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Beyond volume: A surface-based approach to bilingualism-induced grey matter changes

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ABSTRACT

Bilingualism is a sustained experience associated with structural changes in cortical grey matter (GM) morphology. Apart from a few studies, a dominant method used to assess bilingualism-induced GM changes has been the voxel-based morphometry (VBM) analysis. While VBM is sensitive to GM volume/density differences in general, it cannot be used to identify whether the observed difference is due to relative changes in, e.g., cortical thickness, area or folding, as it uses a single combined measure of them all. Here, we used surface-based analysis (SBA) approach to investigate whether early acquisition of a second language (L2) affects the cortical GM morphology relative to late L2 acquisition. More specifically, our aim was to test a hypothesis that early acquisition of two languages induces GM changes that are predominantly surface area-driven, while late acquisition is supposedly characterised with primarily thickness-driven changes. To this end, several surface-based measures were concurrently compared between the groups. In line with the hypothesis, the results revealed that early bilingual experience is associated with significantly extended cortical surface area over the left pars opercularis and the right superior temporal gyrus. Contrary to our expectations, however, we found no evidence supporting the postulated association between late L2 acquisition and increased cortical thickness. Nevertheless, our study highlights the importance of including cortical surface measures when investigating bilingualism-related GM modulations.

1. Introduction

Recently, neurocognitive research on bilingualism has increasingly focused attention on structural brain plasticity related to second language (L2) acquisition and use. Pioneering studies have investigated whether bilingualism is related to quantifiable changes in both cortical grey matter (GM) morphology as well as in underlying white matter (WM) fibre arrangement (for reviews, see e.g., Li et al., 2014; Stein et al., 2014; García-Pentón et al., 2015). While an emerging consensus posits that bilingualism is indeed characterised by both GM and WM structural modulations, the experimental evidence remains relatively scarce and highly varying, regarding, in particular, the GM modulations.

To date, most studies targeting bilingualism-induced GM changes have utilised a voxel-based morphometry (VBM) analysis, which allows for a whole-brain level voxel-by-voxel comparison of the GM density/volume between two groups (Ashburner and Friston, 2000). With VBM, bilingualism-induced increases in GM volume/density have been observed in several fronto-temporal and medial language-related areas (Abutalebi et al., 2015b, 2014; Kaiser et al., 2015; Mechelli et al., 2004) as well as in the cerebellum (Pliatsikas et al., 2014). In contrast to these findings, several other studies using the same whole-brain level approach have not been able to detect any global GM differences associated with bilingualism (Gold et al., 2013; Grogan et al., 2012; Ressel et al., 2012). In two of these studies, however, significant group differences appeared when the number of voxelwise comparisons was constrained to specific, a priori chosen structures; these effects showed increased GM volume bilaterally in Heschl's gyrus (Ressel et al., 2012)

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and in the right posterior supramarginal gyrus (Grogan et al., 2012) in relation to bilingual/multilingual exposure. Other studies using a constrained VBM analysis and/or a mean volume ROI analysis with varying samples have reported bilingualism-induced increases in GM volume also in bilateral temporal poles and orbito-frontal cortices (Abutalebi et al., 2014), bilateral inferior parietal lobules and in the left putamen (Abutalebi et al., 2015a). Although these constrained analyses corroborate the whole-brain level findings in showing that bilingualism can induce structural GM modulations (but see Olsen et al., 2015, with no significant group effects despite a ROI approach), the reported effects have been scattered across the brain, showing little or no consistency between studies in general.

In addition to VBM studies and mean volume analyses, structural GM modulations can also be investigated by using a surface-based analysis (SBA) approach. SBA approach defines the cortical surface as a geometrical mesh model, created by extracting the inner and outer GM boundaries. Several cortical measures such as thickness, surface area, volume and mean curvature can be estimated from the mesh model by calculating distances between the vertices. While SBA has been regularly used to investigate, for instance, changes in cortical volume and thickness associated with typical and atypical development (Wierenga et al., 2014; Zielinski et al., 2014; Wallace et al., 2015), only two prior studies have implemented it to investigate bilingualism-induced GM modulations. Klein and colleagues (2014) performed a cross-sectional study on cortical thickness between monolinguals vs. simultaneous (age of acquisition of L2, AoA = < 3 years), early sequential (AoA = 4–7 years) and late sequential bilinguals (AoA = 8–13 years) and observed differences in the left and right IFG. In the left IFG, the early and late sequential bilinguals had significantly increased cortical thickness compared to monolinguals and simultaneous bilinguals. In the right IFG, however, the effect was reversed, and the difference was significant only between the late bilinguals and monolinguals (i.e., late bilinguals had thinner cortex than monolinguals). In another study, cortical thickness was investigated in participants who underwent intensive language training during three months (Mårtensson et al., 2012). They showed that gaining proficiency in the target language was associated with increased cortical thickness in the left fronto-temporal cortices. More specifically, changes were observed in the left IFG, the middle frontal gyrus and in the superior temporal gyrus (STG); however, only the changes in the STG were significantly correlated with an increase in the target language proficiency. Notably, these SBA results are somewhat more concordant than the VBM/ROI findings in indicating, for example, the left IFG as a potential site for bilingualism-induced GM changes.

