

OPINION

How does the bilingual experience sculpt the brain?

Albert Costa and Núria Sebastián-Gallés

Abstract | 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 affect language acquisition and processing as well as various aspects of cognition. We do so by addressing three main questions. First, how do infants who are exposed to two languages acquire them without apparent difficulty? Second, how does language processing differ between monolingual and bilingual adults? Last, what are the collateral effects of bilingualism on the executive control system across the lifespan? 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.

The pervasive presence of bilingualism shows that humans can learn two languages without apparent difficulty. However, bilingualism is 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 (BOX 1), 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 (BOX 1)). In addition, 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 languages¹. These differences in learning contexts and proficiency level pose methodological challenges in bilingual studies (BOX 2).

Most bilingual research has been carried out on adult successive bilinguals, specifically focusing 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 how simultaneously learning two languages affects the development of these languages (in simultaneous bilinguals), the impact of learning a second language on the processing of the first language (in

successive bilinguals) (BOX 1) and the effects of bilingualism on the mechanisms of cognitive functioning outside the language domain. These are the main topics of the present article. 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 3).

In the first section of this Opinion article, 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’ (REF. 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 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. Last, in the third section, we 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 simultaneous and successive bilingual infants, children, young adults and the elderly.

Language acquisition in bilingual infants

Learning a language involves acquiring knowledge about the specific properties of that language. Infants have to learn the specific phoneme repertoire (BOX 1), the words and the sophisticated grammatical

information (such as the location of articles and prepositions) of the language, 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 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 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 the speech types. 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. These important quantitative and qualitative differences between monolingual and bilingual learning contexts need to be considered when analysing language learning (BOX 4).

Language discrimination. A potential challenge faced by bilingual infants is the need to discriminate between the two languages that 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 between two languages, provided they sound very different, such as Tagalog and English⁵ or Dutch

Box 1 | Key terms and concepts

Cognitive reserve

This term refers to the resistance of certain aspects of cognition to brain damage. For example, neurodegenerative diseases can affect the cognitive abilities of different individuals to varying degrees, suggesting that the cognitive abilities of some individuals are more resistant to brain damage. Cognitive reserve seems to be related to, among other factors, environmental factors such as lifestyle and education.

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.

Convergence hypothesis

This hypothesis states that the neural networks involved in language acquisition and processing are similar for the first and second languages. This is not to say that some additional neural resources are not required when learning and using a second language. Indeed, the second language may, for example, require the recruitment of certain language control neural structures.

First language

This term refers to the first language (or languages) that an individual learns. In the case of simultaneous bilinguals, there is more than one first language. An equivalent term is 'native language'. A related concept is dominant language, which refers to the language that an individual feels more comfortable speaking or is fluent in. It is not uncommon that bilinguals change language dominance following, for example, immigration. Unless specified, in the present review, the term first language is used to refer to a language that was initially learned and that has remained the dominant one.

Inhibition

This term is used to describe a cognitive control mechanism that tunes out stimuli that are irrelevant to the task at hand. In bilingual conversations, it prevents the speaker from producing utterances in the undesired language by keeping its lexical nodes under the threshold for selection.

Lexical retrieval failures

This term refers to those speaking instances in which individuals make an error when producing a word. Such errors may involve saying a semantically related word instead of the target one (for example, 'apple' instead of 'peach'), saying a phonologically related word (for example, 'reach' instead of 'peach') or having difficulties to come up with the intended word in the absence of any intrusion. This type of difficulty in retrieving the intended word, often referred to as a 'tip-of-the-tongue state', seems to be more prevalent in bilinguals than in monolinguals, even if bilinguals try to retrieve the word in any of their two languages.

Monitoring

The process of evaluating the need to apply cognitive control mechanisms (for example, inhibition) in response to the current context. In bilingual conversations, monitoring is involved in determining which language to

speak to whom and, therefore, determines whether cognitive control mechanisms need to be applied to keep speaking in one language or switch to the other language.

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.

Phoneme repertoire

This term refers to the set of phonemes spoken in a specific language. It is also known as the phoneme space.

Phonological regularity distributions

This term refers to the fact that combinations of speech sounds can convey important information about a language. They may represent specific combinations of phonemes or other types of speech information. For example, in English, stress is placed on the first syllable in most nouns (unless they are monosyllables), so syllable stress is a useful cue to segment nouns in this 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 the phoneme space of their first language. This results in bilinguals speaking their first language with an accent. This shift occurs more often when the first language is used less frequently than the second language.

Simultaneous bilinguals

This 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 their second language within the first 2–3 years of life. Such individuals are also called first-language bilinguals.

Successive bilinguals

This term refers to bilinguals who are exposed to a 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 labelled 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 periods associated with language learning (BOX 4), respectively.

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 to demonstrate this principle, two objects are presented to an individual: one for which the individual knows the name and the other whose name is unknown. Upon hearing a new word, humans tend to assign the new word to the nameless object.

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.

and Japanese⁶. This capacity to differentiate between two languages is not restricted to humans. Previous studies have reported that cotton-top tamarin monkeys⁷ as well as Long-Evans rats⁸ can discriminate between Japanese and Dutch. Thus, the initial language discrimination capacities of humans may have nothing to do with previous exposure to language.

The ability to discriminate between more-similar languages, such as English and Dutch or Spanish and Italian, develops a bit later, at around 4–5 months of age, in both monolingual and bilingual infants, if they have previously been 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.

However, the bilingual experience does seem to affect the way in which language discrimination is achieved. One study⁹ involving bilingual and monolingual 4–5-month-olds showed that monolingual infants orientated faster to a familiar

Box 2 | **Methodological considerations in bilingualism research**

In contrast to learning a first language, the acquisition of a second language can occur in many more contexts. Indeed, second-language learners can vary considerably in terms of the age at which second-language acquisition occurs, the amount of exposure to that language, the motivation to learn the language, the type of learning experience and the degree of similarity between their two languages. This natural variation affords the opportunity to test relevant issues about language learning and brain plasticity, such as the presence of critical periods in language acquisition, but it also causes crucial methodological problems, such as finding homogeneous study groups of individuals that share equivalent linguistic experiences. In this regard, computational models might be promising tools to facilitate the identification of relevant variables affecting second-language processing while controlling for potential confounds^{102,103}.

