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The dynamic imprint of word learning on the dorsal language pathway

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ABSTRACT

According to Hickok and Poeppel (2007), the acquisition of new vocabulary rests on the dorsal language pathway connecting auditory and motor areas. The present study tested this hypothesis longitudinally by measuring BOLD signal changes during a verbal repetition task and modulation of resting state functional connectivity (rs-FC) in the dorsal stream. Thirty-five healthy participants, divided into trained and control groups, completed fMRI sessions on days 1, 10, and 24. Between days 1 and 10, the trained group learned 84 new pseudowords associated with 84 native words. Task-related fMRI results showed a reduced activity in the IFG and STG while processing the learned vocabulary after training, returning to initial values two weeks later. Moreover, rs-fMRI analysis showed stronger rs-FC between the IFG and STG in the trained group than in the control group after learning, especially on day 24. These neural changes were more evident in participants with a larger vocabulary. Discussion focuses on the prominent role of the dorsal stream in vocabulary acquisition. Even when their meaning was known, newly learned words were again processed through the dorsal stream two weeks after learning, with the increase in rs-FC between auditory and motor areas being a relevant long-term imprint of vocabulary learning.

1. Introduction

Vocabulary acquisition is especially relevant in native language development during infancy, but it is maintained at a lower rate throughout life. This process is also important for learners of a second language because they have to incorporate new words that are associated with words in their native language. Studies on the neural basis of vocabulary learning have been devoted to unveiling the keys to how these words are processed in the language network (Mestres-Missé et al., 2008; Davis et al., 2009; Hultén et al., 2010; Raboyeau et al., 2010). The aim of the present study was to longitudinally investigate the neural basis of vocabulary acquisition and the imprint this learning may leave on the language network at long-term during task performance and at rest.

The dual stream model of language processing hypothesizes the existence of two functionally distinct streams connecting posterior and anterior speech/language areas (Hickok and Poeppel, 2007). The dorsal stream connects auditory areas in the superior temporal gyrus with motor areas in the premotor cortex and inferior frontal gyrus, and it is responsible for translating acoustic-based representations of speech signals into articulatory representations. The ventral stream involves different areas of the left and right superior, middle, and inferior temporal gyrus, and its function is related to processing the conceptual meaning of speech. According to the dual-route model, the dorsal stream is crucial for new vocabulary acquisition because it involves the generation of a sensory representation of the new word that codes the sequence of segments or syllables, and this representation guides motor articulatory sequences (Hickok and Poeppel, 2007; Hickok, 2012). However, this proposal does not specify how these acquired words are processed after learning their meaning and increasing their familiarity.

Auditory and motor areas communicate directly through the arcuate fasciculus (AF), a prominent white-matter tract proposed as participating in audiomotor processing in language and music (Saur et al., 2008, 2010; Halwani et al., 2011). Saur et al (Saur et al., 2008, 2010). reported that repetition of pseudowords compared to real words, activated the left anterior and posterior parts of the superior temporal region, along with frontal regions such as the left pars opercularis of the inferior frontal gyrus and the premotor areas (BA 44/6). In the same way, in the meta-analysis conducted by Davis et al. (2009), phonological processing during unknown pseudoword processing was related to activation in the STG and opercular frontal areas, whereas processing of existing words

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activated more anterior, posterior and inferior regions of the lateral temporal lobe and inferior parietal regions, along with the pars orbitalis of the frontal lobe, areas related to lexical processing. Consistently with this framework, some studies have reported that activity in the inferior frontal and superior temporal cortex was related to new vocabulary acquisition (Raboyeau et al., 2004; Grönholm et al., 2005; Mestres-Missé et al., 2008; Hultén et al., 2009). Importantly, the enhancement of activity in these areas after training has been related to successful retrieval of this material 10 months later (Hultén et al., 2010).

Learning new vocabulary involves acquiring novel sensorimotor patterns that are likely to result in structural differences as well as functional brain changes. In keeping with this idea, a recent study by López-Barroso et al. (2013) combined tractography and fMRI to study whether the strength of anatomical and functional connectivity between auditory areas of the temporal lobe and Broca's regions was associated with new word learning ability (i.e. learning words of an artificial language through repetition). They found that microstructural properties and the strength of the functional connectivity between these regions in the left hemisphere correlated with word learning performance, which suggests that the human ability to learn new words relies on efficient and fast communication between these regions.

