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fMRI Research on the Bilingual Brain

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In this article, I review the use of the functional magnetic resonance imaging (fMRI) technique to investigate the bilingual brain. Specifically, this review will discuss the types of research questions that can be (and have been) answered using this specific methodology, as well as questions this technique cannot answer. The review will then focus on providing a recent overview of fMRI studies of the bilingual mental lexicon, bilingual sentence processing, and the bilingual advantage in cognitive control. The pros and cons of this technique will be discussed in detail. This review will end with a discussion of the state of the art in the field of bilingual brain research and will provide avenues for future research directions to continue investigating the bilingual brain.

Neuroimaging techniques allow us to investigate online language processing in the brain, giving us insight into processes as they happen in real time. These techniques are becoming more and more refined and are increasingly becoming more accessible to many kinds of researchers. In particular, functional magnetic resonance imaging (fMRI) provides us with information on where in the brain language is being processed; specifically, it allows for researchers to determine what areas take part in the processing of language regardless of whether or not those areas are essential to that processing. This is an improvement from the early years of neurolinguistics (or aphasiology) when neural regions involved in language processing could only be determined by seeing what brain regions were damaged in patients that had language processing problems, and affected regions could usually only be examined via autopsy. The field has moved from only being able to determine the areas required in language processing (and whose damage caused language problems) to being able to determine all areas that participate in language processing even when not absolutely required (i.e., damage to these areas may not cause any noticeable linguistic processing difficulties).

In a nutshell, fMRI measures changes in the magnetic levels of blood oxygenation over time, and this allows researchers to localize different mental processes to different regions of the brain, by tracking where the blood oxy-

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genation is increasing and decreasing. The amount of blood oxygenation in a region of the brain changes quickly after a group of neurons has fired and thus techniques such as fMRI, which measure blood flow and not neuronal firing, do not directly measure neural activity but only indirectly do so.

Due to its excellent spatial resolution, fMRI is most often used to inform researchers about the different neural regions involved in language processing, but it can also be used to determine the degree to which a neural region is used in a language processing task (i.e., whether one region is used more or less in sentence level vs. lexical processing). From previous reviews of neuroimaging of language studies, it is already clear that the classical view of language processing (the predominance of Broca's and Wernicke's area in the left hemisphere only) is not a sufficiently complex model (e.g., Bookheimer, 2002; Stowe, Haverkort, & Zwarts, 2005). Research has shown that many brain regions other than the broadly defined Broca's and Wernicke's area are involved in language processing and that there is also involvement of the right hemisphere in many language tasks. In this article, I first review some principles of the fMRI technique and the necessary neuroanatomical terminology that one must know to follow discussions of language in the brain. Next, I present recent research in the field of language processing that has made use of the fMRI methodology (both more traditional research that uses fMRI to locate where processing is occurring, as well as research that uses fMRI to determine how different regions are connected to each other). The focus of the research reviewed here will be on processing at the lexical and sentence level in bilingual and second language (L2) learner populations. Additionally, I will review the fMRI literature on language switching and cognitive control in bilinguals.

SOME PRINCIPLES OF FMRI

As just mentioned, fMRI can inform researchers about where aspects of language processing are occurring. There are, however, a few points that one must be aware of before fully interpreting the results of fMRI studies.

1. *fMRI only indirectly measures the location of neural activity.* The fMRI technique actually measures increases and decreases in the oxygenation level of regions of the brain. Thus, two assumptions are required: (a) that the oxygenation levels reflect blood activity and (b) that this blood activity represents the main neuronal regions that are firing in a given task.
2. *The time-course of the blood response is relatively slow.* It takes about two seconds for the vascular system to kick in once neural activity has been detected and the peak of the blood-flow response occurs only after five to seven seconds. Here, we must keep in mind that language is processed at the level of milliseconds; thus, fMRI is not the best technique available to get temporal information on language processing. For temporal information, neurophysiological techniques such as

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event-related brain potentials and magneto-encephalography are better suited.

3. *A baseline or comparison condition is required.* As fMRI measures the increase in blood flow, it is technically possible to compare the neural activity when the process starts to when the process is completed. However, comparing two different processes, the (complex) process of interest compared to one simpler process, makes it easier to determine what aspects of the task are actually causing the change in activation pattern.
4. *The activation levels discussed in fMRI research are relative and not absolute.* That is to say you can only determine whether a change compared to a baseline or control has occurred and not whether the activation change is due to the change in the processing of the control or experimental condition.
5. *Blocked versus event-related fMRI experimental paradigms result in very important differences.* The more traditional blocked design required a participant to perform the same task, in one condition, for an entire block (blocks are generally a minimum of 30 seconds) while in the new event-related paradigm, stimuli from different conditions can be presented randomly. The blocked design often results in participants using more strategic processes to perform tasks; however, while the newer event-related designs do not allow for this type of strategic processing, they are based on some additional assumptions (beyond the scope of the current article) about how the neural and blood responses are related.