Some individuals seem to be more 'talented' than others when learning a new language^{104,105}. The inherent variability in the factors that affect second-language learning, however, makes it difficult to determine the origin of the inter-individual differences in second-language proficiency. This issue is particularly relevant for neuroimaging studies that typically explore relatively small samples and thus can be more affected by heterogeneous sampling^{106,107}. Moreover, language studies involving individuals with neurological conditions (usually brain injury or neurodegenerative conditions) are especially affected by this variability, as premorbid language performance is often unavailable in these cases.

Furthermore, monolinguals and bilinguals often differ in terms of fundamental variables such as socioeconomic status and/or emigration. For example, in the United States, bilingualism is often associated with low socioeconomic status, as reflected by the fact that legislation referring to bilingual education is included in a Federal programme for disadvantaged students¹⁰¹. The correlation between emigration and bilingualism may, however, also be influenced by 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 emigrate¹⁰⁸).

language than to an unfamiliar one, whereas bilingual infants showed the opposite pattern (FIG. 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 by 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 discriminate between different languages when watching silent videos of people speaking these languages^{14,15}. One of these studies showed that French- or English-speaking monolingual infants and French-English-speaking bilingual infants (aged 4 and 6 months old) were able to discriminate people speaking French from those speaking English in silent videos. Crucially, however, this ability was only retained at 8 months of age by the bilingual infants¹⁴. In the other study, the same silent videos were presented to 8-month-old Spanish- or Catalan-speaking monolinguals and Spanish-Catalan bilingual infants who were never previously exposed to French or English. Again, only bilinguals were able to discriminate between the two languages¹⁵. Together, these observations suggest that bilingual infants show a specific adaptation in the attentional system that enables them

to perceive and track relevant information in two different systems (FIG. 1).

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.

Establishment of the phoneme repertoire and word learning. The fact that bilingualism does not hinder the ability to discriminate between 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 primarily focused 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 (or languages) that they are exposed to¹⁷. 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 ones²² (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 of assigning a concept to a word form (BOX 1). 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 (BOX 1). One of the regularities that monolingual and bilingual infants have to extract is the 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' but not 'putr' would conform to the pattern of an English word (even though 'putr' is not in fact an English word). In the second half of the first year of life, monolingual infants start showing sensitivity to these kinds of properties in the words of their native language²³. 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 abilities of 10-month-old monolinguals and bilinguals to differentiate possible from impossible word endings²⁴. Monolinguals and bilinguals showed an equivalent capacity to differentiate possible from impossible word endings in their shared language provided that it was the dominant language in the bilinguals' environment. If bilinguals were tested in their non-dominant language, then monolinguals showed greater discrimination of possible word endings than bilinguals. These data suggest that the identification of words in speech may be affected in bilinguals, but only in individuals for whom there is a clear

Box 3 | 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 languages¹¹⁵. Consistent with the ‘convergence hypothesis’ (REF. 116) (BOX 1), the degree of neural overlap between the two languages primarily depends on second-language proficiency and to some extent on the age of onset of second language acquisition. Also, it seems that the linguistic principles governing the organization of the two languages are the same^{117,118}. However, there is also evidence suggesting that some of the brain areas that are involved in language control are differentially recruited during first-language versus second-language use, and this is often attributed to the greater effort associated with second-language processing rather than to differences in the actual representation of the two languages^{53,119,120}.

Taken together, these results indicate that, in bilinguals, the neural circuits that ‘house’ their two languages are similar. Indeed, cortical regions in the left perisylvian areas, including 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.

difference between the exposure times to the two languages and only then in their more infrequently used 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 concepts²⁵ (BOX 1). 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 of time than the known object²⁵. The mutual exclusivity heuristic is a useful learning strategy given that objects tend to be labelled 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 of time, 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 early vocabulary development is compromised in some way 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, on the basis of currently available data, monolingual and bilingual infants are comparable in their capacities to discriminate between languages, to learn phoneme repertoires and to learn words. Certainly, the available evidence suggests that bilingualism does not seem to compromise language acquisition markedly. 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 reflect enhanced language processing in bilinguals compared with monolinguals are yet 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 (see REF. 31 for a review). These consequences have largely been identified in studies involving successive bilinguals, in which the performances of adult bilinguals in their first language in a wide range of tasks have been compared with those of adult monolinguals.

At a semantic level, the mapping of meanings to lexical items in one language may be influenced by the way in which corresponding lexical items in a bilingual’s other language are mapped into semantics³². That is,

word meanings in a given language may differ slightly between monolinguals and bilinguals. At a lexico-syntactic level, bilinguals retrieve and utter words slower than monolinguals and tend to experience more tip-of-the-tongue states than do monolinguals^{33–35}

(BOX 1). Also, bilinguals produce fewer words of a given semantic category in fluency tasks than do monolinguals³⁶. Together, these results show that, compared with monolinguals, bilinguals exhibit reduced speech fluency. Furthermore, the frequency of syntactic constructions in the second language affects bilinguals’ syntactic choices in their first language³⁷. At the phonological level, bilinguals’ phoneme boundaries differ from those of monolinguals. Thus, use of a second language shifts the phoneme space (as has been observed in individuals who have been living in a foreign country for a long period of time) (BOX 1). However, this does not mean that bilinguals cannot have two phonological repertoires, one for each language³⁸.

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 frequently than monolinguals use their language. Indeed, studies suggest that 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 between the first-language and second-language systems, leading to linguistic ‘transfer’ from the second to the first language³². 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 language³⁷. Interestingly, in extreme situations, linguistic transfer along with a reduced use of the first language can lead to first-language attrition⁴¹, such as in the case with international adoptions, in which the first language is often no longer (or very infrequently) used⁴².

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 (BOX 1), bilingual language processing is more taxing on these processes because bilinguals need to ensure that the right language is used in each communicative context. Furthermore, these control processes are especially important as bilinguals activate

Box 4 | 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 these periods, the magnitude of the input needed to elicit changes in the brain dramatically increases¹²¹. 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 7 years of age)¹²⁶. However, statements of this sort are an oversimplification, as 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 few 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 that is often encountered when describing bilinguals is that they may exhibit delayed closing of sensitive periods compared with monolinguals⁵⁸. Although this may be the case, the available evidence is far from conclusive, as 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 populations¹³¹). Importantly, evidence from animal studies that have linked increased brain plasticity to enriched environments primarily comes from studies analysing the recovery from initially extreme deprivation environments. It has been observed¹³² 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.

