11 Studying Bilingualism Through Eye-Tracking and Brain Imaging

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Introduction

On November 24, 1978, a woman living in Morocco was hit by a car. She lost consciousness for fifteen minutes, as well as her ability to speak. Prior to the accident, she had spoken not one but two languages, as she was a native French speaker who had acquired Arabic later in life. After some time, a few words began to return to her – but not in French, the language she grew up with and had spoken since birth. Surprisingly, she could only communicate in Arabic, her second language (L2). Her native language remained lost to her for several more days (Paradis, Goldblum, & Abidi, 1982). Similar cases of multilingual aphasics selectively losing or recovering their languages have been reported on multiple occasions (e.g., Fabbro, 2001; for a discussion of the literature, see Green, 2005). Discoveries that a single language could be selectively disrupted, either through brain damage or through cortical stimulation (e.g., Ojemann & Whitaker, 1978, Rapport, Tan, & Whitaker, 1983), have fueled research into the shared and separate representations of the two languages in the bilingual brain. The question of how bilinguals activate, represent, and control their two languages thus remains a fertile area of theoretical and empirical inquiry, and technological advancements have enabled us to utilize an increasingly diverse set of tools to peer into the black box of bilingual cognition. In the present chapter, we focus on the contributions of two such tools: eye-tracking and functional magnetic resonance imaging (fMRI). We begin by discussing how languages are activated and review evidence from eye-tracking experiments revealing that bilinguals process multiple languages in parallel, even when only one is in use. We then review insights gained from the use of fMRI – first to determine how different languages are represented in the brain and then to identify the neural mechanisms underlying language control.

Eye-Tracking Research on Language Activation

Imagine you are a German-English bilingual and a friend announces that she has brought you a *gift*. Whether you say *thank you* or call the police will likely depend on whether she is speaking to you in English or German – because, in German, *Gift* means poison. What researchers have pondered for many years is whether, in either case, you would consciously or unconsciously consider the alternative. According to the traditional *language switch hypothesis*, bilinguals can selectively turn on and off their two languages (e.g., MacNamara & Kushnir 1971). However, there is now substantial research showing that, when a bilingual uses one language, the other language remains active. Evidence for this parallel activation has been found using numerous methodologies, including behavioral measures such as from lexical decision tasks (e.g., Dijkstra, van Hell, & Brenders, 2015; Duyck et al., 2007) and picture naming tasks (e.g., Christoffels, de Groot, & Kroll, 2006; Costa, Caramazza, & Sebastián-Gallés, 2000), as well as electrophysiological measures such as event-related potentials (ERPs; Carrasco-Ortiz, Midgley, & Frenck-Mestre, 2012; Hoshino & Thierry, 2011). Some of the most compelling evidence, however, comes from the use of eye-tracking, which is often paired with the visual world paradigm (see Huettig, Rommers, & Meyer, 2011 for a review of the methodology).

In these eye-tracking tasks, participants listen to spoken words while looking at a visual display. The pattern of eye movements over the display is thought to reflect real-time cognitive processing as the auditory stimulus unfolds. Studies of monolinguals have revealed that comprehension of spoken language proceeds incrementally, with multiple lexical candidates being considered as more features of the word are revealed over time (e.g., Tanenhaus & Spivey-Knowlton, 1996). For example, when the word *candy* is spoken, the listener will first activate various words that begin with /ca/ (e.g., *candy*, *cast*, *cactus*) and continue to narrow down the possibilities as more of the word is revealed. When a visual display is presented along with auditory input, the listener will often make eye movements not only to the target (e.g., *candy*) but also to competitors that are activated (e.g., *a candle*). This paradigm is thus ideally suited for evaluating whether listening to a word in one language activates only candidates within that language (i.e., selective lexical access) or words from other known languages as well (i.e., nonselective lexical access).

Using this method, Spivey and Marian (1999) demonstrated that, when Russian-English bilinguals listened to speech in one language, they activated phonologically similar words both within and across languages. For example, when asked to *click on the glove* in English,

