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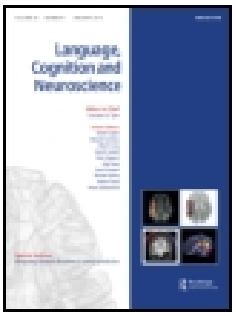

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COMMENTARY

Language experience and the brain: variability, neuroplasticity, and bilingualism

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In the last two decades, we have learned that there is far greater neuroplasticity in adulthood than previously understood. Experiences as varied as driving a taxi cab, playing a musical instrument, physical exercise, or playing video games change the brain both functionally and structurally (e.g. Bavelier, Achtman, Mani, & Föcker, 2012; Erickson et al., 2011; Herholz & Zatorre, 2012; Maguire et al., 2000). In this context, it should come as no surprise that a life in two languages would do the same. The specific consequences of bilingualism may be unique, but the fact of using two languages actively has implications for cognition and the brain networks that support it (e.g. Abutalebi et al., 2012; Bialystok, Craik, & Luk, 2012; Kroll, Dussias, Bice, & Perrotti, 2015). The article by García-Pentón, García, Costello, Duñabeita, and Carreiras (2015) asks what evidence exists to suggest that bilingualism imposes structural changes in the brain and what that evidence implies about whether the use of two or more languages confers cognitive advantages to bilingual speakers. Other recent reviews, notably Li, Legault, and Litckofsky (2014), have also evaluated the available structural data on the consequences of bilingualism.

The word "hazy" in the title of the García-Pentón et al. (2015) paper suggests that there is a problem with the existing research on this topic and the paper is indeed oriented towards two problems. One is that the authors claim that the quality of the data on the consequences of bilingualism for neuroanatomical change is variable: studies are underpowered, use a range of analytic methods that may not be comparable, and anatomical results from similar studies lack convergence. The other concerns the implications that this evidence holds for whether bilinguals are advantaged relative to monolinguals.

In this commentary, we argue that neither of these problems creates haze. Rather, the approach taken to the interpretation of structural imaging data requires additional complexity that considers the relationship between neural function and structure, particularly in identifying the mappings between function to structure and the role of individual differences. We suggest that even if the mappings between neuroanatomical structure and brain function can be understood in detail, the implications for potential cognitive advantages in behaviour will require a theoretical model that maps behaviour to brain structure and function, and that also takes into account differences in the way that bilingualism is manifest for different types of bilinguals across the lifespan (e.g. Bialystok, Craik, Green, & Gollan, 2009; Luk & Bialystok, 2013). Finding changes in neuroanatomical structure as a function of bilingualism need not imply that there will be cognitive advantages to bilinguals that are observed in behavioural performance, nor vice versa. These behavioural advantages need to be understood as well and each of these investigations, at multiple levels of analysis, requires a more sophisticated theoretical model.

Here, we consider what sort of framework is needed to begin to address the apparent inconsistencies in the evidence reviewed by García-Pentón et al. (2015). We then consider the relationship of this work to the extensive body of research on the consequences of bilingualism for behaviour and ask what assumptions might need to be made to begin to understand the causal mechanisms that underlie these consequences.

Understanding the neuroanatomical evidence

We take exception to the authors' guiding hypothesis (p. 9): "if it is the case that bilingualism leads to enhanced language related as well as domain-general executive control processes, then structural differences may be found in the neural regions that underlie these processes". At the current state of our knowledge, the investigation of neurostructural correlates of bilingualism can and perhaps should be explored independent of hypotheses about putative advantages of bilingualism. The guiding hypothesis is in fact conflating two sets of

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Invited commentary on García-Pentón et al. (2015). *The neuroanatomy of bilingualism: How to turn a hazy view into the full picture.*

linking hypotheses that have yet to be fully explicated. The first link is needed to specify how structural differences should be related to differences in brain functional activity. The second link is needed to specify how variations in the brain networks recruited for a given function relate to individual differences in ability. Attempting to directly associate brain structural variation with abilities such as enhanced cognitive control by glossing over these intermediate links will not lead to advances in our understanding of bilingualism. Otherwise we are left with rather naïve implicit theories of the sort: if an area has a particular function, and someone is better at that function, then that area should be structurally different. We consider issues relating to each link below.