A newer use of fMRI technology is the tracking of how regions of the language network are connected to each other using what is called diffusion tensor imaging (DTI). DTI allows visualization of white matter tracts by tracking the diffusion of water molecules. This allows for an examination of not only neural structures, but also of the pathways involved in specific processes.

THE LANGUAGE NETWORK

For the purpose of this review, only brain areas involved in lexical and sentence level processes and bilingual cognitive control will be discussed. The brain is divided into two hemispheres (left and right), each with four main lobes: the frontal lobe, the parietal lobe, the temporal lobe, and the occipital lobe. Within these lobes, the classic language areas are generally located in the perisylvian area, the area surrounding the sylvian fissure (e.g., Abutalebi, Cappa, & Perani, 2001; Binder et al., 1997). This left-hemisphere area consists of Broca's area, Wernicke's area, the arcuate fasciculus, the angular gyrus, the supramarginal gyrus, some subcortical regions, the motor cortex, and the corpus callosus. More specifically, Broca's area is located in the inferior frontal gyrus of the (left) frontal lobe and Wernicke's area in the superior temporal gyrus of the (left) temporal lobe. These two areas are connected via the arcuate fasciculus (a large bundle of neuronal axons that is not present to the same extent, if at all, in nonhuman primates; Rilling et al., 2008). A third area, known traditionally

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as Geschwind's area, is located in the left inferior parietal cortex (in particular the angular gyrus and the supramarginal gyrus). The first thing to note here is that language is generally considered to be processed mainly within the left hemisphere. This is at least the case for the majority of right-handed individuals. It is also the case for the majority of left-handers; however, they are less likely to show full left-hemisphere dominance. This classical view of language in the brain has been extended to include many other neural areas that take part in typical language processing (e.g., Friederici, 2011; Lemaire et al., 2013). In a recent study using fMRI and DTI, Lemaire et al. (2013) found evidence for a language network that included an extended Broca's area (both in terms of surface area and its connective tissue to other parts of the network), Geschwind's area, Wernicke's area, premotor cortex, dorsal supplementary motor area, middle temporal gyrus, dorsal prefrontal cortex, and the frontopolar region. In addition to these regions, other areas of the brain such as the cerebellum and subcortical structures (e.g., caudate and anterior cingulate cortex) have been found to be involved in some aspects of language processing.

FMRI AND LANGUAGE PROCESSING

FMRI has been used to study language processing since the early 1990s, with the early research being used to show that fMRI results supported the findings from positron emission tomography (PET; e.g., Hinke et al., 1993; McCarthy, Blamire, Rothman, Gruetter, & Shulman, 1993). fMRI studies of language quickly started to outnumber PET studies for many important reasons, with one of the top reasons probably being the fact that fMRI is a noninvasive technique not requiring the use of a radioactive tracer (required in PET studies).

Of interest to language researchers is whether or not fMRI can help inform the current theories and models of language processing. For example, can we determine where syntax occurs? In addition, can we determine, within the domain of language, whether sentences and words are processed by the same brain regions? Furthermore, are separate neural regions called upon when more than one language is used by an individual? The use of fMRI is essential to finding the answers to these types of questions.

While a certain amount of agreement exists for native language processing, this is far from where things stand when the issue of the bilingual brain is discussed. In the following section, I discuss second language and bilingual processing at the lexical and sentential levels, as well as bilingual processing in tasks of cognitive control. Findings from this literature will be compared to the previously discussed language network found from studies of native language processing.

Lexical Processing

From neuroimaging data, it is known that regions of the left temporal lobe (left superior, middle, and inferior gyri), left superior frontal cortex, and bilateral angular gyri are important in lexical processing of the native language (Démonet

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et al., 1992; Démonet, Price, Wise, & Frackowiak, 1994; Vandenberghe, Price, Wise, Josephs, & Frackowiack, 1996). In terms of word generation or retrieval, the dorsal and ventral inferior frontal regions and medial frontal regions of the frontal lobe have been implicated. These areas include Broca's area located in the inferior frontal gyrus.

The ability to learn new words in a first or second (or any subsequent) language is a skill that appears to be maintained across the life span (see Gaskell & Ellis, 2011 for a discussion). Neurological evidence supporting this statement can be found in electrophysiological studies that find quantitatively similar processing effects (even if sometimes delayed) in both first language (L1) and L2 processing (see Sabourin, Brien, & Tremblay, 2013 for a review). Using electrophysiological techniques, however, we are not able to determine where the lexical items of each language are stored and whether this storage occurs in overlapping or separate (but possibly adjacent) regions of the brain.