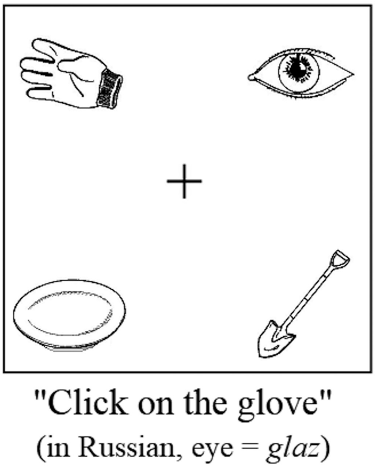

Figure 11.1 Example of a visual world display with a between-language competitor

participants would look not only at the picture of the glove but also at a picture of an eye (*glaz* in Russian; see Figure 11.1). The fact that bilinguals consider candidates both within and across languages suggests that different languages are not entirely separated within the cognitive architecture, in terms of either their representations or their selection processes. Since Spivey and Marian's (1999) initial findings, numerous eye-tracking experiments have found evidence of parallel activation during language comprehension (e.g., Blumenfeld & Marian, 2007; Marian & Spivey, 2003a, 2003b), spanning a diverse set of language pairs including Spanish and English (e.g., Ju & Luce, 2004), Japanese and English (e.g., Cutler, Weber, & Otake., 2006), Dutch and English (e.g., Lagrou, Hartsuiker, & Duyck, 2013; Weber and Cutler, 2004), German and Dutch (e.g., Lemhöfer, Huestegge, & Mulder, 2018), German and English (e.g., Blumenfeld & Marian, 2007; Hopp, 2017a, 2017b), French and German (e.g., Weber & Paris, 2004), Hindi and English (e.g., Mishra & Singh, 2014), and even across modalities in the case of American Sign Language (ASL)-English bilinguals (e.g., Giezen et al., 2015; Shook & Marian, 2012).

The majority of eye-tracking studies have demonstrated what may be considered "overt" coactivation, where the lexical item in the non-target language shares phonological features with the target stimulus (i.e., the word that is spoken in the task). However, there is also evidence of coactivation even when there is no phonological overlap between the spoken word and the competitor in the nontarget language. One example comes from Shook and Marian (2017), who found evidence of “covert activation” using the eye-tracking and visual world paradigm. When English-Spanish bilinguals were asked to click on a picture of a duck in English, they were more likely to fixate on a picture of a shovel than on other competitors in the display. This was despite the fact that the Spanish translation of *shovel* (*pala*) sounds nothing like *duck*; rather, the Spanish translations of the two words *pato* (*duck*) and *pala* (*shovel*) overlap phonologically at word onset. This pattern is predicted by connectionist models such as the *bilingual language interaction network for comprehension of speech* (BLINCS; Shook & Marian, 2013), which suggests that interconnected phonological, phono-lexical, ortho-lexical, and semantic representations organize themselves based on similarities and co-occurrences. An important feature of the model is that activation can spread across multiple levels of representation, as well as different languages, depending on their proximity within the representational space. In the present example, the English word *duck* activates its Spanish translation (*pato*), either via their shared concept or through a direct lexical association, which in turn activates phonological neighbors (e.g., *pala*) and their corresponding concepts (e.g., *a shovel*). In other words, phonological and lexical representations in the nontarget language can become activated even when there are no overt references to them at all.

In addition to phonological and lexical representations, there is evidence of parallel activation for syntax and grammar (Hopp, 2017a, 2017b; Morales et al., 2016). One way to assess syntactic coactivation using the visual world paradigm is to present participants with sentences that would lead to different interpretations depending on the syntax of each language. One then observes eye movements toward pictures depicting each of the interpretations. For example, a sentence such as “Which cow is the goat pushing?” unambiguously identifies the goat as the pusher according to English syntactic rules; yet activation of German syntax could lead to the conclusion that the cow is the pusher. Using this method, Hopp (2017a) observed that, when the syntax of the two languages could lead to conflicting interpretations, German-English bilinguals would look more often at a picture depicting the scene that would align with the syntax of the nontarget language compared to when there was no conflict. Together, these studies provide robust evidence of parallel activation at various levels of representation. The degree of coactivation, however, can vary depending on a number of factors.

Factors Constraining Language Activation

Language Background

Evidence of parallel activation is most often observed in cases where a more proficient nontarget language affects how a less proficient target language is processed (Cutler et al., 2006; Shook & Marian, 2016; Weber & Cutler, 2004). This pattern may feel quite intuitive to anyone who has tried to remember a foreign word while the native language looms stubbornly in its place. It may be more surprising, however, to find out that a lower proficiency language can influence how we process a higher proficiency language. Indeed, several studies utilizing different methodologies, including eye-tracking, have shown that a less proficient nontarget language can be activated in a monolingual dominant-language context (e.g., Lagrou et al., 2013; Lemhöfer et al., 2018; Shook & Marian, 2017). In other words, bilinguals can activate both dominant and nondominant languages even when they are not in use.

However, proficiency makes a difference to the extent and threshold of coactivation. For example, Blumenfeld and Marian (2007) observed that, while both English-German and German-English bilinguals fixated on nontarget German competitors when listening to English cognates (words that overlap with German in both form and meaning), those who were dominant in English showed no activation of German when listening to English noncognates. The fact that substantial lexico-semantic overlap was necessary to activate a nondominant, nontarget language demonstrates that coactivation is less robust when proficiency is lower in the nontarget language. In addition to differences in proficiency between L1 and L2, the degree of fluency *within* L2 can impact coactivation, both when the target language is an L2 (Hopp, 2017a; Pivneva, Mercier, & Titone, 2014) and when it is an L1 (Blumenfeld & Marian, 2013; Titone et al., 2011). In cases where the L2 is the target language, lower L2 proficiency has generally been associated with greater coactivation of L1. Libben and Titone (2009) and Pivneva et al. (2014) found that, while bilinguals were generally faster at processing L2 cognates than noncognates, those with lower L2 proficiency experienced the most facilitation as a result of overlapping forms and meanings with their L1. Hopp (2017a) similarly found that lower L2 proficiency was associated with greater L1 influence, though, in this case, processing of the L2 was compromised rather than facilitated due to activation of conflicting L1 syntax.