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 that they want to express, and hence they need to decide continuously which one to utter, in accordance with the situation, and to avoid intrusions from the other language (BOX 1). 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 of 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

(BOX 1) 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 than monolinguals⁵¹. However, the conclusions of these studies are limited by the fact that 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 use of bilingual or monolingual settings.

Perhaps the most convincing evidence for increased language-processing demands in bilinguals compared with monolinguals comes from a study⁵² in which highly proficient early successive bilinguals performed several linguistic tasks only in 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 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^{53–56} have convincingly argued that the head of the left caudate and the left anterior cingulate cortex are preferentially recruited during bilingual language processing in highly proficient early bilinguals. Furthermore, these authors suggest

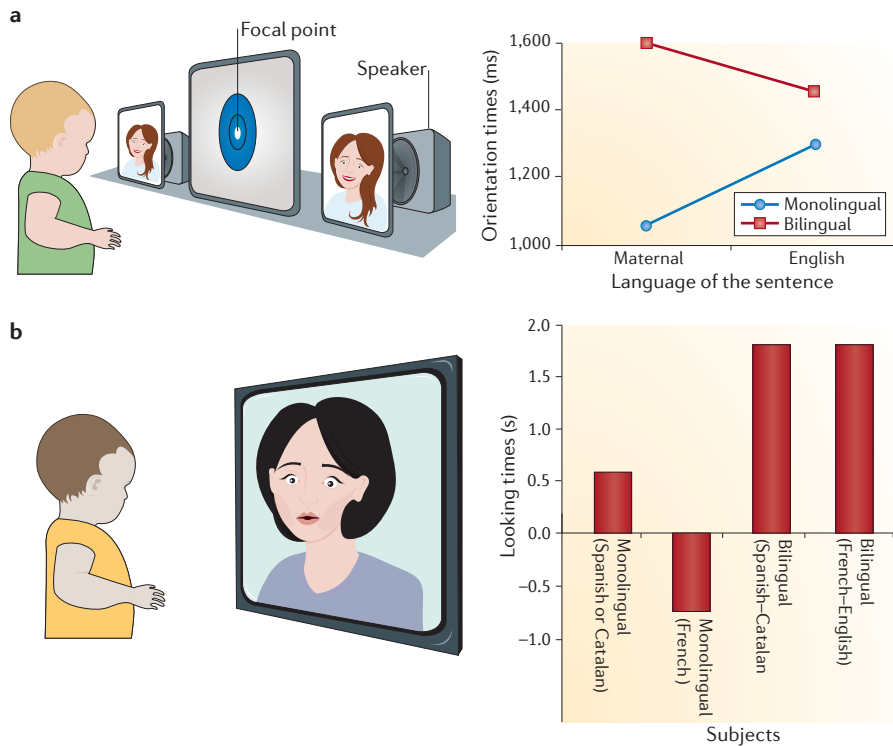


Figure 1 | Two experiments comparing monolingual and bilingual infants' capacities to discriminate between languages. **a** | In the first study, Spanish or Catalan monolingual and Spanish–Catalan bilingual 4–5-month-old infants were presented with English sentences (an unknown language to the infants) or with sentences of their maternal language (either Spanish or Catalan)⁹. These sentences from each language were randomly presented from one of two loudspeakers that were hidden behind pictures of women that were arranged on either side of a central screen (two colourful, dynamic images were successively displayed on the screen at the beginning of each trial (that is, before a sentence was played) to attract infants' attention). Previous research with monolingual infants¹⁵⁰ had established that infants orientate their gaze faster to the familiar than to the unfamiliar language. Indeed, monolingual Catalan and monolingual Spanish infants displayed the expected pattern (in blue). However, Spanish–Catalan bilingual infants showed the opposite pattern: they orientated faster to the unknown language than to the maternal one (in red). **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 between the languages. However, at 8 months of age, only bilingual infants seemed to be able to discriminate between the silent video clips^{14,15}. Furthermore, previous experience with the languages in the silent video clips did not seem to have any marked influence on the capacity of bilingual 8-month-olds to discriminate between them. The capacity to discriminate French from English visually was equivalent for infants exposed to French and English and for infants exposed to Spanish and Catalan. The bar chart shows 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) for monolingual and bilingual infants aged 8 months old. As can be seen, only the bilingual infants markedly increased their looking times. The graph in part **a** is reproduced, with permission, from REF. 9 © (1997) Elsevier. The chart in part **b** is reproduced, with permission, for REF. 15 © (2012) SAGE Publications.

that both of these 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). However, it must be mentioned

that the increase in processing demands associated with bilingualism can also lead to some processing benefits. For example, early highly proficient bilinguals show increased subcortical representation of linguistic sounds, as revealed by a larger electrical brain response in the range of the sounds'

fundamental frequencies, suggesting that bilinguals have more efficient and flexible auditory processing than monolinguals⁵⁸.

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 highly proficient bilinguals, on average, show increased grey matter in areas involved in verbal fluency tasks (left inferior parietal structures⁵⁹), articulatory and phonological processes (left putamen⁶⁰) and auditory processing (Heschl's gyrus⁶¹). Furthermore, changes in white matter tracts have also been reported to be associated with bilingualism⁶². A study of older highly proficient successive bilingual adults (70-year-olds) reported higher white matter integrity in the corpus callosum in bilinguals than in monolinguals⁶³. 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 variables⁵⁹. 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 that sustains the executive control system across the lifespan.

Behavioural consequences of the bilingual effect on executive control processes. The multifactorial executive control system involves processes such as inhibition (BOX 1), 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 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 lifespan; 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 crosstalk 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. Simultaneous bilingual infants are able to switch their attention more efficiently than monolingual infants in non-linguistic tasks at the age of 7 months⁷⁴, and at 18 months of age, they appear to have more-developed memory generalization processes⁸¹. 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 behavioural consequences for the mechanisms involved in executive control processes. Given these behavioural 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 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 monolinguals⁸². Moreover, early bilinguals seem to recruit fewer brain resources in conflict monitoring tasks than monolinguals, as revealed by a reduction in brain activity in the anterior cingulate cortex⁸³. Indeed, the anterior cingulate cortex seems to be specially tuned by bilingualism, given that its grey matter density (volume) is greater in early bilinguals than in monolinguals⁸³. Thus, neuroimaging studies convincingly show that bilingualism does have effects on brain structures involved in

executive control processes. These observations nicely complement the behavioural effects of bilingualism on the executive control system reviewed above (see also REF. 31).

