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Functional activity and white matter microstructure reveal the independent effects of age of acquisition and proficiency on second-language learning

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ABSTRACT

Two key factors govern how bilingual speakers neurally maintain two languages: the speakers' second language age of acquisition (AoA) and their subsequent proficiency. However, the relative roles of these two factors have been difficult to disentangle given that the two can be closely correlated, and most prior studies have examined the two factors in isolation. Here, we combine functional magnetic resonance imaging with diffusion tensor imaging to identify specific brain areas that are independently modulated by AoA and proficiency in second language speakers. First-language Mandarin Chinese speakers who are second language speakers of English were scanned as they performed a picture-word matching task in either language. In the same session we also acquired diffusion-weighted scans to assess white matter microstructure, along with behavioural measures of language proficiency prior to entering the scanner. Results reveal gray- and white-matter networks involving both the left and right hemisphere that independently vary as a function of a second-language speaker's AoA and proficiency, focused on the superior temporal gyrus, middle and inferior frontal gyrus, parahippocampal gyrus, and the basal ganglia. These results indicate that proficiency and AoA explain separate functional and structural networks in the bilingual brain, which we interpret as suggesting distinct types of plasticity for age-dependent effects (i.e., AoA) versus experience and/or predisposition (i.e., proficiency).

1. Introduction

Prior studies of bilingualism have identified ways in which the neural representation of a second language (L2) differs from that of an individual's first language (L1). Specifically, there are several differences in activation between L2 and L1, both in terms of degree and extent. L2s tend to not only show more activity within traditional left-hemisphere language areas, but also tend to activate more regions outside the traditional language network (Chee et al., 2004; Dehaene et al., 1997; Kim et al., 1997; Perani et al., 1998; Wartenburger et al., 2003). Much of the current data come from studies using fMRI to compare cortical activity, although an emerging literature also reveals differences between L2 and L1 in white matter connectivity as examined with diffusion tensor imaging (DTI).

There are two predominant theories as to why neural signatures of L2 differ from those of L1. The first is that these differences reflect reduced neuroplasticity during L2 learning that occurs at a later age than L1 learning. On this account L2 learning requires increased neural resources due to maturational changes in neural plasticity within regions and pathways supporting first language learning (Abutalebi, 2008; Klein et al., 2013; Li et al., 2014; Mechelli et al., 2004; Pakulak and Neville, 2011; Perani et al., 1996; Wartenburger et al., 2003; Weber-Fox and Neville, 1996). Concordant with this view, studies have found that age-of-acquisition (AoA) modulates these effects; individuals who are early L2 learners show patterns of brain activity that are more similar for L1 compared to late L2 learners (Perani and Abutalebi, 2005; Wartenburger et al., 2003). Additionally, structural connectivity, as measured using DTI, appears to vary as a function of AoA. A common measure of white matter microstructure is fractional anisotropy (FA), which ranges from zero to one and represents the cohesiveness of white matter tracts. High FA suggests that water diffusion is restricted to a single direction and thus the white matter tract is cohesive, while low FA suggests that water diffusion is unrestricted and the tract is less cohesive. FA varies with AoA such that children who learned two languages from birth (simultaneous bilinguals) show higher white matter integrity in the left inferior fronto-occipital fasciculus (IFOF), the tract connecting anterior frontal regions with posterior temporal regions when

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compared to children who learned their two languages sequentially (Mohades et al., 2012). However, lower integrity was also found in the tracts projecting from the anterior portion of the corpus callosum to orbitofrontal cortex compared to late L2 learners. These results highlight how differences in brain connectivity may be related to L2 AoA. Research suggests that there are separate L1 and L2 networks that are complementary in their importance as a function of AoA (Mohades et al., 2012). The differing influence of AoA on separate tracts may reflect their relative importance in L1 versus L2 processing.

The alternative theory is that neural differences in L1 versus L2 are instead driven by the fact that individuals' L2 is generally lower in proficiency than their L1. On this account, second language processing involves increased processing demands, and therefore greater neural resources. While greater processing demands may induce experience-based plasticity, these changes should be separable from age-induced plasticity. Indeed, prior neuroimaging studies have observed that higher-proficiency L2 users do show patterns of neural activity that more closely resemble those of L1 users, compared to lower-proficiency L2 users, even when AoA is controlled for (Chee et al., 1999; Newman et al., 2012; Pakulak and Neville, 2011; Perani et al., 1998; Wartenburger et al., 2003).