In addition to proficiency, language exposure has been shown to modulate the amount of parallel activation. For instance, Spivey and Marian

(1999) observed that Russian-English bilinguals were especially likely to fixate on between-language competitors when the nontarget language was English, the language of most frequent exposure. In an eye-tracking study assessing how Spanish-English bilinguals resolved syntactically ambiguous sentences in their L1, Dussias and Sagarra (2007) similarly observed that those with extensive L2 exposure were influenced by L2 syntax, while monolinguals and bilinguals with limited exposure were unaffected.

Linguistic Features

Language coactivation can vary depending on the degree of similarity between the bilingual's languages. Eye-tracking studies have demonstrated effects of variable overlap in linguistic features at the lexical level (e.g., cognates; Blumenfeld & Marian, 2007), as well as similarities in acoustic-phonological features (e.g., voice-onset times; Ju & Luce, 2004) and suprasegmental information (e.g., tones; Shook & Marian, 2016). At the phonological level, Ju and Luce (2004) found that Spanish-English bilinguals were more likely to fixate nontarget English competitors when the target Spanish word was altered to have English-appropriate voice-onset times. It would thus appear that features such as fine-grained phonetic information can constrain the pool of potential word candidates for selection (thereby reducing or increasing language coactivation depending on how much overlap there is in linguistic properties). At the lexical level, as noted in the previous section on "Language Background," Blumenfeld and Marian (2007) demonstrated that English-German bilinguals were more likely to fixate nontarget German competitors when the target English word was a German cognate (e.g., *guitar-Gitarre*) than when it was a noncognate. This suggests that, while a nontarget language can become activated through phonological overlap with words from the target language, additional semantic overlap leads to even greater coactivation.

While structural similarity between languages can influence the degree of parallel activation, evidence of coactivation has been found even among highly dissimilar languages. For example, Shook and Marian (2012) observed evidence of language coactivation among bimodal bilinguals. When English-ASL bilinguals heard a word in their L1, they were more likely to fixate on pictures of competitors that shared ASL phonology (e.g., hand shape, orientation) with the target translation. This finding demonstrates that parallel activation is not restricted to unimodal language processing and can emerge even when the two languages are highly dissimilar. Furthermore, it demonstrates that language coactivation can emerge not only from bottom-up features such as phonological input but also from top-down influences. In other words, in cases where the two languages have high phonological overlap, the phonological input can directly activate the lexical forms of the target and nontarget languages. However, even without shared phonology, phonological input can set off a chain of cascading activation. Phonological input activates lexical and semantic information in the target language, which then activates the corresponding lexical and phonological information in the nontarget language (eventually spreading to phonologically similar words in the nontarget language).

In sum, evidence from research utilizing eye-tracking suggests that the bilingual's languages are highly interactive. While the degree of coactivation can vary depending on factors such as relative proficiency in the two languages and cross-linguistic similarities, parallel activation has consistently been observed with speakers of many different languages and at multiple levels of representation. The studies reviewed thus far have examined how bilinguals process linguistic input in order to understand how different languages are accommodated in the mind. Other methods such as fMRI have allowed researchers to approach the puzzle of bilingual cognition in a different way – by examining how different languages are processed and represented at the neurological level.

fMRI Research on Neural Representation and Language Control

fMRI has become a popular tool for investigating language processing due to its high spatial resolution, making it ideal for identifying which regions and networks in the brain are associated with particular cognitive tasks. As neurons fire, the amount of blood oxygenation in that area changes, making it an indirect measure of brain activity. The question of whether different languages have shared or separate representations has thus been investigated by examining the neural activation associated with each language. A key point to keep in mind, however, is that cognitive processes are not supported by single isolated regions of the brain but rather complex networks of activity that can vary depending on task demands, individual differences, environmental factors, and more. Additionally, even if overlapping *neural* representations are observed, it does not necessarily mean that different languages have a shared mental store or even that they recruit the same processes, as the same brain areas may be used in different ways (see van Heuven & Dijkstra, 2010 for a discussion of functional vs. neural separation). The question of whether the bilingual's languages have shared or separate representations, especially beyond the neurological level, is thus unlikely to have a simple answer. Rather, it may be more informative to try to understand the factors that influence the degree of neural overlap in order to reveal the complex interactions between language, behavior, the environment, and the brain.

We begin by examining how language background, linguistic features, and stages of processing influence the neural activity elicited by different languages. While we will touch on both the loci and the strength of neural activation, our initial discussion will primarily center on how different variables moderate the degree of overlap across languages rather than on particular brain regions. The involvement of specific cortical and subcortical areas will be discussed in greater detail when we approach the topic of language control. How bilinguals resolve linguistic conflicts can be inferred by identifying the areas of the brain that are recruited for the task and considering whether other, nonlinguistic functions make use of these same regions. We start with the question of whether neural representations are shared across L1 and L2 and end with whether control processes are shared across linguistic and nonlinguistic domains.

