Brain & Language 144 (2015) 35–47

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Second language lexical development and cognitive control: A longitudinal fMRI study

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ARTICLE INFO

Article history:
Received 15 November 2014
Accepted 26 March 2015
Available online 17 April 2015

Keywords:
Second language acquisition
Vocabulary
Executive function
fMRI
Longitudinal design

ABSTRACT

In this paper we report a longitudinal functional magnetic resonance imaging (fMRI) study that tested contrasting predictions about the time course of cognitive control in second language (L2) acquisition. We examined the neural correlates of lexical processing in L2 learners twice over the course of one academic year. Specifically, while in the scanner, participants were asked to judge the language membership of unambiguous first and second language words, as well as interlingual homographs. Our ROI and connectivity analyses reveal that with increased exposure to the L2, overall activation in control areas such as the anterior cingulate cortex decrease while connectivity with semantic processing regions such as the middle temporal gyrus increase. These results suggest that cognitive control is more important initially in L2 acquisition, and have significant implications for understanding developmental and neurocognitive models of second language lexical processing.

1. Introduction

More than half the world's population is bilingual (Grosjean & Li, 2013; Chapter 1). This statistic is based on the broad definition that we give to "bilingual": from the prototypical idea of someone raised from birth speaking two or more languages, to the struggling undergraduate fulfilling a language requirement, to the business person learning the language of the country to which he or she has been transferred (Bialystok & Hakuta, 1994). For any second language (L2) learner, however, one of the first steps in acquiring a language is to learn the vocabulary. Not surprisingly, much of the psycholinguistic literature on bilingualism and L2 acquisition has been devoted to understanding how words in one's second language are learned and processed, and how such processes compare to those in the learning of one's first language (e.g., Kroll & Stewart, 1994). With the advent of neuroimaging technology, a new stream of research has begun to ask questions concerning word learning in the L2. Would L2 processing occur in the same brain areas as the L1 (e.g., Abutalebi & Green, 2007; Chee, Tan, & Thiel, 1999)? Would age of acquisition (AoA) or proficiency modulate the types of areas activated (e.g., Hernandez, 2013; Hernandez & Li, 2007)? How do non-linguistic skills, such as cognitive control, impact L2 acquisition (e.g., Abutalebi, 2008; Van Hell & Tanner, 2012)? Interesting questions like these have been pursued in the last decades with a variety of neuroimaging methodologies and techniques (see Li, Legault, & Litcofsky, 2014 for a recent review).

Few previous studies, however, have attempted to longitudinally track the development of the lexical processing networks in question (but, see Osterhout, Mclaughlin, Pitkänen, Frenck-Mestre, & Molinaro, 2007). Consequently, much of our knowledge is based on cross-sectional research that does not allow us to observe the individual differences in the development of L2 processing. The current study aims to address this gap by examining a group of classroom Spanish L2 learners across a period of one academic year. Our study expands on previous research by using functional magnetic resonance imaging (fMRI), with two main goals: to track the neurocognitive changes in late L2 learners during lexical processing, and to investigate how these linguistic processes are influenced by individual differences in cognitive control.

1.1. Models of second language lexical development

In what follows we begin with a brief review of several models of bilingual lexical processing that motivate the current study.

1.1.1. The BIA-d model

Motivated by the predictions of the Revised Hierarchical Model (RHM) and the Bilingual Interactive Activation (BIA) models, Grainger, Midgley, and Holcomb (2010) proposed a developmental amendment to bilingual models of lexical access (Dijkstra & Van

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http://dx.doi.org/10.1016/j.bandl.2015.03.010
0093-934X/

Heuven, 1998; Kroll & Stewart, 1994). The original BIA model considered how features, letters, and words from two languages might interact in the bilingual word recognition processes. During reading of a word, feature nodes activate appropriate letters, and letter nodes activate appropriate words in the appropriate language. Importantly, because of the interactive nature across languages in the model, activation of features and letters in one language not only spreads to words in that target language, but also to words in the other language. In order to control this cross-language activation, the BIA model proposes a top-down inhibitory control mechanism from the language nodes (for details, see Dijkstra & Van Heuven, 1998).

The BIA-d model is a developmental version of the BIA model, which is concerned primarily with the development of these inhibitory connections. It models its developmental aspect on the predictions of the RHM (Kroll & Stewart, 1994). The RHM accounts for lexical processing through two different routes: L1–L2 form-based connections and L2-form to conceptual store connections. The basic assumption is that learners at different proficiency levels utilize these routes to differing degrees. That is, early learners are more likely to depend on form-based connections, while later learners, due to their increased exposure to the language, are able to circumvent the first language and draw directly on the conceptual store. The BIA-d suggests that although learners initially proceed in the manner described by the stages of the RHM, later conceptual connections are facilitated by form-level inhibitory connections between translation equivalents. Fig. 1 presents an illustration of the BIA-d model. The three initial stages are very similar to the RHM. The BIA-d differs from the RHM, however, with the addition of a fourth stage, wherein inhibitory connections between L1 and L2 word forms are introduced, and L2-semantic connections are strengthened.

