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The pace of vocabulary growth during preschool predicts cortical structure at school age

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ABSTRACT

Children vary greatly in their vocabulary development during preschool years. Importantly, the pace of this early vocabulary growth predicts vocabulary size at school entrance. Despite its importance for later academic success, not much is known about the relation between individual differences in early vocabulary development and later brain structure and function. Here we examined the association between vocabulary growth in children, as estimated from longitudinal measurements from 14 to 58 months, and individual differences in brain structure measured in 3rd and 4th grade (8–10 years old). Our results show that the pace of vocabulary growth uniquely predicts cortical thickness in the left supramarginal gyrus. Probabilistic tractography revealed that this region is directly connected to the inferior frontal gyrus (pars opercularis) and the ventral premotor cortex, via what is most probably the superior longitudinal fasciculus III. Our findings demonstrate, for the first time, the relation between the pace of vocabulary learning in children and a specific change in the structure of the cerebral cortex, specifically, cortical thickness in the left supramarginal gyrus. They also highlight the fact that differences in the pace of vocabulary growth are associated with the dorsal language stream, which is thought to support speech perception and articulation.

1. Introduction

Babies are born without speech; the word infant comes from Latin *infant*- 'unable to speak'.[2] Nevertheless, they acquire language with remarkable speed and sophistication, starting with phoneme discrimination and babbling during the first months, and continuing to produce their first words by the end of the first year (Kuhl, 2004). Unlike a second language learner who typically receives explicit instruction, babies acquire their vocabulary implicitly, using statistical learning (computing the probability of a syllable being preceded or followed by another syllable) to extract words from continuous speech (Saffran et al., 1996). The acquisition of a word form, in turn, facilitates mapping it to meaning (Estes et al., 2007).

Although most children learn words according to a common trajectory, rate and timing of vocabulary development show striking variability across children (Fenson et al., 1994). Variation in vocabulary development during the first years of life is important because it is associated with later academic success. The *size* of oral vocabulary at 24 months of age predicts academic achievement (reading and math), as well as behavioral functioning (self-regulation and social behavior), at kindergarten, even after controlling for covariates such as socioeconomic status (SES), gender, birth weight, parenting quality, and maternal health (Morgan et al., 2015). Moreover, the *rate* of vocabulary growth at 30 months of age can uniquely predict vocabulary skill before entering kindergarten (Rowe et al., 2012).

Despite the ample evidence demonstrating that variations in vocabulary early in development predict subsequent skills, little is known about the biological underpinnings of these effects. In the current study, for the first time, we examined the relation between individual differences in early vocabulary growth at preschool and structural differences in the brain at school age. More specifically, we examined the association between early vocabulary growth from 14 months to 58 months of age and individual variation in gray and white matter in brain regions previously implicated in vocabulary processing at school age (3rd and 4th grade) in 20 typically developing children.

Studying the underlying brain mechanisms of first language vocabulary acquisition can be methodologically challenging because of the nature of the subject population (excessive motion, anxiety, lack of

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[2] *Random House Kernerman Webster's College Dictionary*, (2010). Retrieved December 22, 2015 from http://www.thefreedictionary.com/infant.

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sustained attention, to name but a few) (Dehaene-Lambertz and Spelke, 2015). Nonetheless, there is an increasing number of studies investigating speech processing in infant brain using magnetic resonance imaging (MRI), functional near-infrared spectroscopy, magnetoencephalography, and electroencephalography (Benavides-Varela et al., 2012; Dehaene-Lambertz et al., 2006, 2010; Junge et al., 2012; Mahmoudzadeh et al., 2013; Travis et al., 2011). These studies reveal a continuity between the patterns of brain activation to speech in infants and those observed in adults. Dehaene-Lambertz and Spelke (2015) thus suggest that developmental changes in behavior may be mediated by maturational changes in cortical regions and their connections. The maturation of frontal, temporal, and parietal cortical areas, and their white matter connectivity, provide children with increasingly efficient networks for language (Dubois et al., 2016; Leroy et al., 2011; Pujol et al., 2006). But in addition to maturational processes, the child's interaction with her environment has been found to contribute significantly to individual differences in language development (Hackman and Farah, 2009; Johnson, 2001).

Although there is a paucity of neuroimaging studies of young children during the preschool years, a time when vocabulary shows the largest growth (Kuhl, 2010; Nazzi and Bertoncini, 2003), several studies have been done on vocabulary learning in older children (Richardson and Price, 2009). These studies have shown that gray matter density in the posterior supramarginal gyrus (SMG) is positively associated with vocabulary knowledge in young teenagers (Lee et al., 2007; Richardson et al., 2010), as are the posterior superior temporal sulcus (pSTS) and posterior temporo-parietal junction across the lifespan (ages 7–73). Sowell et al. (2004) found that cortical thinning in the left lateral dorsal frontal and the left lateral parietal regions correlates with improvement in vocabulary competence in children between ages 5 and 10 (Sowell et al., 2004).

