first language and second language, often attributed to a more effortful processing of second language rather than to differences in the actual representation of the two languages[53, 119, 120].

Taken together, these results point in the direction of the neural circuitry housing the two languages of a bilingual being rather similar. Indeed, cortical regions in the traditional left perisylvian areas, involving specific frontal, temporal and parietal regions, together with some subcortical structures (such as the basal ganglia) seem to be functionally specialized in the processing of language computations, both for the first and second languages.

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BOX 3

Critical periods in language learning

Critical (or sensitive) periods refer to periods of time in which brain structures are especially sensitive to a specific environmental input, meaning that outside of these periods, the magnitude of the input needed to elicit changes in the brain increases dramatically[121]. The existence of critical periods in language learning — in particular, in second language acquisition — has been (and still is) a debated topic[122-125]. It is popularly assumed that native-like acquisition of a second language can be achieved if children are exposed to this second language before puberty (another common version of this assumption places the limit at before seven years of age)[126]. However, statements of this sort are an oversimplification, since they do not consider the different aspects of language learning, which may have different critical periods. Language requires various types of knowledge and computations (for example, auditory perception and abstract rule learning), which are supported by different brain structures, with different maturational timings[127-129]. Of note, the maturation of structures involved in auditory perception occurs within the first months of life[128, 130], whereas the maturation of the prefrontal structures (involved in planning and rule computations) extends well beyond puberty[98, 128]. Thus, the critical period relating to phonological computations that depend to some extent on auditory processing is quite restricted, but the critical period for grammatical rules may extend for much longer. Hence, the issue of critical periods in language learning needs to be considered in the context of the different linguistic domains.

The bilingual environment has often been considered to exemplify an enriched environment. As a result, one recurring statement often encountered when describing bilinguals is that they may exhibit delayed closing of sensitive periods relative to monolinguals[58]. Although this might be the case, the available evidence is far from conclusive, and studies showing delayed closure of critical periods in bilinguals have compared monolingual and bilingual groups from different populations, hence making it difficult to be certain about the origin of such a delay (for example, in some cases, socioeconomic status may have been the reason for differences between the study populations[131]). Importantly, evidence from animal studies that have linked increased brain plasticity to enriched environments comes primarily from studies analyzing the recovery from initially extreme deprivation environments. It has been observed[132] that enriched environments (that is, large cages with running wheels and toys) greatly reduce the adverse effects of early deprivation and improve visual acuity in adult animals (for a review, see REF[121]). Extrapolating the results from these deprivation studies to the case of differences in input between monolingual and bilinguals remains far-fetched.

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BOX 4

Brain damage and bilingualism

Since the first theories of language impairment in bilingual speakers were proposed in the XIX century, the issue of how brain damage affects the two languages of bilingual speakers has attracted the attention of neuropsychologists[133, 134]. This research has mostly focused on the differential effects that brain damage may have on the two languages of a bilingual. Indeed, several patterns regarding the relative impairment of the two languages have been described in these individuals (see[135] for a review). For example, there have been several reports of patients that, after a stroke, show a disproportionate impairment in one of their languages. Cases such these have been often used to inform theories regarding the cortical representation of the two languages and the control mechanisms that allow bilingual speakers to activate the intended language at will[136, 137]. Informative as these studies have been, there have also been some difficulties in interpreting their results. This is because it has been unclear what the premorbid characteristics of the bilingual patients have been and whether their deficits have arisen as a consequence of damage to linguistic knowledge or damage to the language control mechanisms[136].

Another aspect of the research involving neuropsychological patients that has attracted much interest is the type of language treatment that is most appropriate for any given patient; that is, should linguistic rehabilitation target the two languages simultaneously, or if only one, which one (for example, the first language or the better preserved language)? Is there transfer between the language targeted by the treatment and the other language? These questions are still debated, and it seems that each particular case may require different solutions[138]. Beyond the clear clinical implications that this research has, it can also help us to understand the relationship between the cortical representation of two languages and how the brain recovers functions after injury[139, 140].