Neural Representation

Why might we expect different languages to be associated with distinct representations and/or processes? It is possible that we store and process linguistic information differently depending on the contexts in which it is acquired (Weinreich, 1953). Alternatively, the memory systems utilized at different levels of representation (e.g., lexical, grammatical) may vary depending on the amount of exposure to each language. According to Ullman's (2001) *declarative/procedural model*, lexical information such as vocabulary is represented and processed by the declarative memory system, which handles semantic knowledge (e.g., dates, facts), while grammatical information recruits the procedural memory system, which is associated with skills and habits (e.g., riding a bike). However, even procedural tasks that eventually become second nature often begin as a series of steps that must be explicitly recalled from declarative memory. As such, Ullman suggests that grammar may be represented and processed by different memory systems depending on the amount of linguistic expertise. Since each memory system is subserved by different brain regions (primarily temporal/parietal in the case of declarative memory and frontal/subcortical in the case of procedural), it is plausible that L1 and L2 could be associated with distinct patterns of neural activation.

Numerous researchers have set out to investigate this possibility, but the results have been mixed. While there has been some indication of neural segregation (e.g., Golestani et al., 2006; Ip et al., 2017;

Kovelman, Baker, & Petitto, 2008; Marian et al., 2007; Tham et al., 2005; Xu et al., 2017), most evidence suggests that bilinguals recruit similar brain regions when using their two languages (e.g., Consonni et al., 2013; Gandour et al., 2007; Jeong et al., 2007; Johnson et al., 2018; Liu et al., 2010). These discrepant findings highlight the need to consider potential moderators that may be influencing how and when different languages elicit distinct patterns of neural activity. While it can be difficult to isolate the impact of a specific variable due to the fact that most studies differ from each other along multiple dimensions, general trends can help identify the factors that are most likely to matter.

Language Background

In one of the most prominent examples of neural segregation, Kim et al. (1997) observed distinct centers of activation in the left inferior frontal gyrus (LIFG) when late bilinguals silently generated sentences in either their L1 or L2, the latter of which was acquired at the mean age of eleven. Interestingly, no such difference was detected for early bilinguals who had been exposed to both languages since infancy. Age of acquisition (AoA) was therefore proposed to be a significant factor in influencing the functional organization of the brain. However, AoA is often confounded with proficiency; and several studies have failed to find an effect of AoA once late and early bilinguals are matched on proficiency (e.g., Briellmann et al., 2004; Chee, Tan, & Thiel, 1999; Frenck-Mestre et al., 2005; but see Archila-Suerte, Zevin, & Hernandez, 2015; Wartenburger et al., 2003). Proficiency, on the other hand, has consistently been shown to affect neural activation patterns (see Abutalebi, Cappa, & Pareni, 2001). Most commonly, less proficient languages are associated with greater activation of the same regions as L1 (Chee et. al, 2001; Golestani et al., 2006; Perani et al., 2003). These increased activation patterns are often interpreted as resulting from the greater cognitive effort required for processing less proficient languages (Hasegawa et al., 2002). In other words, when differential activity is found between L1 and L2, it is likely to reflect different levels of demand placed on the cognitive system rather than separate linguistic representations. Greater activation in overlapping neural regions has even been observed among native English speakers processing ASL, their nondominant language (Johnson et al., 2018; Williams, Darcy, & Newman, 2018). This demonstrates that even highly dissimilar languages recruit similar regions and follow typical patterns of differential activation based on proficiency.

Linguistic Features

While variables related to language ability are the most frequently examined moderators, the amount of neural overlap between languages can also vary as a function of linguistic features. For example, Jeong et al. (2007) observed that more structurally distant languages were associated with more distinctive activation patterns (but see Chee, Caplan et al., 1999). In some cases, researchers have observed differential activation due to features of specific languages such as orthographic transparency (Meschyan & Hernandez, 2006) and morphology demands (Ip et al., 2017). Momenian and colleagues (2018) observed that there was greater activation in BA44, a region associated with syntactic processing, when late bilinguals covertly generated verbs in their more morpho-syntactically complex native language, Persian, relative to their L2, English. Note that this finding runs counter to the usually observed increase in activation when using a less proficient language. Indeed, when engaged in a noun generation task that did not involve syntactic processing, the pattern reversed, with greater BA44 activation in English, following the typical pattern. This finding demonstrates not only that the degree of overlap can vary as a function of participant and linguistic characteristics but that these factors may interact with the stage of processing.

