HHS Public Access

Author manuscript

Handb Clin Neurol. Author manuscript; available in PMC 2023 April 30.

Published in final edited form as:

Handb Clin Neurol. 2022 ; 184: 397–414. doi:10.1016/B978-0-12-819410-2.00021-7.

Plasticity of the language system in children and adults

Kelly C. Martin[1], **W. Tyler Ketchabaw**[1], **Peter E. Turkeltaub**[1,2]

[1]Center for Brain Plasticity and Recovery, Georgetown University Medical Center, Washington, DC, USA

[2]Research Division, MedStar National Rehabilitation Hospital, Washington, DC, USA

A. INTRODUCTION

Humans are the only animals known to be capable of complex language. It has long been a quest of cognitive neuroscience to understand how our brains are uniquely capable of the hierarchical pattern processing and advanced rule learning required for language. In fact, the ability to learn language is innate to the human brain: infants demonstrate the ability to detect complex patterns in speech and automatically generate implicit rules to reliably detect and produce these patterns in the future. The ability to learn certain aspects of language, however, is limited after early childhood. This sensitive period for language learning makes it an important model system for the study of developmental plasticity in children. Unlike many other neural systems, language is strongly lateralized to one hemisphere—the left hemisphere in the overwhelming majority of neurotypical adults. Although language was once thought to rely only on a few discrete regions of the left cerebral cortex, we now understand that it is actually performed by an extensive network of left-lateralized cortical and subcortical structures (Friederici, 2017; Price, 2012). Language serves as a model system for lateralized cognitive functions more broadly, one that is perhaps better understood than others in terms of its development and neural basis. Thus, understanding how the language system develops, and how it can reorganize in the face of brain injury or dysfunction, could help us to understand brain plasticity in cognitive networks more broadly.

It is also clinically important that we understand the plasticity available to language network organization. Even in typical development, there is variability in language proficiency that may relate to differences in the onset and duration of critical windows for early developing language abilities. In the presence of neural injury or disorder in development, such as early stroke or epilepsy, language outcomes are even more complicated. Many children with early brain dysfunction achieve good language abilities as adults, although their language networks may organize differently than typically developing children. It is important that we understand what factors relate to the resilience of language when it still develops adequately in these cases, so that we can identify children at risk for poor language outcomes and develop new treatments for them. In adults, in whom chronic debilitating aphasia is a common result of left hemisphere brain injury, understanding the plasticity available to support recovery is perhaps even more important. To develop effective treatments for aphasia and related communication disorders, we need to better understand the organization of language processing in the brain when it is functioning successfully, and the plasticity that relates to better and worse outcomes after injury.

In this chapter we will discuss the language network features that are present in infants (and even in utero), and how deviations in typical development of the language network can lead to disordered language. We will also discuss the potential for atypical organization of the language network when the developing brain is impacted by stroke or epilepsy. We will then give an overview of findings from adult stroke and aphasia research, which has focused on the potential for recovering language processing in both the remaining left hemisphere tissue and in the non-dominant right hemisphere. Recent work in this field has leveraged modern neuroimaging methods to improve our mapping of where damage in the language network produces particular language deficits. Altogether, we hope to present a clear picture of what is known about the capacity for plastic change in the neurobiology of the human language system.

B. DEVELOPMENTAL PLASTICITY OF LANGUAGE

The plasticity that drives the development of the language system is important to consider when we try to interpret differences in the organization of language between healthy individuals and those with disordered or atypical organization. It is also central to our ability to understand how the system changes after neural injury and in recovery. This section discusses the developmental critical period when language exposure shapes the neural language network, and the development of left hemisphere dominance (lateralization).

Developmental Critical Period

Humans are born with the ability to learn language, much like we are born with the ability to learn how to walk. For the brain to develop language-readiness, it is believed that there are consistent milestones in structural development that must occur. For example, Eric Lenneberg posited that certain “maturational indices of the brain,” such as cortical density and white matter myelination, must reach at least 65% maturity for language acquisition to begin (Lenneberg, 1969). The concept of a “critical period” for the neurological scaffolding to be in place to develop a function is not specific to language development. In general, critical or sensitive periods are defined by biological constraints that impose a lower bound for how early in development a function can begin developing, and an upper bound for how late in development a function can develop completely (Hensch, 2005).