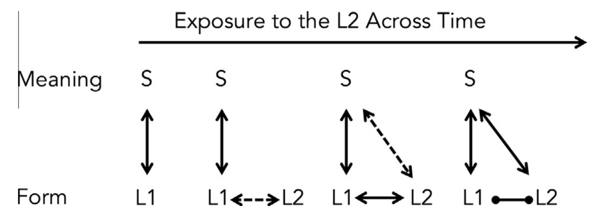

Fig. 1. The BIA-d model, adapted from Grainger et al., 2010. L1 and L2 refer to word forms in the first and second language, respectively. S refers to the semantic representation associated with the word form. Arrows indicate excitatory connections, with dashed arrows indicating weaker connections, and barbell connections indicate inhibitory connections.

1.1.2. The convergence hypothesis

In contrast with the RHM and the BIA-d models, current neurocognitive theories of L2 acquisition suggest that cognitive control is critically involved from the outset. For example, Abutalebi (2008) reviewed the L2 neuroimaging literature and suggested that lower proficiency learners often utilize traditional cognitive control areas (e.g., frontal cortex especially the dorsolateral prefrontal cortex or DLPFC, anterior cingulate cortex or ACC, and the basal ganglia) in addition to traditional L1 resources, such as the middle and inferior temporal gyri. His analysis is consistent with the Convergence Hypothesis (henceforth CH; Green, 2003; Green, Crinion, & Price, 2006), which suggests that with increasing proficiency L2 learners represent and process the L2 similarly to L1 speakers. The CH is based on the idea that the computational requirements for lexical and grammatical processing are different. While it is generally accepted that lexical and grammatical processing draw on differing mechanisms in L1 processing (for example see Kutas & Hillyard, 1983), there have been hypotheses (e.g., Clahsen & Felser, 2006) that suggest that L2 processing differs from L1 processing in that both lexical and grammatical production in the L2 depend primarily on resources associated with lexical processing (see also Ullman, 2001). The CH, however, suggests that the most efficient solution to L2 grammatical and lexical production is to use the same neural circuits as those involved in the L1 (e.g., fronto-basal circuits for syntactic processing, fronto-temporal circuits for lexical processing). Abutalebi and Green (2007) further argue that the evidence appears to support the CH, as a number of studies have found activation of identical areas in both the L1 and L2 (Chee et al., 1999; Hernandez, Dapretto, Mazziota, & Bookheimer, 2001).

Although ample evidence is consistent with the CH that bilinguals must utilize cognitive control to inhibit the language not in use regardless of proficiency, no study has so far tracked how L2 learners develop this inhibitory mechanism across evolving stages of the learning process. Perhaps the most relevant study in this regard was conducted by Raboyeau, Marcotte, Adrover-Roig, and Ansaldo (2010), who examined L2 vocabulary acquisition over the course of 5 days, when participants were scanned after early learning and then again after the vocabulary had been consolidated via additional training. Raboyeau et al. found greater activity in areas of the control network (e.g., ACC and DLPFC) at Time 1 than Time 2. A training study, however, does not completely replicate either the scope or the time course of vocabulary learning under traditional classroom conditions. Given the discrepancies between the predictions of the BIA-d and those of the CH, questions remain regarding how the brain handles the acquisition of L2 vocabulary, and how its approach may change over time.

1.1.3. The bilingual lexical brain network

In order to fully understand these changes, it is necessary to move beyond an region of interest (ROI) research approach, as recent evidence suggests that many of the areas involved in language processing are also active during other cognitive tasks (e.g., Silbert, Honey, Simony, Poeppel, & Hasson, 2014; see also Li et al., 2014, Fig. 3, for the overlap of areas for linguistic and nonlinguistic tasks). To address this, our study uses a directed functional connectivity technique, extended unified Structural Equation Modeling (euSEM; see Gates, Molenaar, Hillary, & Slobounov, 2011), in the analysis of our fMRI data. This technique allows for analysis of lagged relationships – the effect of Area X at Time 1 on Area Y at Time 2 – as well as contemporaneous relationships – the effect of X on Y at Time 1. To help motivate the selection of brain regions and to inform our predictions for this analysis, we turned to Rodríguez-Fornells, Cunillera, Mestres-Missé, and de Diego-Balaguer (2009), who provided a neurocognitive model of second language lexical learning based on the interaction between three main streams of cortical and subcortical regions: a dorsal auditory-motor interface, a ventral meaning inference interface, and an episodic-lexical interface. As our study is concerned primarily with semantic and lexical access, we focus on the latter two streams here.

Beginning with the episodic-lexical interface, Rodríguez-Fornells et al. (2009) identified the medial temporal lobe (MTL) as being responsible for the fast mapping of new words to concepts. Specifically, they suggest that bilateral hippocampus and posterior entorhinal cortex are involved in the initial process of word learning, while later conceptual traces develop in the anterior entorhinal cortex, as well as the perirhinal and parahippocampal MTL regions. Within the parahippocampus, they suggest that the bilateral anterior parahippocampus is involved in encoding, while the left posterior parahippocampus is involved in retrieval. The role of MTL has long been studied in memory research and MTL is believed to be the hub for declarative memory (e.g., semantic representation; Squire, Stark, & Clark, 2004). In addition to these MTL areas, semantic storage and retrieval is also thought to recruit