Stages of Processing

Overlapping neural regions for L1 and L2 have been observed during multiple stages of processing (e.g., phonological, syntactic, semantic). However, the degree of activation can vary, most often with greater activation in the less proficient language. During phonological processing, the detection of nonnative phonetic contrasts has been associated with greater activation of auditory and articulatory brain regions relative to native contrasts (e.g., Callan et al., 2004). With increased proficiency, however, nonnative activation begins to converge to a greater extent with that of native phonetic contrast processing (e.g., Golestani & Zatorre, 2004; see Golestani, 2016 for review). While there have been relatively few fMRI studies comparing L1 and L2 phonology, the available data indicate that the same neural networks are recruited, regardless of language, even at early stages of linguistic processing.

Overlapping neural activation has also been observed during syntactic processing. Frontotemporal and subcortical regions are associated with both L1 and L2 syntax, with varying degrees of activation depending on proficiency, AoA, and exposure (e.g., Golestani et al., 2006; Johnson et al., 2018; Wartenberger et al., 2003; see Kotz, 2009 for review). The effect of exposure may be further moderated by the degree of cross-linguistic similarity between L1 and L2. Jeong et al. (2007) observed that activation in the basal ganglia decreased with increased exposure to L2 (Japanese) for bilinguals with a syntactically dissimilar L1 (Chinese) but not for those with a syntactically similar L1 (Korean). The amount of activation in a given region thus appears to be highly sensitive to a number of different variables. Yet, contrary to Ullman's (2001) declarative/procedural model, the loci of activation for syntactic processing are remarkably consistent across languages.

Lastly, overlapping activation has also been reported during lexico-semantic processing, with both L1 and L2 engaging frontal, temporal, and parietal regions to varying degrees depending on proficiency (e.g., Chee et al., 2003; Klein et al., 2006). For instance, Chee et al. (2000) observed greater activation in the LIFG when processing semantic information in L2. According to models like Weinreich's (1953) *compound-coordinate model* and Kroll and Stewart's (1994) *revised hierarchical model*, the links between lexical and conceptual representations can vary in strength depending on language expertise. Both models propose that some L2 lexical representations may not even have direct connections to the conceptual level, instead relying on lexical mediation through L1. If so, greater L2 activation observed in the LIFG may reflect more effortful retrieval of semantic information, providing further evidence that different languages are represented in comparable locations but with variable strengths of activation depending on processing demands.

Despite the apparent consistency across different types of language tasks, a number of studies have uncovered interactions between languages and stages of processing. In one experiment, Marian, Spivey, and Hirsch (2003) isolated neural activity associated with lexical processing (by comparing words to nonwords) and phonological processing (by comparing auditory to visual stimuli) in the participants' L1 and L2. Similar areas were activated in the two languages (namely the LIFG and the superior temporal gyrus [STG]); however, some differences emerged, both across languages and across levels of representation. For instance, the LIFG was active during both lexical and phonological processing, but activation of the STG was only observed during phonological processing. Furthermore, consistent with the findings of Kim et al. (1997), there were distinct centers of activation for L1 and L2 (as well as overall greater activation in L2) in the LIFG but not in the STG. Marian et al. (2007) similarly observed distinct centers of activation in the LIFG for phonological and lexical processing but not orthographic processing, potentially as a result of less recruitment of the IFG when visually processing language. In a separate comparison of activity elicited by syntactic and semantic violations, Ruschemeyer et al. (2005) observed greater L2 activation in the IFG for correct and syntactically incorrect sentences but not for semantically incorrect sentences. The authors propose that syntactic violations are easily detected based on structural features in L1 but not in L2, making syntactic processing considerably easier in the L1. Semantic violations, on the other hand, cannot be detected based on structural features and are thus more difficult to detect in both languages. In other words, there was the typical increase in activation when using the more effortful L2 but only when the task was relatively easy in L1. Together, the data suggest that, in spite of generally overlapping neural representations, some differences can emerge as a consequence of specific task demands inherent to a given stage of processing.

Multi-voxel Pattern Analysis

More recently, methods such as multi-voxel (or multivariate) pattern analysis (MVPA) have been employed to obtain a more fine-grained assessment of neural activation in bilinguals. Unlike traditional univariate fMRI analyses, which measure the overall activity of a voxel or brain region, MVPA tracks patterns of activity across voxels to identify the structural distribution associated with a particular task, process, or concept (see Davis & Poldrack, 2013). For instance, using MVPA and machine learning, Just et al. (2010) demonstrated that it was possible to identify a representation of a specific noun (e.g., an apple) among sixty possible candidates.

Applying MVPA to bilingual language processing, Buchweitz et al. (2012) were able to predict what word Portuguese-English bilinguals were silently reading in one language by matching their activity to patterns associated with the other language. That is, the distribution of activity associated with individual concepts had significant overlap across languages. Similar results have been obtained in language production tasks after assuring that translation equivalents did not share any phonological or orthographic features, thereby isolating the effect of semantic processing (Van de Putte et al., 2017). The ability to identify the concept that was comprehended or produced in one language using activation patterns of the other language thus provides strong evidence of at least partial neural overlap of semantic representations. Indeed, a recent study by Zinszer et al. (2015) demonstrated that this type of "neural translation" as a result of overlapping activation patterns could be achieved not only across different languages but across different people, suggesting that neural representations at the semantic level are remarkably consistent. On the other hand, Xu et al. (2017) observed distinct patterns of activation across multiple regions (including middle occipital cortices, fusiform gyri, and lateral temporal, temporoparietal, and prefrontal cortices) when Chinese-English bilinguals completed an implicit reading task in L1 or L2. While the task was not designed to isolate a particular stage of processing, these findings demonstrate that MVPA can be useful in identifying functionally independent neural populations that might be missed when utilizing traditional univariate analyses.