First, we need to examine the neurobiological underpinnings of the various *in vivo* structural measurements currently available. For example, if cortical thickness in a particular region differs between groups, is that due to expanded neuropil in one group, group differences in pruning, or differential rates of intracortical myelination? Similarly, group differences in white matter tracts could be due to differences in axonal sprouting, changes in myelination, or pruning of connections. And group differences in local vs. long-range connectivity will have differing consequences for a variety of neuroanatomical measures (Deng et al., 2014). Without at least considering these issues, we cannot generate strong hypotheses about how structural differences might relate to neural function. It is important to avoid assumptions of the sort that more of something (e.g. thicker cortex) is somehow better functionally. To be sure, the neurobiological bases of current structural measures are being actively investigated (Vandekar et al., 2015; Wagstyl, Ronan, Goodyer, & Fletcher, 2015) and a strong consensus is absent. Nevertheless, it behoves us as (neuro)language researchers to think more deeply about how bilingualism could affect brain structure or brain activity (e.g. increased or decreased connectivity between specific regions, sculpting or expansion of circuits within particular regions) and then seek out appropriate converging methods.

It is important to note, however, that this research programme says little about differences in cognitive abilities. Individuals could rely on differing structural and functional networks, yet be equally adept at the cognitive functions the networks subserve. Acknowledging this possibility does not make the investigation of neurostructural correlates of bilingualism less important or interesting. At a minimum, reliance on alternate neural substrates opens up the possibility of differential outcomes in the face of disease, injury, or senescence – issues with important public health implications for various populations.

The second linking hypothesis concerns how brain function might relate to cognitive ability. Function is not ability, as was noted above. Exploring variations in ability may benefit from an individual differences perspective that acknowledges the wide variability in human population in virtually every measurable trait from cytoarchitecture (Zilles & Amunts, 2013) to mathematical ability (Lourenco, Bonny, Fernandez, & Rao, 2012). Often multivariate approaches are used that require much larger sample sizes than those used in the studies reviewed in the target article (e.g. Friedman & Miyake, 2004). This would appear to be of particular relevance to the study of bilingualism that involves consideration of multiple interacting variables (e.g. age of acquisition, proficiency in various languages, and degree of code switching) that cannot be submitted to experimental control. The differing results across studies that García-Pentón et al. document seem to us not to indict the validity of investigating neurostructural correlates of bilingualism, but rather to be the inevitable result of a relatively new area of investigation in which individual studies are probably underpowered to reliably detect true differences. For example, there is substantial between-subject variation in cortical surface area, thickness, and local gyrification among healthy young adults ($N = 200$) as indexed by the coefficient of variation, and this measure can differ threefold across various cortical regions (Chiarello, Vazquez, Felton, & McDowell, in preparation). From this perspective, one would predict differences across studies with small *N*s and differing measurement methods, even if the studies investigated individuals with similar bilingual backgrounds. García-Pentón et al. note that longitudinal studies obtain more consistent findings than cross-sectional investigations. This is as would be expected if individual variation were a large contributor to the conflicting cross-sectional findings. In addition, we suspect that age/sex differences contribute to differences across studies. Even relatively small differences in age (i.e. 20-year-olds vs. 30-year-olds) are associated with significant differences in measures such as cortical thickness (Zhou, Lebel, Evans, & Beaulieu, 2013) and the authors do not consider whether differences in the sex composition of various studies may have influenced the varying findings. Such variables may have little to do with bilingualism per se, nor with particular measurement techniques.

García-Pentón et al. (2015) suggest that researchers adopt similar measurement techniques in order to promote more valid comparisons across studies. Clearly, this would represent an improvement in many respects, but would come with a cost as well. In a science in which new methods are being developed at a rapid pace, encouraging researchers to rely on older

methods such as voxel based morphometry could have the effect of ossifying the research area and increasing the distance between basic neuroscience research and the study of bilingualism. We suggest that even more attention should be paid to the latest neuroscience findings and methods to better inform theoretical and empirical study of the neural bases of bilingualism.