There are clear advantages to having a window of time early in development when the brain can receive input from the environment that will rapidly shape how it processes information. It takes immense cellular resources to reconfigure neural circuits, so it is prudent to establish a framework early that is as specific as possible to the most important information, with some flexibility after this phase for new information to make minor changes (Werker & Hensch, 2015). In some sensory systems, there is an important early window during which experience must tune the response profiles of the various neuronal populations involved in perception (Hubel & Wiesel, 1964; Wiesel & Hubel, 1965). In the language system, there is also a developmental window during which linguistic input is essential for successful development. The most extreme examples are the rare cases of “wild children,” who, due to tragic circumstances, were raised with close to no exposure to language (e.g., news coverage of Genie: James, 2008). Even when they are rescued as children, these individuals

do not develop full language abilities (Curtiss, 2014). These cases are critical evidence that linguistic input is required early in life for the development of a functioning language system, analogous to visual input being required for the development of a complete visual system. Another clarifying example is when people who immigrate to a new country at different ages attempt to learn a second language. When the amount of experience with the new language is held constant, there is an advantage to being younger than 8 years old for acquiring the second language to proficiency (Johnson & Newport, 1989). In summary, there is an early window for acquiring the necessary foundation for language processing, and a delayed but still early window for acquiring new languages completely.

Phonology (processing the fundamental perceptual units of language, such as phoneme or syllable sounds, and their allowable combinations in speech) has an early critical period that is believed to begin in utero and starts to close after 10–12 months of life (Werker & Hensch, 2015; Werker & Tees, 1984, 2005). In some cases, experience during the critical period provides input that creates and then sharpens perceptual sensitivities. In the case of phoneme discrimination, it has been shown that a full range of representations for phonemes exists at birth, and then through specific listening experience, the native language phoneme classes are maintained and sharpened while unused, non-native classes are weakened (Maurer & Werker, 2014). Werker and Tees (1984) demonstrated that English-learning infants can discriminate Hindi “d” sounds not used in English, but only until 10–12 months, when the critical period for phonology gradually closes (Werker & Tees, 1984). Around this age, the child has accumulated enough specific listening experience to sharpen the phonological representations of their native language through a process called perceptual narrowing (Maurer & Werker, 2014). Interestingly, if specific listening experience begins earlier than normal—such as in the case of infants born prematurely—it does not shift the closure of the critical period to be earlier than what would be estimated from the full-term due date (Peña et al., 2010). This is because the onset, duration, and closure of the critical period are determined both by environmental input *and* by the maturation of key biological players (inhibitory parvalbumin cells in particular; Werker & Hensch, 2015). Thus, a framework for phonology is established early to process the most important information in the child’s linguistic environment. Successful development of a phonological system appears to be the necessary first step in acquiring complete language abilities; the age of acquisition for phonology is correlated with language proficiency later in life (Jansson-Verkasalo et al., 2010; Newport et al., 2001).

Because the developing auditory system is thought to undergo perceptual narrowing that sharpens representations for native language phonemes, it is interesting to consider how these representations change if the individual stops receiving native language input and starts receiving input from a different language. This situation can arise when an infant is adopted from one country to another. Some evidence suggests that even if the individual loses ongoing interaction with the native language, their native phonological representations may remain intact. Korean infants adopted by American families before 1 year of age who go on to take 3 years of Korean in college are better at discriminating Korean consonants than native-English students with the same college-level training (Oh et al., 2010). Related findings from animal work suggest that maps that are established early have a signature or ‘enduring trace’ that can be reanimated later when the same initial conditions are reinstated

(Knudsen, 1998: auditory system in barn owls; Hofer et al., 2006: visual system in mice). Other evidence suggests that the phonological representations for the native language are plastically altered and can undergo ‘first-language attrition’ if the individual stops receiving native language input and acquires a second language (Costa & Sebastián-Gallés, 2014). Korean infants adopted to French families in isolated villages do not discriminate Korean speech sounds better than their native French-speaking peers (Ventureyra et al., 2004). Pallier and colleagues (2003) measured fMRI activation while Korean children adopted by French families and native French speakers listened to speech stimuli from various languages. They found that brain activation in the Korean adoptees was no different for Korean stimuli as any other unknown foreign stimuli. French stimuli evoked activation patterns that were similar in Korean adoptees and native French speakers, however, the activation was stronger in native speakers (Pallier et al., 2003). Linguistic input from the infant’s environment shapes their phonological representations, but these representations can continue to be plastically modified early in life if the input is dramatically altered. It is inconclusive to what extent the native phonological representations are still readily available in these cases for reacquiring the native language in adulthood.

In other situations, an infant may be exposed to two languages simultaneously and to the same extent, such as in bilingual households. Bilingual infants tested on phoneme discrimination paradigms demonstrate perceptual narrowing to both native languages by 10–12 months (Spanish and Catalan: Albareda-Castellot et al., 2011; French and English: Burns et al., 2007; Sundara et al., 2008; for a review: Costa & Sebastián-Gallés, 2014). It is impressive that bilingual infants can simultaneously acquire two sets of phonemes in the same span of time that monolingual infants learn one, because they likely receive less input from each language than in an environment where one language is spoken exclusively (Costa & Sebastián-Gallés, 2014). The neural plasticity involved in tuning phonological representations for multiple native languages is not well understood (see Höhle et al., 2020 for a recent review). In contrast to the previously discussed cases involving ‘first-language attrition’ after adoption to a new country, the ongoing simultaneous input from two languages in bilingual households shapes phonological representations that can be readily used for either language. It is not known whether the two native languages leverage the same phonological representations that are perhaps more broadly tuned than they are in monolinguals, or if separate phonological representations become tuned for each native language separately (Costa & Sebastián-Gallés, 2014).