Second language learning studies in adults also offer some insights into the neural underpinnings of word acquisition. Rodríguez-Fornells et al. (2009) proposed three "interfaces" in the brain that are crucial for second language learning: (1) an interface between auditory and motor processes that enables speech perception and articulation (auditory-motor interface), thought to be mediated by the dorsal language stream; (2) an interface between meaning representations and response selection (meaning integration interface) that enables mapping speech to meaning, mediated by the ventral language stream; and (3) a memory interface enabling consolidation of newly learned words into new lexical representations linked to meaning (memory interface), mediated by the hippocampus and medial temporal lobe (Davis and Gaskell, 2009).

Adult vocabulary learning studies frequently use tasks that tap into a specific interface, be it the meaning integration interface (i.e. the ability to map novel sounds/words to meaning), or the auditory-motor interface (i.e. the ability to map novel sounds/words to articulation). In a study testing the meaning-integration interface (Wong et al., 2011) trained individuals to match non-native spoken words to pictures of items. They found that white matter fractional anisotropy (FA) in a left parieto-temporal cluster in the extreme capsule fiber system (a ventral language pathway) is associated with learning performance. They suggested that this result was consistent with the word-to-meaning mapping required in their task (Wong et al., 2011). Another set of studies focusing on the auditory-motor interface used continuous speech learning paradigms with non-native (Veroude et al., 2010) or artificial languages (Lopez-Barroso et al., 2013, 2015). Veroude et al. (2010) exposed adult learners to a short video clip in Chinese and later asked them to recognize the phonological form of words they had heard in the clip. They found that successful learners showed increased connectivity between the left and right SMG after exposure to the new language. López-Barroso et al. (2015) measured resting-state connectivity before and after word learning training from continuous speech in an artificial language. They found increased connectivity in dorsal fronto-parietal, dorsal auditory-premotor, and ventral fronto-temporal networks after training, and a correlation between learning performance and connectivity in a dorsal auditory-premotor network (Lopez-Barroso et al., 2015) The ability to learn words from continuous speech was also related to white matter radial diffusivity (RD) along the left arcuate fasciculus, connecting posterior temporal and inferior frontal area (Lopez-Barroso et al., 2013). These results stress the importance of the dorsal pathway for learning words from exposure to non-native continuous speech. However, this literature is based on adolescent and adult learners who have already acquired a native language. The focus of our study is to determine which of the three interfaces outlined above—auditory-motor interface, meaning integration interface, memory interface—is more closely related to first language vocabulary acquisition.

The measure of vocabulary competence that we used in our study was based on observations of children's spontaneous interactions with their caregivers. We tallied the number of different word types children uttered at each observation session (taken every 4 months between 14 and 58 months of age). Our measure was thus an expressive rather than receptive vocabulary measure. As a consequence, we would expect contributions from all three interfaces, with an emphasis on the auditory-motor interface. Rather than focus on children's vocabulary at a single point in time, we modeled the growth of children's vocabulary between 14 and 58 months to get a picture of the trajectory of vocabulary development.

Since the main resource available to word-learners is the speech they are immersed in, the variation in children's vocabulary development can be traced back to variations in environmental factors, in particular, to family SES (Hoff, 2006) and to the quantity (Huttenlocher et al., 1991) and quality (Cartmill et al., 2013) of parental linguistic input (Hoff, 2003; Hoff and Naigles, 2002; Montag et al., 2015; Rowe, 2012; Weisleder and Fernald, 2013). Thus, in examining relations between vocabulary development and brain, we included parental SES and input as covariates.

We examined relations between vocabulary development and two brain structure measures: cortical thickness, and white matter connectivity. Cortical thickness measures were extracted from the left inferior frontal gyrus (IFG; pars opercularis and pars triangularis), the middle frontal gyrus (MFG), the posterior middle temporal gyrus (pMTG), the posterior superior temporal gyrus (pSTG), the posterior superior temporal sulcus (pSTS), and the SMG. The areas were selected based on the literature on vocabulary processing, which implicates these regions for processing single words (Davis and Gaskell, 2009; Li et al., 2014; Price, 2010; Rodríguez-Fornells et al., 2009). We focused on cortical thickness because it is a measurable manifestation of important underlying cellular changes: cortical thickness is tied to the number of neurons in a cortical column, the amount of glial and capillary support, and dendritic branching (Rakic, 2009; 1988), all of which are amenable to change as a result of postnatal experience and learning (Anderson et al., 1994; Black et al., 1990; Kleim et al., 1996). To explore the connectivity between cortical areas involved in word learning, we used probabilistic tractography to map white matter connectivity, our second brain structure measure.

Based on existing data on teenagers learning words in their first language, adults learning words in a second language, as well as computer simulations (Ueno et al., 2011), we hypothesized that variations in the rate of early vocabulary acquisition would be primarily associated with variations in gray and white matter structure in brain regions along the dorsal language pathway. To our knowledge, this is the first study to examine the relation between the developmental trajectory of vocabulary acquisition in preschool years and subsequent brain structure in later years.