Brain connectivity can also be studied by means of resting-state functional magnetic resonance imaging (rs-fMRI), which allows us to measure the spontaneous activity of the brain at rest, characterized by the co-activation of anatomically separate but functionally related brain regions. Previous studies have shown that the intensity of correlations within and between brain areas at rest has behavioral significance (Harmelech and Malach, 2013; Guerra-Carrillo et al., 2014; Finn et al., 2015), and that the resting-state activity may reflect the repeated history of co-activation within or between brain regions, which may in turn be a predictor of individual differences while performing perceptual, intelligence, and memory tasks (Lewis et al., 2009; Baldassarre et al., 2012; Cole et al., 2012; Ventura-Campos et al., 2013; Bueichekú et al., 2015). Changes in rs-fMRI connectivity have also been reported in cross-sectional studies comparing effects of expertise, such as in experienced meditators (Taylor et al., 2013) and musicians (Palomar-García et al., 2017). Thus, functional connectivity at rest (rs-FC) may reflect the impact of brain plasticity on the brain after learning and be used as a complement to task-related fMRI in highlighting practice-related functional changes in the brain.

The aim of the present study was to use task-related and resting-state fMRI to investigate the changes in BOLD signal magnitude and functional connectivity (respectively) associated with word learning in three different time windows: at baseline, immediately after one week of learning, and two weeks after learning. We designed the experiment to ensure overlearning of all the new material, in order to obtain high and similar recall scores at both post-training time points of neural testing. A longer interval for the retest would imply lower recall and a less comparable situation. According to the dual route model, learning new vocabulary should be associated with increased participation of the dorsal stream including the left STG and left opercular IFG/premotor areas, as well as their audiomotor connectivity throughout the arcuate fasciculus. Consequently, training would be expected to not only affect these regions separately, but also to produce stable changes in the functional connectivity between the auditory and motor regions. In the present study, we used a verbal repetition task and rs-fMRI at different time points to investigate the dynamic changes in neural activation due to learning the meaning and articulatory representation of new words. We hypothesized that: 1) auditory and premotor regions would be the main areas involved in pseudoword processing at baseline; 2) acquiring new words and their meanings would modify their processing in these areas; 3) this training would also impact on the functional connectivity between these areas during rest; and 4) these neural measures would be related to the measures of vocabulary size.

2. Materials and methods

2.1. Participants

Thirty-nine Spanish speakers participated in the study. Four participants were excluded from the analyses due to excessive head movements (more than 2 mm of translation or 2 degrees of rotation) during one of the three fMRI acquisitions. The final sample consisted of thirty-five Spanish speakers. Eighteen participants formed the trained group (9 women; mean age 19.9 years old, standard deviation (SD; ± 1.16) and 17 were included in the control group (12 women; mean age 20 ± .87 years old). All participants were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Intellectual level was evaluated with the Vocabulary subtest of the WAIS-III (trained group: mean 12.1 ± 1.4; control group: mean 11.5 ± 1.5) and the block design subtests (trained group: mean 11.4 ± 3.03; control group: mean 11 ± 2.8). There were no significant between-group differences in age or on general intellectual functioning measures ($p > 0.10$). None of them had suffered any neurological or psychiatric disorders, and they had no history of head injury with loss of consciousness. Written informed consent was obtained from all participants, and they received monetary compensation for their participation. This research was approved by the Ethics Committee of the University Jaume I.

2.2. Experiment overview

To obtain a longitudinal perspective, the experiment consisted of three identical MRI scan sessions. Session 1 (S1) on day 1 was held before learning; Session 2 (S2) was held on day 10, after six 1-hour learning sessions in the trained group and after a no-training period in the control group; and Session 3 (S3) took place on day 24, after a two-week period with no-training. After S2 and S3, all the participants of the trained group performed cued-recall retention tests (see Fig. 1 for the experimental overview).

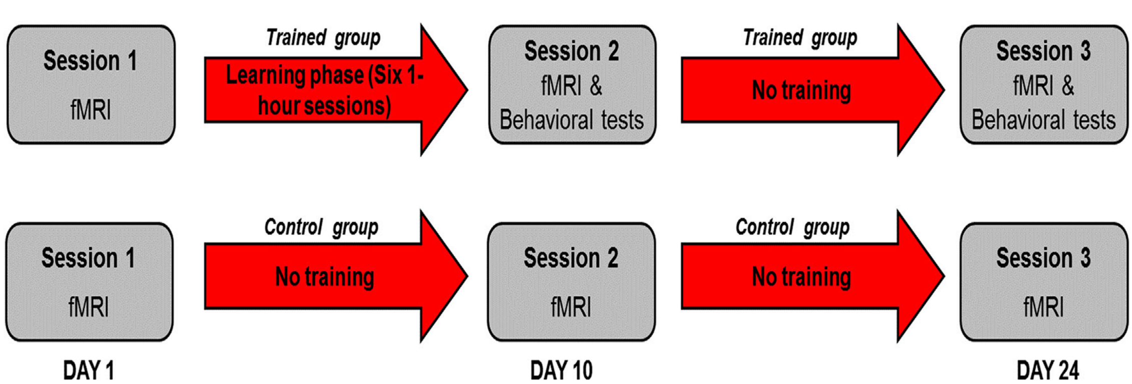

Fig. 1. Overview of the experiment.