We know that phonological representations are tuned in the first year of life as a result of specific listening experience to linguistic information. What happens when a child is born deaf? It is a clinical concern whether the plasticity available to the phonological system is sufficient for a congenitally deaf child to acquire spoken language if they opt to receive a cochlear implant. When a child is born deaf, ‘residual plasticity’ in the auditory system outside of the early critical window makes it possible for speech representations to develop when a cochlear implant is introduced later (Kral et al., 2019; Kral & Sharma, 2012). There have been similar findings in the sensory-deprived developing visual system (e.g., delayed critical period onset in visual cortex after dark-rearing; Hensch, 2005; Mower, 1991). However, there is still a limited window of time for optimal speech acquisition through a cochlear implant. In congenitally deaf infants, the critical period for acquiring

the phonology of a spoken language through a cochlear implant may close around 12–14 months (Houston et al., 2012). When deaf infants who received a cochlear implant within this window (7–15 months) are compared to hearing infants on a spoken word learning task, they perform similarly. Deaf infants who received a cochlear implant later (16–25 months) perform worse (Houston et al., 2001, 2012). It is generally accepted that congenitally deaf children who receive cochlear implants in the first few years of life can typically develop normal spoken language, but after around 3.5 years, the outcomes are more variable (Kral et al., 2019; Kral & Sharma, 2012).

Not everyone who is born deaf decides to receive a cochlear implant, and it has been shown that when congenitally deaf individuals acquire sign language, it follows the same developmental trajectory as spoken language acquisition (Newport & Meier, 1985). Indeed, the critical period for language acquisition is not exclusively for spoken language. This point is clearly observed when congenitally deaf children who are exposed to sign language from their deaf parents at the start of life are compared to congenitally deaf children who are born to hearing parents and do not receive consistent sign language input for years. Deaf children with earlier exposure to sign language outperform their later-learning counterparts on language proficiency measures (e.g., copying stories and answering comprehension questions, verbal working memory, grammatical morphology; Mayberry, 1998; Newport, 1990). Again, we see that a framework is established early to process the most important information in the child's linguistic environment—in this case, sign language. The perceptual narrowing of sign language representations follows the same maturational timeline of perceptual narrowing in spoken language phonology (Krentz & Corina, 2008; Palmer et al., 2012). This evidence supports the conclusion that there is a critical period for language development that requires linguistic input but not necessarily auditory linguistic input; neural representations for sign language follow the same developmental trajectory as spoken language.

In fact, the linguistic structures learned by young children may scaffold later learning of languages, even when the original language and the new language utilize different sensory and motor modalities. When a child is born hearing and acquires spoken language, and then loses hearing during childhood (e.g., due to meningitis) and acquires sign language, there is an interesting and perhaps surprising phenomenon whereby their spoken language representations facilitate sign language acquisition. These initially hearing, late-learning signers tend to outperform congenitally deaf children who learn sign language around the same age as their first language (Mayberry, 1998). This finding further supports the importance of early language exposure to the complete development of the language system, and demonstrates that some of what is learned early about the structure of language is independent of sensory modality.

In summary, there is a biologically constrained window (a critical period) very early in development during which the brain can acquire language if provided linguistic input, and complete, early acquisition of a phonological system seems to be key for language proficiency. We have focused on phonology here because its development is more thoroughly understood and may be foundational to the successful development of other language processes, but similar principles apply to syntax and morphology as well.

Development of Left Hemisphere Dominance (Lateralization)

One feature of language system organization that sets it apart from many other systems, including motor and sensory, is its strong lateralization to the left hemisphere in the majority of adults (Knecht, Dräger, et al., 2000). Language is left-lateralized in 92–96% of right handers (Knecht, Deppe, et al., 2000; Knecht, Dräger, et al., 2000) and 73–78% of left handers (Knecht, Dräger, et al., 2000; Szaflarski et al., 2002). Language also appears to be dominantly processed in the left hemisphere regardless of whether it is spoken or signed (MacSweeney et al., 2008; Newman et al., 2015; Petitto et al., 2000). In fact, the left hemisphere may have a structural advantage for language network development even before birth (e.g., a larger planum temporal: Dubois et al., 2008; Habas et al., 2011; Kasprian et al., 2010; Kivilevitch et al., 2010; Zhang et al., 2011).