In a longitudinal study of beginner word learning, Stein et al. (2009) used fMRI to compare lexical processing activations of English learners of German at the start of an exchange program in Switzerland (following a 3-week intensive introduction to German) to the activations found after 5 months. The initial scans showed increased activations for the German L2 words (compared to English words) in the left and right inferior frontal gyrus, the left inferior frontal sulcus, and the left supplementary motor area. The later scan, when L2 proficiency was higher, only showed increased L2 activation in left inferior frontal sulcus. This finding, suggesting that low proficiency in a language is linked to the need for additional frontal lobe activity, is compatible with other research that has shown less frontal activation in more proficient languages (e.g., Chee, Hon, Lee, & Soon, 2001; Marian, Spivey, & Hirsch, 2003). A similar finding comparing L1 and L2 production was found by Liu, Hu, Guo, and Peng (2010) who investigated late, unbalanced Chinese L1 and English L2 participants and found increased activations in the left inferior frontal gyrus for L2. Liu et al. (2010) claimed that this increased activation is likely due to the difficulty of the L2 articulations and due to a need of inhibiting the L1 word during L2 naming. However, the results of these studies do suggest that overall, a similar neural network is recruited for L1 and L2 lexical processing and that with proficiency, the processing is likely to become more similar to L1 lexical processing.

Another important aspect of lexical processing is the recognition of morphologically complex forms. Processing models have proposed either a full-form storage view where items are stored in their full forms whether morphologically simple or complex, or a decomposition view where a word is decomposed into its stem and affixes before being accessed (see Butterworth, 1983; Niemi, Laine, & Tuominen, 1994; Schreuder & Baayen, 1995; Stockall & Marantz, 2006; Taft, 1979 for discussions of the different viewpoints). A study by Lehtonen et al. (2009) used fMRI to investigate the bilingual processing (in early, highly proficient bilinguals) of visually presented morphologically complex words in Swedish and Finnish to test the storage versus decomposition views of lexical processing. Their results indicate that for the processing of Swedish monomorphemic and inflected forms, there is no difference in the regions recruited during processing. Conversely, these same participants showed increased activations in

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the left occipito-temporal cortex to the Finnish inflected forms compared to the monomorphemic forms. This was concluded to be due to an increase required for lexico-semantic processing. In addition, they claim that bilinguals process each language in the same manner as monolingual speakers of that language. This claim was made based on similar results found in Finnish monolinguals when comparing monomorphemic and inflected forms (Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006).

Park, Badzakova-Trajkov, and Waldie (2012) used a lexical decision task coupled with fMRI scanning to show that while Macedonian-English bilinguals (who learned L2 English after age 6 years) show activations for both languages in the same general language processing regions as English monolinguals, the bilinguals showed a more extensive network of activations in both their L1 (Macedonian) and L2 (English). However, as the authors also say, there was no monolingual Macedonian group for comparison. The greater extent of activations in L2 English versus L1 English still suggests, though, that more effort is exerted in L2 processing. While the bilinguals (in their L2) showed a larger extent of activation in left frontal regions (Broca's area), they showed less activation in left temporal areas (Wernicke's area), suggesting that other areas are being recruited due to the increased difficulty of processing in the L2. Bilinguals also showed more right hemisphere recruitment for L2 lexical processing.

Together, all of these studies suggest very similar processing regions for L1 and L2 with extent of activations depending on either proficiency or the age of acquisition (AoA). Earlier AoA and increased proficiency is linked to more similar L1 and L2 processing. However, in a study that somewhat contradicts these findings, Waldron and Hernandez (2013) compared L1 Spanish speakers with early (AoA $\leq$ 6 years of age) and late (AoA $\geq$ 7 years of age) acquisition of L2 English on a verb generation task and found that early bilinguals recruited left sensorimotor regions to perform the L2 task while the later bilinguals were more likely to also engage regions involved in executive cognitive control (the inferior parietal lobule and the dorsal lateral prefrontal cortex). A similar argument is found in a study by Parker Jones et al. (2012) who claim that extra regions of activation are recruited in L2 because word retrieval in L2/bilingual speakers is more demanding.

Sentence Processing

In studies of native language processing, sentence processing has been found to activate both the anterior and posterior part of the temporal cortex as well as regions of the inferior frontal gyrus (Friederici, 2011). A thorough review of the neural correlates involved in sentence processing can be found in the Friederici (2011) review article and thus will not be presented in detail here.

Weber and Indefrey (2009) investigated syntactic priming in L1 German participants with medium proficiency in L2 English (AoA $\geq$ 9 years of age) to determine if the L1 and L2 syntactic systems interact. Regardless of whether the priming was L1 to L2 or within L2, they found activation in the left inferior frontal, precentral, and middle temporal cortices. They claim the results suggest shared syntactic systems for both the German and English systems. However, it must be

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noted that the regions found in this study are not the typical areas that have been found in syntactic priming studies. Similarly, in a study investigating sentence comprehension in simultaneous and early Italian-Friulian bilinguals, Consonni et al. (2013) found similar activation patterns across both languages. The only difference found was an increased activation during the processing of Friulian (the less exposed language) in the left thalamus. Consonni et al. interpret this as being suggestive of proficiency being more important than AoA in bilingual processing.

