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Reorganization of brain function after a short-term behavioral intervention for stuttering

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ABSTRACT

This study investigated changes in brain function that occurred over a 7-day behavioral intervention for adults who stutter (AWS). Thirteen AWS received the intervention (AWS+), and 13 AWS did not receive the intervention (AWS−). There were 13 fluent controls (FC−). All participants were scanned before and after the intervention. Whole-brain analysis pre-intervention showed significant differences in task-related brain activation between AWS and FC− in the right inferior frontal cortex (IFC) and left middle temporal cortex, but there were no differences between the two AWS groups. Across the 7-day period of the intervention, AWS+ alone showed a significant increase of brain activation in the left ventral IFC/insula. There were no changes in brain function for the other two groups. Further analysis revealed that the change did not correlate with resting-state functional connectivity (RSFC) that AWS showed in the cerebellum (Lu et al., 2012). However, both changes in task-related brain function and RSFC correlated with changes in speech fluency level. Together, these findings suggest that functional reorganization in a brain region close to the left IFC that shows anomalous function in AWS, occurs after a short-term behavioral intervention for stuttering.

1. Introduction

While most children acquire language effortlessly, about 5% of them have problems that lead them to begin to stutter (Craig & Tran, 2005). Roughly four out of five of the cases where stuttering starts in childhood recover spontaneously. Stuttering usually persists into adulthood in the remaining cases, resulting in about 1% of the adult population being affected (Howell, 2011; Yairi & Ambrose, 2005). At present, the neurophysiology behind childhood stuttering, how the brain compensates for stuttering, and what brain reorganization occurs when an intervention is given are not completely understood. Some general consensus has arisen concerning the first two of these issues over the past two decades. Adults who stutter (AWS) show overactivations in regions of the right hemisphere such as the inferior frontal cortex (IFC) and anterior insula, but lower activations in regions of the left hemisphere such as the left IFC and temporal cortex, compared to fluent controls in several speech production and auditory perception tasks (Brown, Ingham, Ingham, Laird, & Fox, 2005; De Nil et al., 2008; Jiang, Lu, Peng, Zhu, & Howell, 2012; Lu et al., 2016). AWS also show altered connectivity between the basal ganglia/cerebellum and cortical brain regions compared to fluent controls in speech production tasks (Chang, Horwitz, Ostuni, Reynolds, & Ludlow, 2011; Howell, Jiang, Peng, & Lu, 2012b; Jiang et al., 2012; Lu, Chen, et al., 2010; Lu et al., 2009; Lu, Peng, et al., 2010). Moreover, the abnormal brain activation in the left hemisphere and altered connectivity in the circuits between basal ganglia and cerebral cortex have been confirmed in children who stutter in auditory speech processing tasks or in the resting-state condition, but the right hemispheric abnormalities have not (Chang & Zhu, 2013; Sato et al., 2011). With respect to the third issue, less is known about the neurophysiological changes that occur when a behavioral intervention for stuttering is given, particularly those that happen when the period of intervention is short-term.

Compared to fluency-enhancing techniques such as choral speech or altered auditory feedback, behavioral interventions have the advantage that they can suppress stuttering to a degree for a relatively long period of time. Several previous studies have used positron emission tomography or functional magnetic resonance

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imaging (fMRI) methods to examine changes in brain function over the course of behavioral interventions. For instance, after a three-week behavioral intervention, the speech-related brain activation in AWS re-lateralizes to the left hemisphere (De Nil, Kroll, Lafaille, & Houle, 2003; Neumann et al., 2003). In particular, activation in the left ventral IFC (vIFC) adjacent to the functionally anomalous region increases in speech production tasks (Neumann et al., 2005). Another study showed that after practice to pace speech along with a metronome for eight weeks, the abnormal activation in the basal ganglia was eliminated, and the activation in the cerebellar vermis decreased (Toyomura, Fujii, & Kuriki, 2015). However, further evidence showed that one to two years later, the overactivations returned to the right hemisphere albeit to a lesser extent (De Nil et al., 2003; Neumann et al., 2003).

This previous evidence suggests that different patterns of changes in brain function occur at different times after behavioral interventions have been delivered to AWS. Evidence from animals also indicates that experience-induced changes in brain structures in the first two weeks differed from those seen after two weeks (Comeau, McDonald, & Kolb, 2010). Thus, it is plausible that the changes in brain function differ between short-term (within two weeks) and long-term (beyond two weeks) interventions for AWS. While the changes in the neural systems over the course of long-term interventions have been investigated in vocal or auditory task conditions previously (De Nil et al., 2003; Kell et al., 2009; Neumann et al., 2003, 2005), little is known about what changes happen in neural systems after a short-term behavioral intervention (i.e., within 2 weeks).