The effects of long-life bilingualism on neural circuitry have been shown to promote cognitive reserve in elderly people⁶⁶. Elderly bilinguals outperform elderly monolinguals on executive control tasks^{66,85}, despite the fact that bilinguals recruit certain brain areas, such as the left lateral frontal cortex and cingulate cortex, to a lesser extent than monolinguals⁸⁶. Also, bilingualism promotes the maintenance of white matter integrity of the corpus callosum in elderly people⁶³, a finding that has further increased our understanding of the basis of cognitive reserve (BOXES 1, 5).

In this context, a striking observation that has deservedly captured media attention is that bilingualism seems to delay the behavioural 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, as 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

In the first section of this article, we have argued that currently available evidence suggests that bilingualism does not seem to compromise language acquisition, although the bilingual input seems to induce specific adaptations in the mechanisms that underlie this process. In subsequent sections, we have described how becoming bilingual affects first-language processing and executive control processes in adulthood. Across the

Box 5 | Brain damage and bilingualism

Since the first theories of language impairment in bilingual speakers were proposed in the nineteenth 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 individual. Indeed, several patterns of impairment of the two languages have been described in such individuals (see REF. 135 for a review). Cases such as these have often been used as the basis of theories about the cortical representation of two languages and the control mechanisms that enable 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 language characteristics of the bilingual patients were and whether their language deficits arose as a consequence of damage to linguistic knowledge or damage to the language control mechanisms¹³⁶.

Another aspect of the research involving bilingual patients with language deficits after brain injury 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)? Moreover, 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 solutions¹³⁸. 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 function after injury^{139,140}.

To complement the studies presented above, researchers have started to explore how neurodegenerative diseases affect linguistic performance in bilinguals. In contrast to linguistic performance in stroke, linguistic performance in neurodegenerative diseases can be tracked alongside the pattern of progressive neuronal loss. Moreover, studies of individuals with such diseases provide greater knowledge of the individuals' premorbid language capacities, enabling better controlled analyses of data. 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}. As AD seems to affect neural structures involved in episodic and semantic memory (at least in its early stages), the study of bilingual individuals with AD 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 primarily affects the subcortical areas, such as the basal ganglia and their connections with the prefrontal structures (frontostriatal network^{147,148}) that are supposed to be involved in bilingual language control¹⁴⁹. However, caution needs to be exercised when drawing generalizations from this research to individual cases, as these diseases are often rather heterogeneous in terms of the brain structures that are affected by the disease process and in the pattern of cognitive deficits.

Importantly, other than a handful of studies investigating international adoptions, few studies have explored the neural changes associated with switched language dominance. A closer inspection of this issue could facilitate the development of a better understanding of how brain plasticity changes across the lifespan. Moreover, a more-complete description of how the age at the time of acquisition of the second language affects first-language processing and executive control will be fundamental for understanding the origin of the reported bilingual effects at the behavioural and neural levels.

From a neural perspective, an outstanding issue that warrants further research is the development of brain networks in monolingual and bilingual children. For a long time, it has been assumed that the complex language network that supports language processing in adulthood is the outcome of a temporally protracted interaction between brain maturation and language exposure. The normal developmental course of language networks has been, and indeed largely still is, considered to involve increasing functional left-lateralization of and increasing involvement of frontal structures in these networks. However, recent findings indicate that such networks (both in terms of left-specialization and in the involvement of their frontal structures) may already be functional at birth⁹⁸, even in premature infants⁹⁹. 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.

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 to 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 cleverer than monolinguals¹⁰⁰. 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 education¹⁰¹.

Albert Costa and Núria Sebastián-Gallés are at the Center for Brain and Cognition, Department of Technology, Pompeu Fabra University, 08018 Barcelona, Spain.

Albert Costa is also at the ICREA (Institut Català de Recerca i Estudis Avançats), Passeig Lluís Companys, 23; 08010 Barcelona, Spain.

*Correspondence to A.C.
e-mail: costalbert@gmail.com
doi:10.1038/nrn3709*

three sections, we have proposed 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, although 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 life, possibly enhancing cognitive reserve in the elderly.

However, these conclusions 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 useful⁹⁴. If these conditions are not met, one finds situations of switched language dominance in which the second language of a bilingual becomes the dominant language^{95,96}. This is frequently the case in minority and immigrant populations⁹⁷. A more balanced use of the two (or more) languages by a bilingual individual should warrant full development of the first language and possibly of the collateral advantages in cognitive processes⁸⁰.