While both AoA and proficiency explanations are appealing, it is difficult to adjudicate among them given that the two are generally confounded: early L2 learners also tend to have higher proficiency than late learners, making it difficult to tease apart the relative contribution of both factors. Indeed, it could be argued that the two are simply reflections of each other, and cannot be disentangled. However, early AoA does not always mean high proficiency, and high proficiency does not always mean early AoA. Although it is well established that children acquire an L2 more easily than adults, adults are still capable of becoming highly proficient (Perani et al., 1998; Wartenburger et al., 2003), and some children fail to fully acquire a second language in spite of adequate opportunity to do so (Frost et al., 2013; Sahinkarakas, 2011). Factors such as motivation and environment also play a key role in successful L2 acquisition (Bernaus and Gardner, 2008; Gardner et al., 2004) unlike in L1, where failure to acquire language is extremely rare outside situations involving severe sensory deprivation (Fromkin et al., 1974). The present study addressed individual differences in L2 learning success by examining neural signatures of L2 processing in adult native speakers of Mandarin who are second language English speakers. These speakers showed significant variation in both AoA and proficiency, allowing us to examine the two factors in parallel. Additionally, this approach allowed us to examine effects of L2 learning using a within-subjects design, rather than creating (potentially arbitrary) groups of high versus low proficiency and early versus late L2 learners.

We first used fMRI to isolate areas involved in L2 processing, and examined how variation in patterns of activation can be explained either by AoA or proficiency. Next, we used DTI to identify regions in which tract coherence correlated with either AoA or L2 proficiency, and which white matter tracts projected from these regions. We identified networks of both functional and structural organisation that were independently explained by proficiency and AoA, suggesting the L2 speaker's brain organisation is not wholly influenced by age-dependent learning, but is also susceptible to L2 language ability levels.

2. Methods

2.1. Subjects

Twenty-two (17 female) neurologically healthy right-handed native speakers of Mandarin were recruited via posters at the University of Western Ontario and from the London, Ontario community. All subjects were English L2 speakers, aged 18–35 ($M=22.18$, $SD=4.24$), and ranged in age of acquisition from 4–30 years ($M=13.82$, $SD=7.12$). Two additional subjects were recruited but excluded from analyses, one due to an incidental finding and one due to chance-level performance on both the English and Mandarin fMRI tasks. Additional subject demographics are presented in Table 1.

Table 1
Subject demographics.

Measure		Mean (SD)	Min	Max
Age (years)		22.18 (4.24)	18	35
Sex	f	17		
	m	5		
Years of schooling		14.8 (2.26)	12	20
Proficiency (% correct)	L1	85.98 (6.34)	72.92	97.92
	L2	68.28 (6.62)	54.17	77.08
Age of Acquisition		13.82 (7.12)	4	30
Duration of exposure to L2 (years)		8.36 (4.47)	0	15

Note: Proficiency score reflects percent correct on each language's proficiency test.

2.2. Behavioural materials

L1 Mandarin and L2 English proficiency levels were assessed prior to scanning using a subset of 48 questions from the Hanyu Shuiping Kaoshi (HSK Centre, Beijing, China) and the Test of English as a Second Language (ETS, Princeton, NJ) respectively, with both tests consisting of three sections: Grammar, reading comprehension, and vocabulary. The three sections were combined to give a final mark out of 48 for each language, representing overall proficiency in these three domains. As the fMRI task was an auditory lexical-semantic one, this general proficiency created from not just lexical knowledge score helped avoid circularity in correlating lexical knowledge with itself. Despite the written form of the proficiency test and the auditory form of the fMRI task, lexical knowledge is amodal (Coccia et al., 2004; Lambon Ralph and Patterson, 2008; Patterson et al., 2007) and thus is not confounded by the modality in which each task was administered.

AoA was defined as the age at which subjects first began learning English. To verify right-handedness, subjects completed an abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971). All behavioural measures were completed in Mandarin aside from the English proficiency test. Letters of information, informed consent and task instructions were likewise administered in Mandarin by a native speaker.

2.3. fMRI task

Subjects completed a picture-word matching task during scanning. This task has been used extensively in the past to study lexical knowledge (Breining et al., 2014; Dräger et al., 2004; Weniger et al., 2000), and was chosen to examine lexical-semantic processing. Because this task does not engage reading or syntax, it provided an ideal task to investigate lexical-semantic processing.

Pictures appeared centred on a screen mounted at the head of the scanner bore, which subjects viewed through a mirror placed above the head coil. At the same time, a word was played binaurally through insert earphones (Sensimetrics Corporation, Malden, MA). Both match and mismatch trials were presented in order to maximise participants' engagement during the task, and to encourage greater depth of processing than what might be expected during passive listening or lexical decision. Subjects were required to indicate as quickly as possible with a button press whether the picture and word matched. Each picture was visible for 2.5 s.