One study that concludes that each of a bilingual's languages are stored and processed differently is a very interesting investigation into the bilingual brain by Kovelman, Baker, and Petitto (2008). These authors tested early bilinguals on a sentence-processing task in both of their languages (English and Spanish) and compared them to monolinguals (English only). Comparing the results of processing, even just in English, showed that bilinguals recruited a more extensive area of the left inferior frontal cortex. Kovelman et al. (2008) further showed that within the bilinguals, a different activation pattern was apparent for each language. These data support the idea for differentiated neural activations for each language. This is directly counter to some earlier research by Chee, Soon, and Lee (2003) and Kim, Relkin, Lee, and Hirsch (1997) where results suggested that early, highly proficient bilinguals show the same neural activation across both languages.

In a study by Sakai et al. (2009), L1 Japanese speakers with either early (AoA approximately between 5 and 6 years of age) or late (AoA approximately 12 years of age) L2 English were tested to investigate the different neural regions involved in L2 syntactic processing. Similar to some of the previously discussed studies on lexical processing, it was found that a region of the left inferior frontal gyrus showed increased activations in the late group (suggesting that the activation in this region initially increases when an L2 is being learned) and reduced activations for the early group who were at a more advanced L2 processing stage.

As for lexical processing, there is currently no final view on whether L1 and L2 sentence processing occurs to the same extent in the same areas. Whether proficiency or AoA factors are more important in the determination of the spatial processing similarities and differences between L1 and L2 also remains a very current debate.

Cognitive Control

Cognitive control (e.g., the abilities to pay attention to relevant input, to ignore irrelevant input, to inhibit inappropriate responses, and to switch between tasks effectively) has recently received much attention. In particular, a growing number of studies link bilingualism with an advantage in cognitive control (e.g. Bialystok, Craik, & Luk, 2008; Coderre, Van Heuven, & Conklin, 2013; Costa, Hernández, & Sebastián-Gallés, 2008). Domain general control processes, which are said to be impacted by bilingual language processing, are carried out by multiple brain regions. Neuroimaging data suggests that some of the main regions involved in cognitive control tasks are the dorsolateral prefrontal cortex, inferior

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parietal cortex, the anterior cingulate cortex, and the basal ganglia (Abutalebi & Green, 2008; Botvinick, Cohen, & Carter, 2004). These same areas are also found to be active in bilinguals during language control tasks (Abutalebi & Green, 2007; Luk, Green, Abutalebi, & Grady, 2012).

In a fMRI study comparing bilinguals and monolinguals on linguistic and nonlinguistic cognitive control tasks, Abutalebi et al. (2012) showed that both kinds of control tasks activate the anterior cingulate cortex (supporting previous findings that this region is involved in general cognitive control). Furthermore, they found that bilinguals not only performed better on these tasks, but also showed less activation of the anterior cingulate cortex. The authors suggest that this decreased activation is due to more proficient processing routines as a result of their bilingualism; the bilingual brain appears to be more capable in adapting to tasks that require higher levels of cognitive control.

However, it must be noted that in investigations of bilingual cognitive control, the task that is chosen is generally a language switching task. While this does test aspects of cognitive control, the task of switching languages is something done only by bilinguals (or multilinguals), and it is difficult to imagine a fully comparable monolingual task. For this reason many of the studies have just looked at language switching tasks within the bilingual populations. In a study by Guo, Liu, Misra, and Kroll (2011), fMRI was used to compare global and local inhibitory processes in late Chinese-English bilinguals. Global inhibitory processes were defined as those required to make a complete switch from processing in one language to processing in the other (akin to using one language in one situation and the other language in a different situation, without mixing the two languages), while more local inhibitory processes were defined as those that would act upon a specific representation such as a single lexical item (akin to having both languages active, but requiring the lexical items from the language not being used to be inhibited). The supplementary motor area and part of the subcortical region of the cingulate cortex, among other areas, were implicated in local inhibition, while regions such as the left dorsal frontal gyrus and parts of the parietal cortex were implicated in global inhibition. The above studies demonstrate not only differential activation for monolinguals and bilinguals, but also differential activation for bilinguals based on the type of task they are performing.

In a study looking only at early high proficiency Spanish-Catalan bilinguals, Garbin et al. (2011) used fMRI to show that when forward switching (switching from the dominant to nondominant language), the left caudate region showed increased activation, while backward switching resulted in increased activity in the pre-supplementary motor area (SMA) and the anterior cingulate cortex (ACC). Based on their results and that of others (Ali, Green, Kherif, Devlin, & Price, 2010; Aron & Poldrack, 2006), Garbin et al. suggested that the left caudate is involved in language selection in high proficiency bilinguals while the pre-SMA/ACC complex is involved in response inhibition.