1. Grosjean, F. What bilingualism is NOT. *Multilingual Living* [online], <http://www.multilingualliving.com/2011/03/03/what-bilingualism-is-not/> (2010).
2. Genesee, F. Bilingual first language acquisition: exploring the limits of the language faculty. *Annu. Rev. Appl. Linguist.* **21**, 153–168 (2001).
3. Gervain, J. & Mehler, J. Speech perception and language acquisition in the first year of life. *Annu. Rev. Psychol.* **61**, 191–218 (2010).
4. Kuhl, P. K. Brain mechanisms in early language acquisition. *Neuron* **67**, 713–727 (2010).
5. Byers-Heinlein, K., Burns, T. C. & Werker, J. F. The roots of bilingualism in newborns. *Psychol. Sci.* **21**, 343–348 (2010).
6. Nazzi, T., Bertoni, J. & Mehler, J. Language discrimination by newborns: toward an understanding of the role of rhythm. *J. Exp. Psychol. Hum. Percept. Perform.* **24**, 756–766 (1998).
7. Ramus, F., Hauser, M., Miller, C., Morris, D. & Mehler, J. Language discrimination by human newborns and by cotton-top tamarin monkeys. *Science* **288**, 349–351 (2000).
8. Toro, J., Trobalon, J. & Sebastian-Galles, N. The use of prosodic cues in language discrimination tasks by rats. *Animal Cogn.* **6**, 131–136 (2003).
9. Bosch, L. & Sebastian-Galles, N. Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. *Cognition* **65**, 33–69 (1997).
10. Bosch, L. & Sebastian-Galles, N. Evidence of early language discrimination abilities in infants from bilingual environments. *Infancy* **2**, 29–49 (2001).
11. Nazzi, T., Jusczyk, P. W. & Johnson, E. K. Language discrimination by English-learning 5-month-olds: effects of rhythm and familiarity. *J. Mem. Lang.* **43**, 1–19 (2000).
12. Calvert, G. A. *et al.* Activation of auditory cortex during silent lipreading. *Science* **276**, 593–596 (1997).
13. van Wassenhove, V., Grant, K. W. & Poeppel, D. Visual speech speeds up the neural processing of auditory speech. *Proc. Natl Acad. Sci. USA* **102**, 1181–1186 (2005).
14. Weikum, W. M. *et al.* Visual language discrimination in infancy. *Science* **316**, 1159–1159 (2007).
15. Sebastian-Galles, N., Albareda-Castellot, B., Weikum, W. M. & Werker, J. F. A bilingual advantage in visual language discrimination in infancy. *Psychol. Sci.* **23**, 994–999 (2012).
16. Kuhl, P. K. Early language acquisition: cracking the speech code. *Nature Rev. Neurosci.* **5**, 831–843 (2004).
17. Kuhl, P. K. *et al.* Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Dev. Sci.* **9**, F13–F21 (2006).
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.* **14**, 395–401 (2011).
19. Burns, T. C., Yoshida, K. A., Hill, K. & Werker, J. F. The development of phonetic representation in bilingual and monolingual infants. *Appl. Psycholinguist.* **28**, 455–474 (2007).
20. Sundara, M., Polka, L. & Molnar, M. Development of coronal stop perception: bilingual infants keep pace with their monolingual peers. *Cognition* **108**, 232–242 (2008).
21. Pettito, L. A. *et al.* The “Perceptual Wedge Hypothesis” as the basis for bilingual babies’ phonetic processing advantage: new insights from fNIRS brain imaging. *Brain Lang.* **121**, 130–143 (2012).
22. Anderson, J. L., Morgan, J. L. & White, K. S. A statistical basis for speech sound discrimination. *Lang. Speech* **46**, 155–182 (2003).
23. Jusczyk, P. W., Friederici, A. D., Wessels, J., Svenkerud, V. Y. & Jusczyk, A. M. Infants’ sensitivity to the sound patterns of native language words. *J. Mem. Lang.* **32**, 402–420 (1993).
24. Sebastian-Galles, N. & Bosch, L. Building phonotactic knowledge in bilinguals: role of early exposure. *J. Exp. Psychol. Hum. Percept. Perform.* **28**, 974–989 (2002).
25. Markman, E. & Wachtel, G. Children’s use of mutual exclusivity to constrain the meanings of words. *Cogn. Psychol.* **20**, 121–157 (1988).
26. Byers-Heinlein, K. & Werker, J. Monolingual, bilingual, trilingual: infants’ language experience influences the development of a word-learning heuristic. *Dev. Sci.* **12**, 815–823 (2009).
27. Byers-Heinlein, K. & Werker, J. Lexicon structure and the disambiguation of novel words: evidence from bilingual infants. *Cognition* **128**, 407–416 (2013).
28. Houston-Price, C., Caloghris, Z. & Raviglione, E. Language experience shapes the development of the mutual exclusivity bias. *Infancy* **15**, 125–150 (2010).
29. Hoff, E. *et al.* Dual language exposure and early bilingual development. *J. Child Lang.* **39**, 1–27 (2012).
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.* **56**, 1637–1649 (2013).
31. Bialystok, E., Craik, F. I. M. & Luk, G. Bilingualism: consequences for mind and brain. *Trends Cogn. Sci.* **16**, 240–250 (2012).
32. Pavlenko, A. & Malt, B. C. Kitchen Russian: cross-linguistic differences and first-language object naming by Russian–English bilinguals. *Biling. Lang. Cogn.* **14**, 19–45 (2011).
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. *J. Exp. Psychol. Learn. Mem. Cogn.* **30**, 246–269 (2004).
34. Ivanova, I. & Costa, A. Does bilingualism hamper lexical access in speech production? *Acta Psychol.* **127**, 277–288 (2008).
35. Sadat, J., Martin, C. D., Alario, F. X. & Costa, A. Characterizing the bilingual disadvantage in noun phrase production. *J. Psycholinguist. Res.* **41**, 159–179 (2012).
36. Gollan, T., Montoya, R. & Werner, G. Semantic and letter fluency in Spanish–English bilinguals. *Neuropsychology* **16**, 562–576 (2002).
37. Runqvist, E., Gollan, T. H., Costa, A. & Ferreira, V. S. A disadvantage in bilingual sentence production modulated by syntactic frequency and similarity across languages. *Cognition* **129**, 256–263 (2013).
38. García-Sierra, A., Ramirez-Esparza, N., Silva-Pereyra, J., Siard, J. & Champlin, C. A. Assessing the double phonemic representation in bilingual speakers of Spanish and English: an electrophysiological study. *Brain Lang.* **121**, 194–205 (2012).
39. Gollan, T. H., Montoya, R. I., Cera, C. & Sandoval, T. C. More use almost always means a smaller frequency effect: aging, bilingualism, and the weaker links hypothesis. *J. Mem. Lang.* **58**, 787–814 (2008).
40. Baus, C., Costa, A. & Carreiras, M. On the effects of second language immersion on first language production. *Acta Psychol.* **142**, 402–409 (2013).
