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Neural activation in speech production and reading aloud in native and non-native languages

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ABSTRACT

We used fMRI to investigate neural activation in reading aloud in bilinguals differing in age of acquisition. Three groups were compared: French–English bilinguals who acquired two languages from birth (simultaneous), French–English bilinguals who learned their L2 after the age of 5 years (sequential), and English-speaking monolinguals. While the bilingual groups contrasted in age of acquisition, they were matched for language proficiency, although sequential bilinguals produced speech with a less native-like accent in their L2 than in their L1. Simultaneous bilinguals activated similar brain regions to an equivalent degree when reading in their two languages. In contrast, sequential bilinguals more strongly activated areas related to speech-motor control and orthographic to phonological mapping, the left inferior frontal gyrus, left premotor cortex, and left fusiform gyrus, when reading aloud in L2 compared to L1. In addition, the activity in these regions showed a significant positive correlation with age of acquisition. The results provide evidence for the engagement of overlapping neural substrates for processing two languages when acquired in native context from birth. However, it appears that the maturation of certain brain regions for both speech production and phonological encoding is limited by a sensitive period for L2 acquisition regardless of language proficiency.

Introduction

The capacity of the brain to comprehend and produce two languages with distinct phonological, syntactic, and semantic properties is a testament to its plasticity. The degree to which competence in specific language functions can be attained may be limited by age of acquisition (AoA) and the extent to which the first language (L1) has been established when the second language (L2) is learned (Hatzidaki et al., 2011; Nosarti et al., 2010; Klein et al., 2006; Tan et al., 2003; Flege et al., 1999; Lenneberg, 1967). These limitations may reflect a critical period (Lenneberg, 1967) due to normal time-sensitive maturational changes in the brain (Bialystok, 1997; Long, 1990). As is true for other types of learned skills, not all facets of L2 proficiency (i.e., phonological, syntactic, and semantic) are likely to reflect the same temporal constraints. The optimal window for phonological learning, in fact, may begin to close prior to one year of age (Kuhl, 2010; Werker and Lalonde, 1988; Werker and Tees, 1984).

Developmental studies have suggested that the ability of an infant raised in a monolingual environment to discriminate the phonetic signatures of different languages begins to wane after six months of life (Kuhl, 2010; Werker and Lalonde, 1988; Werker and Tees, 1984). In contrast, infants exposed to two languages simultaneously from birth continue to discriminate the phonetic representations of each (Burns et al., 2007), indicating that the timeline for the shift from language-general to language-specific processing extends longer for such children (Werker and Byers-Heinlein, 2008). In addition, it has been observed that individuals learning two languages simultaneously from birth (simultaneous bilinguals) speak with a native-like accent in both languages, compared to sequential bilinguals who learned their second language after acquiring their first, despite considerable effort, years of practice, and competence in other aspects of language production (Reiterer et al., 2011; Johnson and Newport, 1989). Indeed, only about one in ten bilinguals acquiring an L2 as an adult can expect to produce speech without a foreign accent in the non-native language (Golestani and Zatorre, 2004, 2009; Golestani et al., 2007; Birdsong, 1999, 2005).

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While much of the neuroimaging literature on bilingual language processing has focused on disentangling the relative effects of AoA from proficiency (e.g., Perani et al., 1998), differences between simultaneous and sequential bilinguals have received limited attention. Of note are studies reporting increased neural activation for late-learning bilinguals relative to monolingual controls in regions involved in speech production (Frenck-Mestre et al., 2005; Klein et al., 1994, 1995) and more recent structural neuroimaging data showing late-learning bilinguals with increased cortical thickness in the left inferior frontal gyrus (IFG) compared to simultaneous bilinguals (Klein et al., 2014). These observations are consistent with a more robust recruitment of language-related brain areas for L2 compared to L1 to compensate for less efficient use of these regions in the second language (Indefrey, 2006). If, indeed, the sensitive period for developing phonology draws to a close in early infancy, then it seems probable that the loss of innate mechanisms for native-like pronunciation would result in greater activation during speech for sequential bilinguals, but not for simultaneous bilinguals.

Explanations as to how some bilinguals manage to accomplish native articulatory competence in a second language, while others do not, remain conjectural, although differences in psycholinguistic processes such as phonological working memory (Baddeley, 2003; Thorn and Gathercole, 2001; Gathercole et al., 1994, 1997) and in the neural activation associated with speech-motor planning and auditory–perceptual processing have been observed (Hu et al., 2013). While studies of proficient bilinguals suggest considerable convergence in the brain loci activated when speaking either language, there is evidence that the extent of activation can vary between L1 and L2 in certain regions, especially those involved in speech articulation (Parker Jones et al., 2012, 2013; Simmonds et al., 2011b; Klein et al., 1994, 1995, 2006; Frenck-Mestre et al., 2005).