It is fairly clear that bilinguals have an advantage in terms of cognitive control abilities; however the mechanism responsible for this advantage still needs to be developed. One possible avenue to explore is the role of the extra practice

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that bilinguals acquire in terms of inhibition, suppression, and switching of languages on regions of cognitive control. Bilingualism requires the constant need for inhibiting/suppressing the language not in use and in switching from one language to another. This is exemplified in code-switching where two different languages or varieties are used in alternation during a speech act. As a result of different types of code-switching behaviors, cognitive control abilities may be affected differentially. While code-switching is a research topic in and of itself, fMRI studies on this topic indicate the involvement of cognitive control regions (Green & Abutalebi, 2013; Green & Wei, 2014).

SUMMING IT ALL UP

The field of neuroimaging and its application to L2 and bilingual language processing is still a very lively area of research. As for L1 processing, fMRI studies of L2 and bilingual language processing implicate the left hemisphere language networks (left inferior frontal gyrus and left temporal regions). While some studies support the idea of neural differentiation for each language in early acquired high proficient bilingual processing (e.g., Kovelman et al., 2008), others claim that such a neural differentiation is only modulated by late acquisition and/or is apparent in only low proficiency bilinguals (e.g., Sakai et al., 2009 for AoA effects). It is important to note here a very important limitation of fMRI data. While group comparisons are, by far, the way analyses are conducted, there is a great deal of within-participant variability that has the potential to mask or enhance (unfairly) any differences that are found. For example, in a study comparing early and late bilinguals (Mahendra, Plante, Magliore, Milman, & Trouard, 2003), the differences found between the groups was similar to the differences found within each group across different scans.

An additional issue brought up here is concerned with how bilingualism may affect the neural substrates involved in cognitive control. Results to date seem to indicate that bilinguals may use slightly different regions for cognitive control, and for those regions that are used by both monolinguals and bilinguals, bilinguals are able to employ them in a much more efficient manner. However, as the tasks used to test this have typically been language switching tasks, it is difficult to determine if task effects are properly controlled when comparing bilingual and monolingual imaging data.

FUTURE DIRECTIONS

The article on bilingual sentence processing by Kovelman et al. (2008), though one of the earlier articles reviewed here, is actually one that holds a lot of promise for future research. By comparing early bilinguals in one of their languages to monolinguals of that language, they make the suggestion that monolingual language processing may not be using the neural language processing network to its full potential. This potential, they claim, must be examined by looking at bilingual processing, and, by extension, possibly at early multilingual

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participants. This message is brought home in a study by Schafer and Constable (2009) who use fMRI to investigate the consequences of bilingualism for the planning of neurosurgeries, since, as they found, early bilinguals have a different language network than monolinguals, it is essential that bi- and multilinguals are tested in all of their languages before surgery near a language area is performed.

Other avenues that require more in-depth research are the comparison of L2 learners to simultaneous bilinguals and comparisons of different language pairs. While some studies have included simultaneous bilinguals among their participants (e.g., Consonni et al., 2013; Kovelman et al., 2008), this has not been always fully controlled. Having a complete group dedicated to simultaneous bilinguals may be essential in determining the bilingual neural organization. Recent behavioral and electrophysiological research (Brien, 2013; Brien & Sabourin, 2012) has suggested that even the presence of a late learned L2 can affect processing in the L1; thus, it may be that in order to determine the effects of AoA and proficiency, L2 learners should be compared to a group of simultaneous bilinguals who have native-like processing and use of more than one language. Moreover, there is a large need to test different groupings of bilinguals to see the effects of different language pairs on bilingualism. As there still is a limited number of fMRI studies investigating L2 processing, the language pairs and groupings tested are also very limited.

In addition to how the bilingual's different languages are processed in their own right, the role of differences due to improved and more efficient cognitive processing needs to be addressed. Several brain regions involved in language switching tasks are mentioned in the current article; however, as a suitable monolingual task that could be used as a control task is hard to imagine, more work still needs to be done in this area. Moreover, the lifelong effects of improved cognitive control in bilinguals still needs more in-depth research to determine the neurological benefits (e.g., Gold, Kim, Johnson, Kryscio, & Smith, 2013).