A framework for interpreting the consequences of bilingualism

As the preceding comments make clear, interpreting structural differences in the brain in response to individual characteristics or experience is at an early stage of investigation that will require more sophisticated analytic models to enable claims about how particular life experiences create changes in the brain. Relating these findings to data from other levels of analysis, for example, from behavioural or electrophysiological studies, is also complex, but complexity itself does not mean that the investigation is doomed. Rather, efforts towards developing theoretical frameworks will require a broader lens to encompass the rapidly changing nature of the data that are available, the relations across different levels of analysis, and a theoretical commitment to how different forms of bilingual experience across the lifespan are likely to become apparent across the available methods.

Two trends in the recent literature have created opposing tensions in achieving this goal. Recent critiques of the bilingual advantage (e.g. Paap & Greenberg, 2013; Valian, 2015) have focused on failures to replicate behavioural studies that have reported executive function advantages for bilingual young adults relative to age-matched monolinguals. The failures to replicate have been interpreted to suggest that the evidence for a bilingual advantage has been greatly exaggerated. Notably, these critiques, much like the García-Pentón et al. (2015) analysis, are directed narrowly to a single method, or to a single age group or type of bilingual, and fail to consider converging evidence across different measures, across the range of bilingual experience, or between the consequences of bilingualism for cognition and for language. Crucially, they fail to provide a principled account of why, other than methodological shortcomings or variability, some studies report positive effects of bilingualism and others do not. Some have gone so far as to suggest that there is bias in the report of these findings that has created an illusion that there is any evidence for bilingual benefits (De Bruin, Treccani, & Della Sala, 2015; but see Bialystok, Kroll, Green, MacWhinney, & Craik, 2015).

Determining whether bilinguals and monolinguals differ in brain structure or function or in behaviour is a correlational exercise. It may provide clues but little in the way of a causal analysis to understand how the way that bilinguals use language may shape language performance, cognition, and the neural systems that support them. Another approach, and one that is more complex but also far more promising, attempts to identify the factors that might be required to model the consequences of bilingualism (e.g. Baum & Titone, 2014; Green & Abutalebi, 2013; Kroll & Bialystok, 2013). García-Pentón et al. (2015) appeal to the adaptive control framework proposed by Green and Abutalebi. Doing so provides a first step, but one that is quite preliminary, in speculating about why different structural imaging studies on bilinguals have produced conflicting results. The adaptive control framework assumes that bilinguals differ in the way that demands on cognitive mechanisms, and their neural underpinnings, are engaged by different types of language experience. Bilinguals differ in how the two languages are used, whether others in the environment are also similarly bilingual, whether they code switch between the two languages or not, and if they do code switch, and whether it first requires a decision about they can code switch with a particular interlocutor. This list is a partial illustration of how different bilinguals may be even if they are similarly proficient in the two languages, share similar demographic characteristics, and come from the same age and gender cohort. Considering developmental changes across the lifespan creates additional complexity (e.g. see Gold, Kim, Johnson, Kriscio, & Smith, 2013). As we noted earlier, any and all of these factors may potentially affect the way that brain networks are adjusted in response to experience and may have both functional and structural consequences. These are not simple effects and how we understand the consequences that are revealed in the brain and/or behaviour will require adopting a theoretical framework that acknowledges that it is unlikely that there will be a single effect of bilingualism. If there are advantages, they are likely to vary. In some instances, there could very well be disadvantages or no effect of bilingualism (see Bialystok et al., 2009, for a consideration of the range of bilingual consequences).

As scientists, we seek explanations that are simple and elegant. Phenomena that cannot be captured by a single variable or that produce inconsistent findings across different tasks, measures, and people may be difficult to investigate, but they are not impenetrable, noisy, or hazy. They require that we develop deeper analyses and new models. The variation in the data that results from newly emerging methods should not be characterised as haze but as an opportunity to challenge the oversimplification of earlier accounts. We need bold new

hypotheses for relating these new methods to experience and some modesty about how deeply we understand an experience as rich as life with two languages.

Disclosure statement

No potential conflict of interest was reported by the authors.

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