Such studies, however, raise the question as to whether this difference in functional activity relates to language proficiency, AoA, or both (Parker Jones et al., 2012; Simmonds et al., 2011a,b). Wartenburger et al. (2003) used grammatical and semantic judgment tasks to disentangle the effects of AoA from proficiency on brain function in Italian–German bilinguals and suggested that the relative importance of these factors depended on the aspect of language examined. To date, however, few neuroimaging studies have investigated the relationship between AoA and phonological skill in a second language. Klein et al. (2006) compared L1 and L2 word repetition in late bilinguals and found greater activity for L2 in speech-motor areas, indicating the increased articulatory demands of pronouncing words in the non-native language. However, the late bilinguals included in that study were not tightly controlled for proficiency nor were they contrasted with an early or simultaneous bilingual group.

Here, we used fMRI to compare neural activation during French and English oral sentence reading in simultaneous bilinguals, sequential bilinguals, and L2-exposed monolinguals. Our bilingual subjects were matched for linguistic proficiency, but differed in native-like accent in L2. We observed similar functional activity for simultaneous bilinguals and monolinguals, but different patterns for sequential bilinguals, supporting the notion that compensatory mechanisms are recruited to achieve oral proficiency when sequential bilinguals read aloud in a late-learned language. The sequential bilinguals engaged brain regions more strongly in their L2 than in their L1, most notably in areas associated with orthographic to phonological mapping (e.g., occipital and occipitotemporal cortex Dehaene et al., 2010; McCandliss et al., 2003; Cohen et al., 2002) and articulatory motor planning (e.g., motor cortex, IFG, and cerebellum Indefrey, 2012; Fiez and Petersen, 1998; Bavelier et al., 1997). The results provide evidence for the engagement of overlapping neural substrates for processing two languages when acquired in native context from birth. However, it appears that the maturation of certain brain regions for both speech production and phonological encoding is limited by a sensitive period for L2 acquisition, regardless of language proficiency.

Materials and methods

Participants

Forty-seven right handed subjects differing in language experience were selected for this study: French–English simultaneous bilinguals who acquired two languages from birth, French (L1)–English (L2) sequential bilinguals who acquired their second language after the age of 5 years, and English monolinguals. Simultaneous bilinguals acquired both of their languages at home, while sequential bilinguals acquired their L2 at school. All bilinguals are exposed to and use French and English on a daily basis as self-reported on the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, 2007). Although monolinguals reported some daily exposure to French as a function of living in Montreal, they considered themselves solely speakers of the English language. As such, these individuals differ from monolinguals most commonly examined. To acknowledge this distinction, we describe our monolingual subjects as exposed to an L2.

All participants were healthy young adults, without hearing or reading impairment, neurological disorder, or history of brain trauma as assessed by a telephone interview prior to scanning. Multilinguals were excluded. Individuals self-reporting a high degree of musical expertise were also excluded, given that there is some suggestion of a correlation between musical skill and language ability (Christiner and Reiterer, 2013). Intelligence was assessed by the Block Design subtest of the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1981; see Table 1). Participants were recruited from the McGill community and gave informed consent. Testing procedures were approved by the Research Ethics Board of the Montreal Neurological Institute, McGill University.

Language assessment

Language competence was assessed with the Language Experience and Proficiency Questionnaire (Marian, 2007). Simultaneous and sequential bilinguals reported a high level of proficiency in both languages, while English-speaking monolinguals maintained a high proficiency in their native language only (see Table 2). Subjects rated their ability to learn a language since it has been shown that greater language learning aptitude is reflected structurally in the brain (Golestani et al., 2002, 2007; Golestani and Zatorre, 2004). Comparable degrees of self-assessed aptitude were obtained.

In addition, recordings were made of the participants producing speech and reading standardized paragraphs aloud in French and English. Participants were instructed to speak for 2 min in each language following simple open-ended prompts (i.e., *S'il vous plaît, décrivez une journée typique pour vous [à la plage/au zoo]. En utilisant un vocabulaire pertinent, vous pouvez vous rappeler d'une journée [à la plage/au zoo] ou créer des histoires qui fonctionnent dans le contexte; Please describe what could be a typical day for you at the [beach/zoo]. Using relevant vocabulary,*

Table 1
Background information on participant groups.

	Simultaneous bilingual	Sequential bilingual	Monolingual
	$N = 16$	$N = 13$	$N = 18$
Gender			
% Male	37	62	67
% Female	63	38	33
Mean age (years)	23.3 (3.1)	25.2 (4.2)	25.8 (4.5)
Mean L2 AoA (years)	1.0 (0.0)	13.9 (5.0)	N/A
% Daily exposure to French	60.0 (16.9)	40.0 (18.5)	15.7 (15.2)
% Daily exposure to English	40.0 (15.4)	60.0 (18.5)	84.3 (15.7)
Formal education (years)	16.1 (2.7)	17.1 (2.8)	16.6 (1.8)
Block Design Subtest, WASI (1–19)	13.6 (1.6)	13.5 (2.5)	13.3 (2.0)

Values are means (SD).