41. Schmid, M. S. Languages at play: the relevance of L1 attrition to the study of bilingualism. *Biling. Lang. Cogn.* **13**, 1–7 (2010).
42. Pallier, C. *et al.* Brain imaging of language plasticity in adopted adults: can a second language replace the first? *Cereb. Cortex* **13**, 155–161 (2003).
43. Green, D. W. Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cogn.* **1**, 67–81 (1998).
44. Kroll, J. F., Bobb, S. C., Misra, M. & Guo, T. Language selection in bilingual speech: evidence for inhibitory processes. *Acta Psychol.* **128**, 416–430 (2008).
45. Colomé, A. Lexical activation in bilinguals’ speech production: language-specific or language-independent? *J. Mem. Lang.* **45**, 721–736 (2001).
46. Thierry, G. & Wu, Y. J. Brain potentials reveal unconscious translation during foreign-language comprehension. *Proc. Natl Acad. Sci. USA* **104**, 12530–12535 (2007).
47. Spivey, M. J. & Marian, V. Cross talk between native and second languages: partial activation of an irrelevant lexicon. *Psychol. Sci.* **10**, 281–284 (1999).
48. Kovelman, I., Baker, S. A. & Pettito, L. Bilingual and monolingual brains compared: a functional magnetic resonance imaging investigation of syntactic processing and a possible “neural signature” of bilinguals. *J. Cogn. Neurosci.* **20**, 153–169 (2008).
49. Kovelman, I., Shalinsky, M. H., Berens, M. S. & Pettito, L. Shining new light on the brain’s “bilingual signature”: a functional near infrared spectroscopy investigation of semantic processing. *Neuroimage* **39**, 1457–1471 (2008).
50. Crinion, J. *et al.* Language control in the bilingual brain. *Science* **312**, 1537–1540 (2006).
51. Nosarti, C., Mechelli, A., Green, D. W. & Price, C. J. The impact of second language learning on semantic and nonsemantic first language reading. *Cereb. Cortex* **20**, 315–327 (2010).
52. Parker Jones, O. *et al.* Where, when and why brain activation differs for bilinguals and monolinguals during picture naming and reading aloud. *Cereb. Cortex* **22**, 892–902 (2012).
53. Abutalebi, J. Neural aspects of second language representation and language control. *Acta Psychol.* **128**, 466–478 (2008).
54. Abutalebi, J. *et al.* Language control and lexical competition in bilinguals: an event-related fMRI study. *Cereb. Cortex* **18**, 1496–1505 (2008).
55. Abutalebi, J. & Green, D. Bilingual language production: the neurocognition of language representation and control. *J. Neurolinguist.* **20**, 242–275 (2007).
56. Garbin, G. *et al.* Neural bases of language switching in high and early proficient bilinguals. *Brain Lang.* **119**, 129–135 (2011).
57. Zou, L., Ding, G., Abutalebi, J., Shu, H. & Peng, D. Structural plasticity of the left caudate in bimodal bilinguals. *Cortex* **48**, 1197–1206 (2012).
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. USA* **109**, 7877–7881 (2012).
59. Mechelli, A. *et al.* Neurolinguistics: structural plasticity in the bilingual brain. *Nature* **431**, 757 (2004).
60. Abutalebi, J. *et al.* The role of the left putamen in multilingual language production. *Brain Lang.* **125**, 307–315 (2013).
61. Ressel, V. *et al.* An effect of bilingualism on the auditory cortex. *J. Neurosci.* **32**, 16597–16601 (2012).
62. García-Pentón, L., Pérez Fernández, A., Iturría-Medina, Y., Gilón-Downs, M. & Carreiras, M. Anatomical connectivity changes in the bilingual brain. *Neuroimage* **84**, 495–504 (2014).
63. Luk, G., Bialystok, E., Craik, F. I. M. & Grady, C. L. Lifelong bilingualism maintains white matter integrity in older adults. *J. Neurosci.* **31**, 16808–16813 (2011).
64. Miyake, A. *et al.* The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: a latent variable analysis. *Cogn. Psychol.* **41**, 49–100 (2000).
65. Shallice, T. & Burgess, P. The domain of supervisory processes and temporal organization of behaviour. *Phil. Trans. R. Soc. Lond. B* **351**, 1405–1411 (1996).
66. Bialystok, E., Craik, F. I. M., Klein, R. & Viswanathan, M. Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychol. Aging* **19**, 290–303 (2004).
67. Costa, A., Hernandez, M. & Sebastian-Galles, N. Bilingualism aids conflict resolution: evidence from the ANT task. *Cognition* **106**, 59–86 (2008).
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* **113**, 135–149 (2009).
69. Bialystok, E. & Martin, M. M. Attention and inhibition in bilingual children: evidence from the dimensional change card sort task. *Dev. Sci.* **7**, 325–339 (2004).
70. Martin-Rhee, M. M. & Bialystok, E. The development of two types of inhibitory control in monolingual and bilingual children. *Biling. Lang. Cogn.* **11**, 81–93 (2008).
71. Prior, A. & MacWhinney, B. A bilingual advantage in task switching. *Biling. Lang. Cogn.* **13**, 253–262 (2010).
72. Hernández, M., Martin, C. D., Barceló, F. & Costa, A. Where is the bilingual advantage in task-switching? *J. Mem. Lang.* **69**, 257–276 (2013).
73. Stroop, J. R. Studies of interference in serial verbal reactions. *J. Exp. Psychol.* **18**, 643–662 (1935).
74. Kovacs, A. M. & Mehler, J. Cognitive gains in 7-month-old bilingual infants. *Proc. Natl Acad. Sci. USA* **106**, 6556–6560 (2009).
75. Hilchey, M. D. & Klein, R. M. Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychon. Bull. Rev.* **18**, 625–658 (2011).
76. Paap, K. R. & Greenberg, Z. I. There is no coherent evidence for a bilingual advantage in executive processing. *Cogn. Psychol.* **66**, 232–258 (2013).
77. Kousaie, S. & Phillips, N. A. Conflict monitoring and resolution: are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Res.* **1446**, 71–90 (2012).
78. Dunabeitia, J. A. *et al.* The inhibitory advantage in bilingual children revisited. *Exp. Psychol.* <http://dx.doi.org/10.1027/1618-3169/a000243> (2013).
79. Calabria, M., Hernandez, M., Branzi, F. M. & Costa, A. Qualitative differences between bilingual language control and executive control: evidence from task-switching. *Front. Psychol.* **2**, 399 (2012).
80. Prior, A. & Gollan, T. H. Good language-switchers are good task-switchers: evidence from Spanish–English and Mandarin–English bilinguals. *J. Int. Neuropsychol. Soc.* **17**, 682–691 (2011).