To complement the studies presented above, researchers have started to explore how neurodegenerative diseases affect linguistic performance in bilinguals. Compared with post-stroke patients, patients with neurodegenerative diseases offer the opportunity of tracking linguistic performance alongside different patterns of progressive neuronal loss, and they also allow for a better control of premorbid knowledge of the two languages. At present, research has mostly focused on how Alzheimer’s disease (AD) and Parkinson’s disease (PD) affect language performance in bilinguals. Interestingly, given the different neural structures affected by these diseases, these studies can inform us about different aspects of bilingual language processing[136, 137, 141-144]. Since AD seems to affect neural structures involved in episodic and semantic memory (at least in its early stages), the study of bilingual AD patients can help us to better understand to what extent the representations of the two languages share a common neural substrate, and how robust such representations are[145, 146]. By contrast, understanding how PD affects linguistic performance in two languages in bilinguals can inform models of language control. This is because PD affects primarily the subcortical areas, such as the basal ganglia, and its connections with the prefrontal structures (frontostriatal network)[147, 148] that are supposed to be involved in bilingual language control[149]. However, caution needs to be exercised when drawing generalizations from this research to individual cases, since these diseases are often rather heterogeneous both in the brain structures affected and in the pattern of cognitive deficits.

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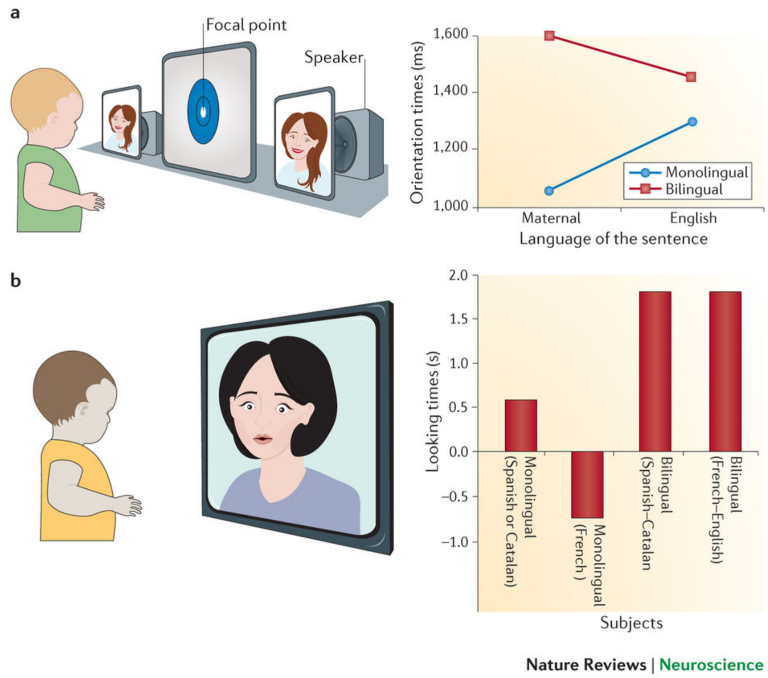

Figure 1. Two experiments comparing monolingual and bilingual infants' capacities to discriminate languages

(A) A study[9] presented 4-5 month old monolingual and bilingual Spanish-Catalan infants with English sentences (an unknown language to the infants) or with sentences of their maternal language (either Spanish or Catalan). Sentences from each language could randomly appear from the right or from the left from loudspeakers hidden behind pictures of women. Previous research with monolingual infants[150] had established that infants orientate their gaze faster to familiar than to unfamiliar languages. Indeed, monolingual Catalan and monolingual Spanish infants displayed the expected pattern (in blue in the figure). However, Spanish-Catalan bilingual infants showed the opposite pattern, and they oriented faster to the unknown language than to the maternal one. (B) In other studies infants were familiarized with silent video-clips of individuals speaking either French or English. Infants first saw silent video clips of three different French-English bilingual speakers speaking either in French or in English and their attention to the images was measured (looking times). Once their attention declined (habituation criterion) half of the infants saw new sentences in the same language and half of the infants saw new sentences in the other language. At the test phase monolingual and bilingual infants before the age of 8 months looked longer when presented with video clips from a different language from the one in the familiarization phase, indicating that all infants were able to discriminate the languages. However, at 8 months of age, only bilingual infants seem to be able to discriminate between the silent video-clips[14, 15]. Furthermore, previous experience with the languages of the silent video-clips does not have any significant influence on the capacity of bilingual 8-month-olds to discriminate them. The capacity to visually discriminate French from English is equivalent for infants exposed to French and English and for infants exposed to Spanish and Catalan. The figure shows the results of the monolingual and bilingual infants that saw the new sentences. It is shown the increment (or decrement) in looking times between the last trials of the habituation phase and the trials in the test phase (when a language change was introduced). As it can be seen, only bilingual 8-month olds significantly increased their looking times.