Considering that GM volume is the product of surface area and thickness (Panizzon et al., 2009), a major shortcoming of the previous studies examining bilingualism-related changes in the cortical GM morphology, is that these measures have not been investigated concurrently. First, accumulating evidence from several studies on cortical development and cellular architecture suggests that surface area and thickness are independent rather than redundant features of cortical structure (Im et al., 2008; Panizzon et al., 2009) with little to no covariation between them (Pakkenberg and Gundersen, 1997). Consequently, comparisons restricted to the GM volume alone risk obstructing bilingualism-related modulations that might be specific to either surface area or cortical thickness. In other words, two groups could, in theory, exhibit identical GM volume and still differ significantly from each other with respect to the underlying surface area to thickness ratio (for illustration, see Fig. 1). Conversely, two studies conducted with different bilingual samples could reveal seemingly concordant GM volume findings, while, in fact, the underlying cause for the observed GM difference (surface area vs. thickness-driven) might differ substantially between the studies.

Second, cortical surface area and thickness have been suggested to reflect distinct cellular mechanisms (Rakic, 2009; Raznahan et al., 2011), inasmuch as cortical surface area is thought to reflect the

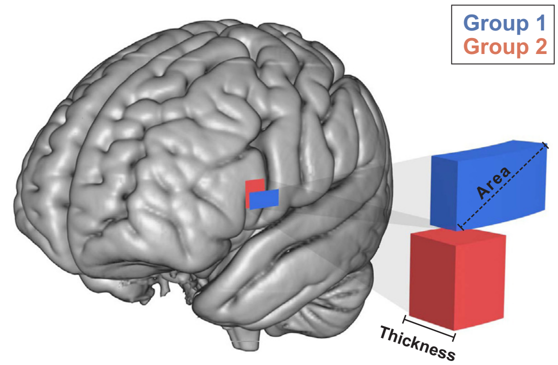

Fig. 1. A hypothetical situation where GM volume (blue and red cubes) appears identical between the groups despite significant differences in cortical surface area (dashed line) and thickness (solid line).

number of neuronal columns perpendicular to the pial surface, whereas cortical thickness relates to the number (Rakic, 2009) and, possibly, to the size of cells within these columns (Panizzon et al., 2009). Crucially, cortical surface area has been shown to increase rapidly through maturation during infancy (0–2 years of age; Lyall et al., 2015) and early childhood (1–6 years of age; Remer et al., 2017), and to remain relatively stable from thereafter (Tamnes et al., 2017). Cortical thickness, on the other hand, appears well established at birth (Lyall et al., 2015), but has been suggested to alter dynamically across the entire life span in response to experience-dependent learning (Meyer et al., 2014). As the brain is considered to be particularly susceptible to the effects of the environment during periods of rapid growth (Lyall et al., 2015), early acquisition of two languages could be hypothesised to induce GM changes that are predominantly surface area-driven, whereas acquiring an L2 later in life, after surface area development has already been largely set, might lead to primarily thickness-driven GM changes. To test this hypothesis, we used SBA approach to investigate whether early exposure to L2 affects cortical morphology relative to late L2 exposure. Comparisons of several cortical measures on both whole-brain level as well as within a priori defined ROIs relevant for language processing were conducted. The ROI analysis was motivated by the reviewed literature suggesting that some of the effects might be discoverable only by limiting the analysis to specific language-related regions (Grogan et al., 2012; Ressel et al., 2012). We therefore included five bilateral ROIs encompassing areas where structural effects related to bilingualism or language processing have typically appeared; the inferior parietal cortex (IPC; Mechelli et al., 2004), the adjacent supramarginal gyrus (SMG; Grogan et al., 2012), the inferior frontal gyrus (pars opercularis and triangularis, POp and PTr) (Kaiser et al., 2015; Klein et al., 2014; Mårtensson et al., 2012; Stein et al., 2012) and the STG (Mårtensson et al., 2012), which includes, for instance, the primary auditory cortex and Heschl's gyrus (Ressel et al., 2012). The ROIs are illustrated in Fig. 2A.

Regarding the participant selection, our early and late bilingual participants were highly similar to Kaiser and colleagues' (2015) participants (early vs. late bilinguals) and relatively similar to Klein and colleagues' (2014) participants (simultaneous/early sequential vs. late sequential bilinguals). Based on Kaiser and colleagues' VBM findings, group differences in GM architecture should be observable bilaterally in fronto-temporal and parietal regions, where late sequential bilinguals are expected to have increased GM volume (possibly due to thicker cortex) compared to early bilinguals. VBM and SBA have, however, been occasionally shown to produce slightly differing results (e.g., Bermudez et al., 2009), bringing into question the extent to which SBA findings can be predicted from the prior VBM observations. Thus, based on Klein and colleagues' (2014) SBA findings in particular, we expect to