In fact, only one study has investigated changes in brain function and structure in AWS over the course of a short-term behavioral intervention. In this work they looked at changes of brain function in the resting-state condition (Lu et al., 2012). Lu et al.'s (2012) intervention was based on recent dual-route models of stuttering. Alm's (2004, 2006) dual premotor model of stuttering suggested that the basal ganglia-supplementary motor area complex is impaired in AWS, and that the cerebellum-premotor area (PMA) is employed to bypass the impaired circuit. The EXPLAN model complements this by focusing on the coordination or 'interlocking' of linguistic planning and execution stages at the language–speech interface and proposes that the cerebellum organizes motor plans for output (Howell, 2004, 2007; Howell, Au-Yeung, & Sackin, 2000; Howell & Dworzynski, 2005). However, EXPLAN lacked imaging evidence that directly supported the model. Consequently, a dual-route neural model was developed and tested empirically in classic speech production tasks (i.e., overt and covert picture naming tasks) (Lu, Chen, et al., 2010; Lu et al., 2009; Lu, Peng, et al., 2010). This dual-route model assumed that two neural circuits were impaired in AWS: (1) the connectivity in the basal ganglia-IFC circuit was altered and this was closely associated with atypical linguistic planning; (2) the connectivity in the cerebellum-PMA circuit was affected and this was associated with atypical speech motor execution (Howell et al., 2012b; Jiang et al., 2012; Lu, Chen, et al., 2010; Lu et al., 2009; Lu, Peng, et al., 2010). The dual-route model also hypothesized that improvement in linguistic planning (particularly phonological processing) and articulatory motor execution and repair of both the basal ganglia-IFC and cerebellum-PMA circuits are probably essential for full recovery from stuttering in adulthood. Thus, training on phonological processing and articulatory motor execution should change the function of brain regions in the basal ganglia-IFC circuit and/or cerebellum-PMA circuit, and reduce the severity of stuttering.

Lu et al. (2012) showed that a behavioral intervention administered to AWS for a 7-day period significantly enhanced speech fluency in AWS. The intervention also eliminated the stronger resting-state functional connectivity (RSFC) between the midline of the cerebellum and the whole language network in AWS compared to fluent controls. According to the dual-route neural model of stuttering (Lu, Chen, et al., 2010; Lu et al., 2009; Lu, Peng, et al., 2010), the basal ganglia-IFC and cerebellum-PMA circuits should show functional changes when an intervention targeting phonological processing and articulatory motor execution is given to AWS. However, Lu et al. (2012) did not detect any functional changes in the left vIFC that have been reported in other studies that employed speech tasks rather than a resting-state paradigm (Kell et al., 2009; Neumann et al., 2005). The left IFC is involved in various aspects of speech production such as phonological processing (Costafreda et al., 2006) and phonetic encoding (Papoutsi et al., 2009). Its functional and structural anomalies have also been implicated in stuttering (Cykowski, Fox, Ingham, Ingham, & Robin, 2010; Jiang et al., 2012; Kell et al., 2009; Lu, Chen, et al., 2010; Lu et al., 2009, 2012; Salmelin, Schnitzler, Schmitz, & Freund, 2000). Moreover, it appears that an increase of activation in the left vIFC relates to full recovery from stuttering (Kell et al., 2009). Hence, it remains necessary to determine whether the left vIFC shows changes in brain function in a speech task conducted before and after a short-term behavioral intervention for AWS.

The cerebellum-PMA circuit was involved in the atypical motor execution in AWS in the dual-route neural model of stuttering (Lu, Chen, et al., 2010; Lu et al., 2009; Lu, Peng, et al., 2010). Thus, the cerebellum was also expected to show functional changes after a short-term intervention, which was confirmed (Lu et al., 2012). Previous evidence has shown that individual variability in resting-state neural activity can predict individual differences in task performance such as perceptual learning and memory (Baldassarre et al., 2012; Hampson, Driesen, Skudlarski, Gore, & Constable, 2006; Tambini & Davachi, 2013; Tambini, Ketz, & Davachi, 2010; Wang et al., 2010). This raises the possibility that similar influences may apply to speech tasks, too. Thus, if the task-related changes of brain function in the vIFC were identified, it would also be interesting to know whether the two types of changes in brain function, i.e., the task-independent changes in the resting-state condition and task-related changes in the speech tasks, are related to one another or not.

The present study examined task-related changes in brain function after a short-term behavioral intervention for stuttering. Based on the dual-route neural model of stuttering (Lu, Chen, et al., 2010; Lu et al., 2009; Lu, Peng, et al., 2010), brain regions in the basal ganglia-IFC and/or cerebellum-PMA circuits may show functional changes after a short-term behavioral intervention that targets phonological processing and articulatory motor execution. The results were compared to previous findings that identified differences between AWS and controls in the resting-state condition (Lu et al., 2012) in order to provide a comprehensive picture of changes in brain function after a short-term behavioral intervention. This comparison should elucidate the relationship between task-related and task-independent changes in brain function after the short-term intervention.

2. Materials and methods

2.1. Participants

Twenty-eight AWS were recruited who had participated in the study of Lu et al. (2012). They were randomly assigned to groups who received the intervention (AWS+) or who did not receive the intervention (AWS−). Any AWS assigned to AWS+ who reported that they could not adhere to the intervention schedule during the test period was moved to AWS−, and another AWS from AWS− was selected at random and re-assigned to AWS+. Two AWS+ did not complete the task-related fMRI experiment and were excluded