81. Brito, N. & Barr, R. Influence of bilingualism on memory generalization during infancy. *Dev. Sci.* **15**, 812–816 (2012).
82. Garbin, G. *et al.* Bridging language and attention: brain basis of the impact of bilingualism on cognitive control. *Neuroimage* **53**, 1272–1278 (2010).
83. Abutalebi, J. *et al.* Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cereb. Cortex* **22**, 2076–2086 (2012).
84. Rodríguez-Pujadas, A. *et al.* Bilinguals use language-control brain areas more than monolinguals to perform non-linguistic switching tasks. *PLoS ONE* **8**, e73028 (2013).
85. Kave, G., Eyal, N., Shorek, A. & Cohen-Mansfield, J. Multilingualism and cognitive state in the oldest old. *Psychol. Aging* **23**, 70–78 (2008).
86. Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J. & Smith, C. D. Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *J. Neurosci.* **33**, 387–396 (2013).
87. Bialystok, E., Craik, F. I. M. & Freedman, M. Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia* **45**, 459–464 (2007).
88. Craik, F. I. M., Bialystok, E. & Freedman, M. Delaying the onset of Alzheimer disease: bilingualism as a form of cognitive reserve. *Neurology* **75**, 1726–1729 (2010).
89. Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I. M. & Bialystok, E. Bilingualism as a contributor to cognitive reserve: evidence from brain atrophy in Alzheimer's disease. *Cortex* **48**, 991–996 (2012).
90. Chertkow, H. *et al.* Multilingualism (but not always bilingualism) delays the onset of Alzheimer disease: evidence from a bilingual community. *Alzheimer Dis. Assoc. Disord.* **24**, 118–125 (2010).
91. Crane, P. K. *et al.* Use of spoken and written Japanese did not protect Japanese-American men from cognitive decline in late life. *J. Gerontol. B Psychol. Sci. Soc. Sci.* **65**, 654–666 (2010).
92. Gollan, T. H., Salmon, D. P., Montoya, R. I. & Galasko, D. R. Degree of bilingualism predicts age of diagnosis of Alzheimer's disease in low-education but not in highly educated Hispanics. *Neuropsychologia* **49**, 3826–3830 (2011).
93. Sanders, A. E., Hall, C. B., Katz, M. J. & Lipton, R. B. Non-native language use and risk of incident dementia in the elderly. *J. Alzheimers Dis.* **29**, 99–108 (2012).
94. Schmid, M. S. in *Language Attrition. Theoretical Perspectives* (eds Köpke, B., Schmid, M. S., Keijzer, M. & Dostert, S.) 135–153 (John Benjamins, 2007).
95. Dewaele, J. M. in *First Language Attrition: Interdisciplinary Perspectives on Methodological Issues* (eds Schmid, M. S., Köpke, B., Keijzer, M. & Weilemar, L.) 81–104 (John Benjamins, 2004).
96. Schmid, M. S. & Dusseldorp, E. Quantitative analyses in a multivariate study of language attrition: the impact of extralinguistic factors. *Second Lang. Res.* **26**, 125–160 (2010).
97. Schmid, M. S. *Language Attrition* (Cambridge Univ. Press, 2011).
98. Leroy, F. *et al.* Early maturation of the linguistic dorsal pathway in human infants. *J. Neurosci.* **31**, 1500–1506 (2011).
99. Mahmoudzadeh, M. *et al.* Syllabic discrimination in premature human infants prior to complete formation of cortical layers. *Proc. Natl Acad. Sci. USA* **110**, 4846–4851 (2013).
100. Bhattacharjee, Y. Why bilinguals are smarter. *The New York Times* SR12 (18 Mar 2012).
101. Wiese, A. & García, E. The Bilingual Education Act: language minority students and US Federal education policy. *Int. J. Bilingual Educ. Biling.* **4**, 229–248 (2010).
102. Li, P. Computational modeling of bilingualism: how can models tell us more about the bilingual mind? *Biling. Lang. Cogn.* **16**, 241–245 (2013).
103. Dijkstra, T. & van Heuven, W. J. B. Modeling bilingual word recognition: past, present and future. *Biling. Lang. Cogn.* **5**, 219–224 (2002).
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. USA* **105**, 16083–16088 (2008).
105. Ventura-Campos, N. *et al.* Spontaneous brain activity predicts learning ability of foreign sounds. *J. Neurosci.* **33**, 9295–9305 (2013).
106. Tversky, A. & Kahneman, D. K. Belief in the law of small numbers. *Psychol. Bull.* **76**, 105–110 (1971).
107. Button, K. S. *et al.* Power failure: why small sample size undermines the reliability of neuroscience. *Nature Rev. Neurosci.* **14**, 365–376 (2013).
108. Chiswick, B. R. Are immigrants favorably self-selected? *Am. Econ. Rev.* **89**, 181–185 (1999).
109. Hartsuiker, R. J., Pickering, M. J. & Veltkamp, E. Is syntax separate or shared between languages? Cross-linguistic syntactic priming in Spanish–English bilinguals. *Psychol. Sci.* **15**, 409–414 (2004).
110. Dijkstra, A. & Van Heuven, W. J. B. in *Localist Connectionist Approaches to Human Cognition* (eds Grainger, J. & Jacobs, A. M.) 189–225 (Lawrence Erlbaum Associates, 1998).
111. Kroll, J. F., Bobb, S. C. & Wodniecka, Z. Language selectivity is the exception, not the rule: arguments against a fixed locus of language selection in bilingual speech. *Biling. Lang. Cogn.* **9**, 119–135 (2006).
112. Klein, D., Zatorre, R. J., Milner, B., Meyer, E. & Evans, A. C. Left putamen activation when speaking a second language: evidence from PET. *Neuroreport* **5**, 2295–2297 (1994).
113. Chee, M. W. Dissociating language and word meaning in the bilingual brain. *Trends Cogn. Sci.* **10**, 527–529 (2006).
114. Chee, M. W., Soon, C. S. & Lee, H. L. Common and segregated neuronal networks for different languages revealed using functional magnetic resonance adaptation. *J. Cogn. Neurosci.* **15**, 85–97 (2003).
115. Perani, D. *et al.* The bilingual brain. Proficiency and age of acquisition of the second language. *Brain* **121**, 1841–1852 (1998).
116. Green, D. W. in *The Interface between Syntax and the Lexicon in Second Language Acquisition* (eds van Hout, R., Hulk, A., Kuiken, F. & Towell, R.) 197–217 (John Benjamins, 2003).
117. Kotz, S. A. A critical review of ERP and fMRI evidence on L2 syntactic processing. *Brain Lang.* **109**, 68–74 (2009).