Future studies employing increasingly sensitive methods may continue to uncover evidence of distinct neural activity associated with different languages. However, what is clear from the available data is that different languages not only are represented by similar (if not the same) neural networks but can remain active in the background even when they are not in use. So how are bilinguals able to avoid interference and function in a monolingual language mode? The next section discusses findings from fMRI experiments that may help elucidate the mechanisms underlying bilingual language control.

Language Control

The degree to which bilinguals are able to resolve competition both within and across languages has been linked to individual differences in cognitive control (e.g., Blumenfeld & Marian, 2011; Pivneva, Mercier, & Titone, 2014). Blumenfeld and Marian (2013) observed that English-Spanish bilinguals with greater cognitive control, as assessed by nonlinguistic Stroop performance, initially experienced greater levels of parallel activation followed by greater inhibition of cross-linguistic competitors at later stages of lexical processing. Giezen et al. (2015) observed that greater cognitive control was associated with reduced parallel activation even among bimodal bilinguals. This suggests that control processes may be involved in the resolution of competition at the lexico-semantic level as well as at the phonological level.

Consistent with the behavioral evidence, studies utilizing fMRI have revealed that brain regions associated with domain-general cognitive control are activated during the detection and resolution of cross-linguistic conflict. A common way of assessing the neural correlates of bilingual language control involves language switching, usually during language production (e.g., picture naming). In a typical language switching task, participants are presented with a stimulus and are cued to identify or respond to it in one of the two languages. Differences in activation observed when switching vs. not switching languages are believed to capture neural processes underlying bilingual language control. While activity in numerous brain regions has been associated with language switching, which can vary depending on task, language, and participant characteristics, areas consistently implicated in language control include the prefrontal cortex (PFC), anterior cingulate cortex (ACC) and the neighboring pre-supplementary motor area (pre-SMA), and subcortical regions such as the basal ganglia (BG).

Prefrontal Cortex

The PFC, and especially the dorsolateral prefrontal cortex (DLPFC), is strongly implicated in cognitive control processes, goal maintenance, and the resolution of conflict (including both response selection and inhibition; Branzi et al., 2016; Hernandez et al., 2001). While the PFC is associated with domain-general cognitive control (Miller & Cohen, 2001), it is also believed to be involved in a number of functions related to language processing, including semantic retrieval (Badre et al., 2005), phonological retrieval (Gold & Buckner, 2002), and conflict resolution during bilingual language production (Abutalebi & Green, 2008; Hernandez et al., 2009). Within the PFC are the superior, middle, and inferior frontal gyri, the latter of which is believed to be specifically associated with reducing interference from irrelevant inputs, such as a nontarget language (Abutalebi & Green, 2016). Activity in the PFC is especially sensitive to differences in proficiency, with greater activation when utilizing less proficient languages, likely as a result of greater demands (e.g., Hernandez & Meschyan, 2006; Wartenburger et al., 2003). Indeed, one of the most commonly observed differences across languages is a relative increase in PFC activation when using L2.

Pre-supplementary Motor Area/Anterior Cingulate Cortex

Whereas the PFC is commonly associated with conflict resolution, both the ACC and the pre-SMA are associated with conflict monitoring and the regulation of attention during general cognitive processing (Kerns et al., 2004; Ullsperger & Von Cramon, 2001), as well as bilingual language control (Branzi et al., 2016; Seo, Stocco, & Prat, 2018). In a recent study, Seo et al. (2018) observed that the most significant ACC activity occurred during the language cueing phase of a switch task rather than during the execution of the language task itself, suggesting that it may be primarily recruited during the "planning" stages of bilingual language processing. In comparison to the PFC, the role of proficiency for ACC activation is less consistent. For example, Wang et al. (2007)

observed activation in the left ACC when participants switched into the nondominant language but not when they switched into the dominant language, suggesting that the ACC may be more involved when preparing to utilize a less proficient language. Similar patterns have been observed in the pre-SMA (de Bruin et al., 2014). In contrast, Abutalebi et al. (2013) observed similar pre-SMA/ACC activation during switches regardless of proficiency. Instead, the researchers observed that switching into a lower proficiency language enhanced activation of the left caudate nucleus, located in the BG.