As mentioned in the introduction, one of the main goals of neuroimaging the neural substrates of language processing is to help inform current theories and models of language processing. This is a goal that is yet to be achieved. Similar to the position taken by de Bot (2008), I feel that the neuroimaging literature is still not advanced enough to add much, if anything, to the theoretical models of linguistic analyses. However, I would argue, as I have before (Sabourin, 2009), that neuroimaging data is essential to laying the foundations for models of bilingual and L2 processing. fMRI studies of the bilingual and language learning brain should ultimately be able to shed light on what neural substrates are involved in both the process and manner of acquisition (using longitudinal designs; e.g., Andrews, Frigau, Voyvodic-Casabo, Voyvodic, & Wright, 2013) and in the end-state achieved by L2 learners. Understanding AoA effects has been deemed one of the most important issues in the field of L2 processing (Hakuta, Bialystok, & Wiley, 2003; Hernandez & Li, 2007; Kennedy & Normal, 2005). However, it is likely that AoA alone cannot give a full picture of how multiple languages are represented in the mind; in fact, it is likely that effects of proficiency affect organization differently at different times. Additionally, it is important to keep in mind that neuroimaging the bilingual brain (from beginner to native-like) will also inform theories of neural plasticity.

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ANNOTATED BIBLIOGRAPHY

Friederici, A. (2011). The brain basis of language processing: From structure to function. *Physiological Review*, *91*, 1357–1392.

This article is a thorough review and introduction to the neurological structures that are involved in all of the levels of language processing in both typical and atypical (i.e., impaired) participants. This article complements the present review in that it provides a much more detailed overview of the neuroanatomical regions involved in general language processing. This article will allow the reader to compare bilingual processing to what happens in the (monolingual) processing of a native language.

Green, D. W., & Wei, L. (2014). A control process model of code-switching. *Language, Cognition and Neuroscience*, *29*(4), 499–511.

In this article the authors discuss how different bilingual language environments may affect the neural organization of language processing in bilinguals. Three different types of code-switching (which result from different types of bilingual environments) are discussed: alternations, insertions, and dense code-switching. In order to fully comprehend the specifics of bilingualism in the brain, a thorough description of participant groups (and their bilingual environments) in each study must be provided. It is likely the case that differences in results are due to not only proficiency and age of acquisition effects, but that strong effects of the bilingual environment are also present.

Kovelman, I., Baker, S. A., & Petitto, L-A. (2008). Bilingual and monolingual brains compared: A functional magnetic resonance imaging investigation of syntactic processing and a possible "neural signature" of bilingualism. *Journal of Cognitive Neuroscience*, *20*(1), 153–169.

This article is of particular interest in that it not only compares monolingual to bilingual language processing, but also compares the brain regions involved during the processing of each of a bilingual's two languages. Specifically, this article shows that for highly proficient early bilinguals that each language has its own neural signature. This suggests that it is not just that language is processed in one way within the brain, but that different patterns are found for each language even in cases of "true" bilingualism.

Waldron, E. J., & Hernandez, A. E. (2013). The role of age of acquisition on past tense generation in Spanish-English bilinguals: An fMRI study. *Brain and Language*, *125*(1), 28–37.

This article provides insight into the precise role of how age of acquisition affects neural organization for linguistic processing. The authors find, contrary to Kovelman et al. (2008) that early learned languages show similar neural patterns of processing. Conversely, they further show that later learned languages result in neural processing patterns that include regions dedicate to executive functioning.

REFERENCES

Abutalebi, J., Cappa, S. F., & Perani, D. (2001). The bilingual brain as revealed by functional neuroimaging. *Bilingualism: Language and Cognition*, *4*, 179–190.

https://doi.org/10.1017/S0267190514000038 Published online by Cambridge University Press

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., … Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex*, *22*, 2076–2086.

Abutalebi, J., & Green, D. W. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*, 242–275.

Abutalebi, J., & Green, D. W. (2008). Control mechanisms in bilingual language production: Neural evidence from language switching studies. *Language and Cognitive Processes*, *23*, 557–582.

Ali, N., Green, D. W., Kherif, F., Devlin, J. T., & Price, C. J. (2010). The role of the left head of caudate in suppressing irrelevant words. *Journal of Cognitive Neuroscience*, *22*, 2369–2386.

Andrews, E., Frigau, L., Voyvodic-Casabo, C., Voyvodic, J., & Wright, J. (2013). Multilingualism and fMRI: Longitudinal study of second language acquisition. *Brain Sciences*, *3*, 849–876.

Aron, A. R., & Poldrack, R. A. (2006). Cortical and subcortical contributions to stop signal response inhibition: Role of the subthalamic nucleus. *Journal of Neuroscience*, *26*, 2424–2433.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 859–873.

Binder, J. R., Frost, J. A., Hammeke, T. A., Cox, R. W., Rao, S. M., & Prieto, T. (1997). Human brain language areas identified by functional magnetic resonance imaging. *The Journal of Neuroscience*, *17*, 353–362.

Bookheimer, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience*, *25*, 151–188.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Science*, *8*, 539–546.

Brien, C. (2013). *Neurophysiological evidence of a second language influencing lexical ambiguity resolution in the first language*. Unpublished doctoral dissertation, University of Ottawa, Ontario, Canada.

