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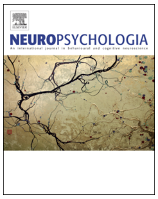

Neural signatures of second language learning and control

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ABSTRACT

Experience with multiple languages has unique effects on cortical structure and information processing. Differences in gray matter density and patterns of cortical activation are observed in lifelong bilinguals compared to monolinguals as a result of their experience managing interference across languages. Monolinguals who acquire a second language later in life begin to encounter the same type of linguistic interference as bilinguals, but with a different pre-existing language architecture. The current study used functional magnetic resonance imaging to explore the beginning stages of second language acquisition and cross-linguistic interference in monolingual adults. We found that after English monolinguals learned novel Spanish vocabulary, English and Spanish auditory words led to distinct patterns of cortical activation, with greater recruitment of posterior parietal regions in response to English words and of left hippocampus in response to Spanish words. In addition, cross-linguistic interference from English influenced processing of newly-learned Spanish words, decreasing hippocampus activity. Results suggest that monolinguals may rely on different memory systems to process a newly-learned second language, and that the second language system is sensitive to native language interference.

1. Introduction

Experience-dependent plasticity refers to the lifelong process of neural specialization as a result of practice in a domain. Different types of visual (Gauthier et al., 2000; Kwok et al., 2011), spatial (Maguire et al., 2000), and auditory (Krizman et al., 2014; Sluming et al., 2002) experiences have lasting effects on informational processing and cortical structure. Knowledge of multiple languages is one such form of experience with far-reaching outcomes that has been examined in a number of studies (see Hernandez, 2013). For example, in bilinguals, changes in gray matter volume have been directly related to both age of acquisition and proficiency in a second language (Mechelli et al., 2004), demonstrating that cortical changes are sensitive to different types and amounts of language exposure.

Neural plasticity from second language experience extends beyond language processing to affect core cognitive processes, and these changes also lead to differences in cortical structure. Bilinguals are uniquely challenged to prevent interference from the non-target language during both language comprehension (Chambers and Cooke, 2009; Ju and Luce, 2004; Marian and Spivey, 2003a; Spivey and Marian, 1999) and production (Colomé and Miozzo, 2010; Green, 1998) in the target language. Bilinguals' lifelong experience controlling access to two languages is thought to heighten their executive functioning abilities (Bialystok, 2015; for an opposing view see Hilchey and Klein, 2011). This increase in ability is reflected in changes in the prefrontal cortex during attentional control tasks compared to monolinguals (Bialystok et al., 2005; Luk et al., 2010), and in recruitment of the frontal cortex during language processing (Abutalebi, 2008; Hernandez et al., 2001; Marian et al., 2014).

Critical to our understanding of bilingual language processing in adults is how changes in language experience correspond to changes in neural structure and processing. Beginning second language learners process two languages differently than fluent bilinguals because of learners' asymmetry in proficiency (Kroll and Bogulski, 2013; Kroll and Stewart, 1994). This asymmetry also affects how language learners control interference between languages (Bartolotti and Marian, 2012; Costa and Santesteban, 2004). By studying patterns of second language acquisition, it is possible to assess the trajectory of experience-related changes in neurological processing. The effects of second language acquisition on the brain have been explored in a wide body of research covering multiple timescales and types of information processing. Long-term training paradigms have identified the processes that contribute to storage and use of a novel language, whereas short-term training studies demonstrate learning mechanisms at early stages, which involves transfer of word knowledge from short-term memory to long-term lexical storage.

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Specifically, long-term training experiments show that extended study of a second language results in experience-related changes in gray matter density in frontal regions and the hippocampus. Adults undergoing intensive study of a foreign language over a three month period had increases in gray matter volume in the hippocampus, left inferior frontal gyrus, middle frontal gyrus, and superior temporal gyrus (Mårtensson et al., 2012). The magnitude of these changes correlated with proficiency gains over a three-month period, suggesting that gray matter increases were related to learning success. Similarly, college students tested before and after five months studying a language abroad showed greater gray matter density in left inferior frontal gyrus and the left anterior temporal lobe, two areas implicated in lexical access and semantic integration (Stein et al., 2012). Second language training in a controlled laboratory setting has also been shown to affect neural structure. Native Japanese speakers with limited English experience who engaged in a 16 week series of English vocabulary training sessions showed increased gray and white matter density in right inferior frontal gyrus, and this increase was positively correlated with their proficiency gains (Hosoda et al., 2013).

Compared to the long-term changes observed primarily in frontal cortical regions, short-term training effects are seen in additional areas involved in learning and memory. The hippocampus in particular is a potential marker for the onset of second language learning due to its utility in the formation of memories for diverse components of language. Learning paired associates in another language, for example pictures of objects with novel words, is related to changes in hippocampus activation (Breitenstein et al., 2005; Henke et al., 1999). Transcranial stimulation of areas of cortex that have direct connections to the hippocampus can further improve novel vocabulary learning through these same mechanisms (Flöel et al., 2008). The role of the hippocampus is not limited to vocabulary, but extends to early stages of grammar learning. As grammatical knowledge in a second language shifts from a collection of semantic facts to procedural rules, an associated shift is observed from initial hippocampal activity to distributed cortical activation (Helmstaedter et al., 1997; Opitz and Friederici, 2003; Wagner et al., 1998).