Basal Ganglia

The BG, which include a number of subcortical structures such as the caudate, putamen, and substantia nigra, are involved in coordination and control for numerous functions related to procedural memory, skill learning, and planning, as well as language (see Stocco, Lebiere, & Anderson, 2010 for review). BG are believed to play an important role in controlling and keeping track of multiple languages (Crinion et al., 2006). Indeed, damage to the region has been associated with pathological switching between languages (Abutalebi, Miozzo, & Cappa, 2000). Seo et al. (2018) observed that, unlike the ACC, which was primarily active during language cueing stages of a switch task, consistent BG activity was found throughout the task. The researchers therefore proposed that the ACC's role may be primarily top-down language monitoring and preparation, whereas the BG, and especially the left caudate, may be used to keep track of the two languages and control interference throughout execution. An important feature of the BG is that they are rich in dopamine, potentially allowing for quick reward-mediated learning and high cognitive flexibility (Pasupathy & Miller, 2005). They may thus be ideally suited for coordinating with the slower DLPFC to efficiently select and inhibit different languages, as proposed by Abutalebi and Green's (2008) *model of language control networks*.

Neural Correlates of Cross-Linguistic Conflict Resolution During Comprehension

The fMRI studies reviewed thus far demonstrate that a network of brain regions associated with domain-general executive control is recruited to manage interference from nontarget languages during bilingual processing. However, the majority of fMRI studies on language control have involved language production tasks. While there are likely to be overlapping neural regions recruited to resolve language conflict in both production and comprehension, each task comes with distinct processing demands as well. Activation of domain-general executive control regions is predicted by some models of both language production (e.g., the *inhibitory control model*; Green, 1998) and comprehension (e.g., *bilingual interactive activation plus [BIA+] model*; Dijkstra & van Heuven, 2002). The BIA+ model and the previously discussed BLINCS model (Shook & Marian, 2013) both seek to explain language comprehension, though the former is centered on visual word recognition (i.e., reading) while the latter is designed for spoken word recognition (i.e., listening). A shared feature of the two models is the inclusion of an integrated lexicon that is accessed through bottom-up activation of lexical representations (e.g., phonological, orthographic, and semantic information). According to the BIA+ model, candidates from both languages are activated by the word-identification system and an independent task/decision system resolves the competition by recruiting domain-general executive control functions. The BLINCS model, on the other hand, allows for language-specific selection without necessarily recruiting top-down control mechanisms as a result of how lexical representations organize themselves based on shared features. The model does, however, include the flexibility to accommodate general inhibitory control mechanisms. The potential involvement of both domain-general and language-specific selection processes during comprehension thus merits direct examination of its neural substrates.

Abutalebi et al. (2007) conducted a study in which Italian-French bilinguals passively listened to sentences that either did or did not contain a language switch. Switching activated a network involving prefrontal (including the LIFG) and temporal regions. As in some language production studies (e.g., Wang et al., 2007), the researchers observed activation in the caudate nucleus and the ACC when switching into the nondominant language. Van Heuven et al. (2008) investigated language conflict using two lexical decision tasks involving interlingual homographs (words from different languages that overlap orthographically but not semantically, e.g., *boom*, meaning “tree” in Dutch). Participants were Dutch-English bilinguals reading words in their L2 (English). For the English lexical decision (ELD) task, participants had to press a button if they saw a real English word. Parallel activation of the Dutch word was expected to cause interference as the response (English/not English) would differ for the two activated representations. For the general lexical decision (GLD) task, participants pressed a button if they saw a real word in either language and thus did not involve response competition. The ELD task activated the pre-SMA, ACC, and caudate nucleus/BG implicating these regions in the resolution of response conflict. The left IFG was activated when processing interlingual homographs compared to control words in both tasks, demonstrating the involvement of the PFC in the resolution of stimulus-based conflict. Together, these findings indicate that similar executive control regions are recruited to resolve conflict during comprehension and production, though the activation of specific regions differs depending on whether or not the two languages require different responses. In a similar study, Hseih et al. (2017) observed greater activation in the bilateral IFG, SMA, caudate nucleus, and left fusiform gyrus when processing interlingual homographs relative to cognates (i.e., during response-based conflict). Greater activity in the ACC, left thalamus, and left middle temporal gyrus were observed for interlingual homographs compared to cognates and control words of both languages, implicating their possible involvement in semantic conflicts.

During auditory comprehension using a visual world paradigm, Marian et al. (2017) demonstrated that there is differential activation and recruitment of neural resources depending on whether participants experienced between- or within-language phonological competition. Specifically, increased activation was observed in the left putamen and caudate, the right middle frontal gyrus, and superior frontal gyrus during between-language competition but not during within-language competition. Furthermore, greater activation was observed when the target language was lower proficiency, mirroring behavioral findings. Together, these findings once again demonstrate the involvement of domain-general executive control regions and that greater neural resources are recruited to resolve competition between languages compared to within. This latter finding is especially informative in light of the result of another auditory comprehension study in which Marian et al. (2014) observed that executive control regions were activated for resolving within-language competition for monolinguals but not bilinguals. One explanation may be that the consistent practice managing both within- and between-language competition results in more efficient deployment of neural resources for bilinguals compared to monolinguals. Indeed, this would be consistent with the numerous studies finding evidence of enhanced executive control among bilinguals (see Bialystok, 2009 for review). Bilingualism has also been associated with structural changes such as increased white (Mohades et al., 2012) and gray matter density (Mechelli et al., 2004), demonstrating that the cognitively complex task of controlling multiple languages can have consequences that extend beyond language processing.