Brien, C., & Sabourin, L. (2012). Second language effects on ambiguity resolution in the first language. *EUROSLA Yearbook*, *12*, 191–217.

Butterworth, B. (1983). Lexical representation. In B. Butterworth (Ed.), *Language production: Vol. 2. Development, writing and other language processes* (pp. 257–294), London, UK: Academic Press.

Chee, M. W., Hon, N., Lee, H. L., & Soon, C. S. (2001). Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. Blood oxygen level dependent. *NeuroImage*, *13*, 1155–1163.

Chee, M. W., Soon, C. S., & Lee, H. L. (2003). Common and segregated neuronal networks for different languages revealed using functional magnetic resonance adaptation. *Journal Cognitive Neuroscience*, *15*, 85–97.

Coderre, E. L., Van Heuven, W. J. B., & Conklin, K. (2013). The timing and magnitude of Stroop interference and facilitation in monolinguals and bilinguals. *Bilingualism: Language and Cognition*, *16*(2), 420–441.

Consonni, M., Cafiero, R., Marin, D., Tettamanti, M., Iadanza, A., Fabbro, F., & Perani, D. (2013). Neural convergence for language comprehension and grammatical class production in highly proficient bilinguals is independent of age of acquisition. *Cortex*, *49*, 1252–1258.

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids in conflict resolution: Evidence from the ANT task. *Cognition*, *106*, 59–86.

de Bot, K. (2008). The imaging of what in the multilingual mind? *Second Language Research*, *24*, 111–133.

Démonet, J.-F., Chollet, F., Ramsay, S., Cardebat, D., Nespoulous, J.-L., Wise, R., … Frackowiak, R. (1992). The anatomy of phonological and semantic processing in normal subjects. *Brain*, *115*, 1753–1768.

https://doi.org/10.1017/S0267190514000038 Published online by Cambridge University Press

Démonet, J.-F., Price, C., Wise, R., & Frackowiak, R. J. (1994). A PET study of cognitive strategies in normal subjects during language tasks: Influence of phonetic ambiguity and sequence processing on phoneme monitoring. *Brain*, *117*, 671–682.

Friederici, A. (2011). The brain basis of language processing: From structure to function. *Physiological Review*, *91*, 1357–1392.

Garbin, G., Costa, A., Sanuan, A., Forn, C., Rodriguez-Pujadas, A., Ventura, N., ... Ávila, C. (2011). Neural bases of language switching in high and early proficient bilinguals. *Brain and Language*, *119*, 129–135.

Gaskell, M. G., & Ellis, A. W. (2011). Word learning and lexical development across the lifespan. *Philosophical Transactions of the Royal Society*, *364*, 3608–3615.

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *Journal of Neuroscience*, *33*, 387–396.

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*, 515–530.

Green, D. W., & Wei, L. (2014). A control process model of code-switching. *Language, Cognition and Neuroscience*, *29*, 499–511.

Guo, T., Liu, H., Misra, M., & Kroll, J. F. (2011). Local and global inhibition in bilingual word production: fMRI evidence from Chinese-English bilinguals. *NeuroImage*, *56*, 2300–2309.

Hakuta, K., Bialystok, E., & Wiley, E. (2003). Critical evidence: A test of the critical-period hypothesis for second-language acquisition. *Psychological Science*, *14*, 31–38.

Hernandez, A.E., & Li, P. (2007). Age of acquisition: Its neural and computational mechanisms. *Psychological Bulletin*, *133*, 638–650.

Hinke, R. M., Hu, X., Stillman, A. E., Kim, S. G., Merkle, H., Salmi, R., & Ugurbil, K. (1993). Functional magnetic resonance imaging of Broca's area during internal speech. *NeuroReport*, *4*, 675–678.

Kennedy, D., & Normal, C. (2005). What don't we know? *Science*, *309*, 5731.

Kim, K. H. S., Relkin, N. R., Lee, K-M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature*, *388*, 171–174.

Kovelman, I., Baker, S. A., & Petitto, L-A. (2008). Bilingual and monolingual brains compared: A functional magnetic resonance imaging investigation of syntactic processing and a possible "neural signature" of bilingualism. *Journal of Cognitive Neuroscience*, *20*, 153–169.

Lehtonen, M., Vorobyev, V. A., Hugdahl, K., Tuokkola, T., & Laine, M. (2006). Neural correlates of morphological decomposition in a morphologically rich language: An fMRI study. *Brain and Language*, *98*, 182–193.

Lehtonen, M., Vorobyev, V., Soveri, A., Hugdahl, K., Tuokkola, T., & Laine, M. (2009). Language-specific activations in the brain: Evidence from inflectional processing in bilinguals. *Journal of Neurolinguistics*, *22*, 495–513.