118. Willms, J. L. *et al.* Language-invariant verb processing regions in Spanish–English bilinguals. *Neuroimage* **57**, 251–261 (2011).
119. Golestani, N. *et al.* Syntax production in bilinguals. *Neuropsychologia* **44**, 1029–1040 (2006).
120. Luk, G., Green, D. W., Abutalebi, J. & Grady, C. Cognitive control for language switching in bilinguals: a quantitative meta-analysis of functional neuroimaging studies. *Lang. Cogn. Process.* **27**, 1479–1488 (2012).
121. Hensch, T. K. Critical period plasticity in local cortical circuits. *Nature Rev. Neurosci.* **6**, 877–888 (2005).
122. Epstein, S., Flynn, S. & Martohardjono, G. Second language acquisition: theoretical and experimental issues in contemporary research. *Behav. Brain Sci.* **19**, 677–714 (1996).
123. Li, P. Lexical organization and competition in first and second languages: computational and neural mechanisms. *Cogn. Sci.* **33**, 629–664 (2009).
124. Werker, J. & Tees, R. Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Dev. Psychobiol.* **46**, 233–251 (2005).
125. Juffs, A. Second language acquisition. *Wiley Interdiscip. Rev. Cogn. Sci.* **2**, 277–286 (2011).
126. Hu, W. Parents take language class into their own hands. *The New York Times* [online], <http://www.nytimes.com/2006/09/30/nyregion/30play.html> (2006).
127. Hickok, G. & Poeppel, D. The cortical organization of speech processing. *Nature Rev. Neurosci.* **8**, 393–402 (2007).
128. Huttenlocher, P. R. & Dabholkar, A. S. Regional differences in synaptogenesis in human cerebral cortex. *J. Comp. Neurol.* **387**, 167–178 (1997).
129. Huttenlocher, P. R. Dendritic and synaptic development in human cerebral cortex: time course and critical periods. *J. Dev. Neuropsychol.* **16**, 347–349 (1999).
130. Pujol, J. *et al.* Myelination of language-related areas in the developing brain. *Neurology* **66**, 339–343 (2006).
131. García-Sierra, A. *et al.* Bilingual language learning: an ERP study relating early brain responses to speech, language input, and later word production. *J. Phon.* **39**, 546–557 (2011).
132. Bartoletti, A., Medini, P., Berardi, N. & Maffei, L. Environmental enrichment prevents effects of dark-rearing in the rat visual cortex. *Nature Neurosci.* **7**, 215–216 (2004).
133. Pitres, A. Étude sur l'aphasie chez les polyglottes. *Rev. Méd.* **15**, 873–899 (in French) (1895).
134. Pearce, J. M. S. A note on aphasia in bilingual patients: Pitres' and Ribot's laws. *Eur. Neurol.* **54**, 127–131 (2005).
135. Paradis, M. in *Handbook of Neuropsychology* (ed. Berndt, R. S.) 69–91 (Elsevier Science, 2001).
136. Abutalebi, J., Rosa, P. A. D., Tettamanti, M., Green, D. W. & Cappa, S. F. Bilingual aphasia and language control: a follow-up fMRI and intrinsic connectivity study. *Brain Lang.* **109**, 141–156 (2009).
137. Green, D. W. & Abutalebi, J. Understanding the link between bilingual aphasia and language control. *J. Neurolinguist.* **21**, 558–576 (2008).
138. Farooqi-Shah, Y., Frymark, T., Mullen, R. & Wang, B. Effect of treatment for bilingual individuals with aphasia: a systematic review of the evidence. *J. Neurolinguist.* **23**, 319–341 (2010).
139. Green, D. W. in *Handbook of Bilingualism: Psycholinguistic Approaches* (eds Kroll, J. F. & de Groot, A. M. B.) 516–530 (Oxford Univ. Press, 2005).
140. Kiran, S., Grasmann, U., Sandberg, C. & Mäkkiläinen, R. A computational account of bilingual aphasia rehabilitation. *Biling. Lang. Cogn.* **16**, 325–342 (2013).
141. Costa, A. *et al.* On the parallel deterioration of lexicosemantic processes in the bilinguals' two languages: evidence from Alzheimer's disease. *Neuropsychologia* **50**, 740–753 (2012).
142. Gollan, T. H., Salmon, D. P., Montoya, R. I. & da Pena, E. Accessibility of the nondominant language in picture naming: a counterintuitive effect of dementia on bilingual language production. *Neuropsychologia* **48**, 1356–1366 (2010).
143. Zanini, S. *et al.* Greater syntactic impairments in native language in bilingual Parkinsonian patients. *J. Neurol. Neurosurg. Psychiatry* **75**, 1678–1681 (2004).
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.* **113**, 84–89 (2010).
145. de Souza, L. C., Lehericy, S., Dubois, B., Stella, F. & Sarazin, M. Neuroimaging in dementias. *Curr. Opin. Psychiatry* **25**, 473–479 (2012).
146. Ferreira, L. K., Diniz, B. S., Forlenza, O. V., Busatto, G. F. & Zanetti, M. V. Neurostructural predictors of Alzheimer's disease: a meta-analysis of VBM studies. *Neurobiol. Aging* **32**, 1733–1741 (2011).
147. Pavese, N. PET studies in Parkinson's disease motor and cognitive dysfunction. *Parkinsonism Relat. Disord.* **18**, S96–S99 (2012).
148. Ray, N. J. & Strafella, A. P. The neurobiology and neural circuitry of cognitive changes in Parkinson's disease revealed by functional neuroimaging. *Mov. Disord.* **27**, 1484–1492 (2012).
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* **19**, 462–469 (2012).
150. Dehaene-Lambertz, G. & Houston, D. Faster orientation latencies toward native language in two-month old infants. *Lang. Speech* **41**, 21–43 (1998).

Acknowledgements

The authors thank J. Abutalebi, D. Green, M. Bargaleta, P. Li, J. Corey, Y. Gilchinskaya and several members of the Center for Brain and Cognition at Pompeu Fabra University, Spain, for their comments on the manuscript. The authors are supported by grants from the European Community's Seventh Framework Programme (FP7/2007-2013): ERG grant agreement number 323961; Cooperation grant agreement number 613465 - ATHEME; the Spanish Ministerio de Economía y Competitividad (PSI2011-23033; PSI2012-34071; Consolider-Ingenio2010-CD5-2007-00012) and the Catalan Government (SGR 2009–1521). N.S.G. received the prize "ICREA Acadèmia" for excellence in research, funded by the Generalitat de Catalunya.

Competing interests statement

The authors declare no competing interests.