General Conclusions

In the present chapter, we have reviewed the various ways in which studies utilizing eye-tracking and fMRI shed light on the cognitive architecture underlying bilingual language processing. By focusing on the contributions of these specific methods, we highlight not only the findings that have enhanced our understanding of bilingualism but also the ways in which different methodologies are optimal for solving different components of a problem. Eye-tracking is ideally suited to identifying the features of the environment that have captured attention. By observing what people attend to in response to a given stimulus, it is possible to make inferences regarding the underlying associations. This, in turn, can inform the types of processes that would be necessary and compatible with a given structure. In the case of bilingual language processing, eye-tracking studies have revealed that presenting a word in one language activates words in the other language, suggesting that the bilingual mind does not keep different languages entirely separate. Yet, functionally, bilinguals are able to operate in a single language without notable interference from the other language. Naturally, this begs the question of *how*. One way to find out is by identifying the pattern of neural activity associated with the resolution of linguistic conflicts.

Using fMRI, researchers have been able to determine that the neural networks recruited for language control may also be involved in domain-general executive function. Furthermore, by examining the types of factors that lead to different patterns of neural activation (such as AoA and proficiency), we can gain insights regarding the plasticity and developmental trajectory of the language system. Just as the representational structure can inform the types of processes that may be involved, a greater understanding of how the system functions can shed light on its organization. Echoing the interactive nature of bilingual processing, different methodologies can be mutually informative in advancing bilingual research.

Our brief summary reviews how currently available tools have contributed to present-day understanding of bilingualism – but we have only begun to uncover how multiple languages coexist within a single cognitive system. Throughout history, scholars have continuously updated, and often dispelled, commonly held beliefs based on new discoveries and increasingly advanced technology. Some of the brightest minds of the nineteenth century subscribed to the principles of phrenology, thinking that a person's mental faculties and personality could be determined by the size and shape of their skull. This once widely accepted idea has since been entirely discredited, replaced by our current understanding of the brain, informed by technology such as fMRI.

The evolution of knowledge continues, as with the study of bilingualism and the question of whether multiple languages have shared or separate representations. We began our review by describing early case studies on selective aphasia, which had contributed to the idea that a bilingual's two languages may be stored and processed independently of each other. Since then, we have come to understand that the question of shared versus separate representations is too simplistic to capture the complexity of the bilingual mind. Given that language processing results from highly interconnected networks of activity, this question should be revised to ask what representations and processes are shared under specific conditions and to what extent. We have begun to answer some of these questions through the use of tools such as eye-tracking and fMRI – revealing how individual attributes (such as proficiency), as well as language characteristics (such as phonological properties), influence the degrees to which different languages overlap in linguistic processing and neural representation. While we have made great strides toward understanding the structure and function of the bilingual neurocognitive system, it is important to remember that we do not stand at the end of history and new methodologies will inevitably provide novel insights as the journey of science continues onward.

Keywords

Age of acquisition (AoA), American Sign Language (ASL), Bilingual interactive activation plus (BIA+) model, Bilingual language interaction network for comprehension of speech (BLINCS), Bilingual production, Cognitive control, Compound-coordinate model, Control networks, Covert activation, Cross-linguistic conflict, Declarative/procedural model, Domain-general cognitive control, English lexical decision (ELD) task, Event-related potential (ERP), Eye movements, Eye-tracking, functional magnetic resonance imaging (fMRI), General lexical decision (GLD) task, Homographs, Inhibitory control model, Language switch hypothesis, Lexical-semantic processing, Multi-voxel pattern analysis (MVPA), Nonselective lexical access, Parallel activation, Picture naming tasks, Revised hierarchical model, Selective lexical access, Separate representation, Switch cost, Visual word recognition, Visual world paradigm

Thought Questions

1. Many of the bilingual comprehension models (including BLINCS and BIA+) assume that there are bidirectional connections between different

levels of representation (semantic, phono-lexical, etc.). Do you think it is possible for phono-lexical representations to influence semantic concepts? If so, how might this process differ for monolinguals vs. bilinguals?

2. Findings suggest that L1 and L2 recruit similar neural regions when engaged in the same task, but does this necessarily mean they are using the same exact processes? Likewise, if there is neural separation, does that necessarily imply functional differences?

Internet Sites

Bilingual Language Processing Eye-Tracking Laboratory: www.personal.psu.edu/ped10/Giuli_Dussias/Home.html
Bilingualism and Psycholinguistics Lab: www.bilingualism.northwestern.edu/
fMRI for Newbies: www.fmri4newbies.com/
Lab Eye-Tracking Tutorial: https://sites.google.com/site/kenmcraelab/lab-tutorials
OpenfMRI: https://openfmri.org/

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