Lemaire, J-J., Golby, A., Wells, W. M., Pujol, S., Tie, Y., Rigolo, L., ... Kikinis, R. (2013). Extended Broca's area in the functional connectome of language in adults: Combined cortical and subcortical single-subject analysis using fMRI and DTI tractography. *Brain Topography*, *26*, 428–441.

Liu, H., Hu, Z., Guo, T., & Peng, D. (2010). Speaking words in two languages with one brain: Neural overlap and dissociation. *Brain Research*, *1316*, 75–82.

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes*, *27*, 1479–1488.

Mahendra, N., Plante, E., Magliore, J., Milman, L., & Trouard, T. P. (2003). FMRI variability and the localization of languages in the bilingual brain. *NeuroReport*, *14*, 1225–1228.

Marian, V., Spivey, M., & Hirsch, J. (2003). Shared and separate systems in bilingual language processing: Converging evidence from eyetracking and brain imaging. *Brain and Language*, *86*, 70–82.

McCarthy, G., Blamire, A. M., Rothman, D. L., Gruetter, R., & Shulman, R. G. (1993). Echo-planar magnetic resonance imaging studies of frontal cortex activation during word generation in humans. *Proceedings of the National Academy of Science*, *90*, 4952–4956.

https://doi.org/10.1017/S0267190514000038 Published online by Cambridge University Press

Niemi, J., Laine, M., & Tuominen, J. (1994) Cognitive morphology in Finnish: Foundations of a new model. *Language and Cognitive Processes*, *9*, 423–446.
Park, H. R. P., Badzakova-Trajkov, G., & Waldie, K. E. (2012). Language lateralisation in late proficient bilinguals: A lexical decision fMRI study. *Neuropsychologia*, *50*, 688–695.
Parker Jones, Õ., Green, D. W., Grogan, A., Pliatsikas, C., Filippopolitis, K., Ali, N., … Price, C. J. (2012). Where, when and why brain activation differs for bilinguals and monolinguals during picture naming and reading aloud. *Cerebral Cortex*, *22*, 892–902.
Rilling, J. K., Glasser, M. F., Preuss, T. M., Ma, X., Zhao, T., Hu, X., & Behrens, T. E. J. (2008). The evolution of the arcuate fasciculus revealed with comparative DTI. *Nature Neuroscience*, *11*, 426–428.
Sabourin, L. (2009). Neuroimaging and research into second language acquisition. *Second Language Research*, *25*, 5–11.
Sabourin, L., Brien, C., & Tremblay, M-C. (2013). Electrophysiology of second language processing: The past, present and future. In M. del Pilar García Mayo, M. Junkal Gutierrez-Mangado, & M. Martínez Adrián (Eds.), *Contemporary approaches to second language acquisition* (pp. 221–242). Amsterdam, The Netherlands: John Benjamins.
Sakai, K. L., Nauchi, A., Tatsuno, Y., Hirano, K., Muraishi, Y., Kimura, M., … Yusa, N. (2009). Distinct roles of left inferior frontal regions that explain individual differences in second language acquisition. *Human Brain Mapping*, *30*, 2440–2452.
Schafer, R. J., & Constable, R. T. (2009). Variation in language networks in monolingual and bilingual English speakers: Consequences for language mapping for surgical preplanning. *Journal of Clinical and Experimental Neuropsychology*, *31*, 945–954.
Schreuder, R., & Baayen, R. H. (1995). Modelling morphological processing. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (pp. 131–154). Hillsdale, NJ: Erlbaum.
Stein, M., Federspiel, A., Koenig, T., Wirth, M., Lehmann, C., Wiest, R., Strik, W., … Dierks, T. (2009). Reduced frontal activation with increasing 2nd language proficiency. *Neuropsychologia*, *47*, 2712–2720.
Stockall, L., & Marantz, A. (2006). A single route, full decomposition model of morphological complexity. MEG evidence. *The Mental Lexicon*, *1*, 85–123.
Stowe, L. A., Haverkort, M., & Zwarts, F. (2005). Rethinking the neurological basis of language. *Lingua*, *115*, 997–1042.
Taft, M. (1979). Recognition of affixed words and the word frequency effect. *Memory & Cognition*, *7*, 263–272.
Vandenberghe, R., Price, C., Wise, R., Josephs, O., & Frackowiack, R. S. J. (1996). Functional anatomy of a common semantic system for words and pictures. *Nature*, *383*, 254–256.
Waldron, E. J., & Hernandez, A. E. (2013). The role of age of acquisition on past tense generation in Spanish-English bilinguals: An fMRI study. *Brain and Language*, *125*, 28–37.
Weber, K., & Indefrey, P. (2009). Syntactic priming in German-English bilinguals during sentence comprehension. *NeuroImage*, *46*, 1164–1172.

https://doi.org/10.1017/S0267190514000038 Published online by Cambridge University Press