Models of second language acquisition explicitly mark the transition from initial hippocampal storage to later integration with the existing lexicon in a more distributed fashion (Davis and Gaskell, 2009). Behavioral evidence for this consolidation phase comes from vocabulary training studies. After learning novel words that are neighbors of existing English words (e.g., *cathedruke*, which differs in the final phoneme from *cathedral*), competition from the novel word is observed only after a period of intervening sleep, during which time the novel word can be integrated into the lexicon and cortically distributed (Dumay and Gaskell, 2007). The learned words continue to affect native language processing for several months (Tamminen and Gaskell, 2008), consistent with the timecourses involved in hippocampal and cortically-distributed memory systems.

Whereas competition from the novel language during native language processing is dependent on lexical integration of the newly-learned words, the converse case may be observed at earlier stages. In bilinguals, relative proficiency can modulate the amount of competition, with the dominant language leading to more competition during processing of the less dominant language (Blumenfeld and Marian, 2007). In second language learners, for whom there is a large asymmetry between their two languages, native language competition should occur at early stages of learning. This type of competition is less well examined, although some behavioral studies have shown that native English words can compete with newly-learned vocabulary in an artificial language immediately post-training (Bartolotti et al., 2013; Bartolotti and Marian, 2012).

The current study was designed to investigate language learning and control in monolingual adults and had two aims. *The first aim* was to compare neural signatures for auditory processing of native language words and of newly-learned words in a second language. *The second aim* was to determine the extent to which native language knowledge interferes with recently-learned second language vocabulary. We taught English monolinguals 40 spoken Spanish words paired with concrete pictures (e.g., *muñeca*, meaning *doll*) through brief paired-associate learning. Then, in separate English and Spanish language blocks, participants identified the picture that matched a spoken target in a four-alternative forced choice task. Comparing performance in English and Spanish language trials allowed us to detect differences in how first and second languages are represented at early stages of learning. Because of the short timescale over which training occurs, we predict strong activation of the hippocampus during Spanish word processing. Spanish language trials were divided into Competitor and No-competitor trials, based on the properties of other pictures in the visual display. In Competitor trials, the English name of one of the non-target pictures overlapped with the Spanish spoken target (e.g., target *muñeca* and English competitor *moon*). This critical comparison was included to examine the processes used by monolinguals to control cross-linguistic competition at early stages of second language learning.

2. Materials and methods

2.1. Participants

Eighteen English monolinguals (12 females, mean age=22.28 years, SD=3.69) participated in the current study. All participants were university students and were right-handed, healthy adults with no history of neurological or psychiatric illness. Because language learning and phonological competition are affected by cognitive factors including memory span and inhibitory skill (Gass et al., 2013; Mackey and Sachs, 2012), we measured participants' executive functioning (colored shapes version of the Simon task, Simon and Rudell, 1967), academic achievement (grade point average), phonological memory, and sequence memory (non-word repetition and digit span subtests, respectively, from the *Comprehensive Test of Phonological Processing*, Wagner et al., 1999).

2.2. Materials

Participants learned 40 Spanish words that referred to concrete, imageable objects. Twenty of the Spanish words shared phonological onset with an English competitor word (e.g., the Spanish word *sobre*, meaning envelope, overlaps with the English competitor *soap*). Each of the twenty stimuli sets included a Spanish target (e.g. *sobre*, meaning 'envelope'), an English competitor (e.g. *soap*), a matched control word (e.g. *meat*, which does not overlap with *sobre* or its translation *envelope*), and two unrelated words (e.g. *fin* and *paintbrush*); a full list is provided in Appendix. The five words within a set were used to construct two matched trials with four objects each: a competitor trial including the target, competitor, and both unrelated items (e.g., *envelope/sobre*, *soap*, *fin*, and *paintbrush*); and a control trial in which the competitor was replaced with the control item (e.g., *envelope/sobre*, *meat*, *fin*, and *paintbrush*). All stimuli in a set were matched on word frequency (SUBTLEXUS, Brysbaert and New, 2009), orthographic and phonological neighborhood size (CLEARPOND, Marian et al., 2012), and concreteness, familiarity, and imageability (MRC Psycholinguistic Database, Coltheart, 1981) (all $ps > .05$). Items in a set were visually represented by black and white line drawings obtained from the International Picture Naming Project (IPNP) database (Bates et al., 2003) or from Google Images. IPNP pictures were selected for high naming consistency, and pictures from Google Images were independently normed by 20 English monolinguals on Amazon Mechanical Turk (https://www.mturk.com). Across all items, picture naming reliability from the IPNP or Turk ratings was 92% (SD=10.8). Naming reliability for the critical Competitor condition ranged from 75% to 100%.

2.3. Procedure

Testing took place in two sessions for each participant. In the first session, the participant gave informed consent in accordance with the Institutional Review Boards of Northwestern University and the University of Houston. Then the participant was screened for claustrophobia, health conditions, and presence of metal in