While there may be hemispheric asymmetries at birth that bias left hemisphere dominance for language processing, lateralization strengthens over the course of brain and cognitive development. Eric Lenneberg argued that both hemispheres may be viable for language processing early in life (Lenneberg, 1969). He based his theory of “equipotentiality” on case studies of developmental unilateral brain injuries, in which language developed successfully regardless of which hemisphere was affected, as long as the event occurred early in development. Young children are also able to use their right hemisphere for language processing when the left hemisphere is anesthetized (“Wada test”; Rasmussen & Milner, 1977; Wada & Rasmussen, 1960). Recently, Olulade and colleagues (2020) showed using fMRI that the right hemisphere homologues of left hemisphere language regions are active during language processing in young children (4–7 years old), but right hemisphere activation is nearly absent in adults (Olulade et al., 2020). Another recent fMRI study in young children and adults demonstrated that language lateralization to the left hemisphere stabilizes around age 10, first in the temporal and then frontal language regions (Berl, Mayo, et al., 2014). Focality of activation during language processing may also increase over development (e.g., Durston et al., 2006, but also see response by Brown et al., 2006).

Although developmental changes in lateralization of language networks may occur partly as a consequence of brain maturation, some changes in lateralization are driven by language experience. One interesting example is pitch processing: pitch processing is typically right-lateralized, but becomes left-lateralized in native tonal language speakers (Chinese and Thai: Xu et al., 2006; English and Thai: Gandour et al., 2002). Thus, when pitch carries necessary linguistic information it is processed in the left hemisphere, but when it carries non-essential contextual information such as speaker gender or emotion, as it is used by speakers of non-tonal languages, it is processed in the right hemisphere.

Typical lateralization also seems to require linguistic input during the critical period for language acquisition: if language learning happens outside of the critical period, cerebral asymmetry may not be fully established (Locke, 1997). Mayberry and colleagues have studied a rare sample of congenitally deaf individuals who could not learn spoken language and did not learn sign language during early childhood. These individuals went on to have poor language abilities as adults. Their activation during language processing is more bilateral and diffuse, and includes visual areas in addition to typical language processors (Mayberry et al., 2018).

Atypical language lateralization (bilateral or right-lateralized) may relate to developmental language impairments, but this idea is largely based on evidence showing the co-occurrence of these factors rather than a mechanistic relationship. The prevalence of atypical lateralization is approximately twice as high in those who score the lowest on language assessments compared to the population (Bishop, 2013). Studies investigating the genetic relationship between cerebral asymmetry and language impairment have identified a number of candidate genes (FOXP2, ATP2C2, CMIP, CNTNAP2, DCDC2, DYX1, KIAA0319, MRPL19/C2ORF3) but the relationships are complex and likely polygenetic (Darki et al., 2012; Graham & Fisher, 2013; Newbury & Monaco, 2010; Ocklenburg et al., 2014). Reduced asymmetry in the size of the planum temporale has been associated with dyslexia, but this relationship depends on how dyslexia and symmetry are classified (Eckert & Leonard, 2000; Leonard et al., 2002) and this structural asymmetry does not directly correlate with lateralization of language functions (Bishop, 2013; Dorsaint-Pierre et al., 2006; Keller et al., 2010). Reduced laterality has been observed in adults with developmental language disorder and dyslexia (Badcock et al., 2012; de Guibert et al., 2011; Illingworth & Bishop, 2009; Krishnan et al., 2016; Sun et al., 2010; Whitehouse & Bishop, 2008), which has for example been measured during fMRI word generation tasks that produce robust left hemisphere activation in neurotypical adults. Poor phonological skills are also associated with more diffuse and bilateral processing of speech sounds in children (Bishop et al., 2012). There may be a relationship between atypical lateralization of language and language impairments, but there is no conclusive evidence that atypical lateralization drives this outcome.

In addition, left-lateralization of language is not consistently correlated with better language performance in healthy individuals. In children, vocabulary scores have been found to correlate with lateralization of the arcuate fasciculus as measured with diffusion tensor imaging (Lebel & Beaulieu, 2009) and hemispheric asymmetry of blood flow velocity with functional transcranial Doppler sonography (fTCD; Groen et al., 2012). However, this relationship has not been observed in adults, and in fact some children in these studies were right-lateralized for language and had above-average vocabulary scores. There is overwhelming evidence that language is left-lateralized, but the significance of this organization remains a mystery.

Visual attention is another cognitive function that tends to be lateralized in neurotypical adults, but to the right hemisphere (Cai et al., 2013). One common question about lateralization of cognitive functions is whether language and visual attention always segregate into opposite hemispheres. There is no evidence that the strength of language lateralization determines the strength of visuospatial lateralization (Cai et al., 2013). Laterality of activation in language tasks does not appear to correlate with laterality of visuospatial processing (Badzakova-Trajkov et al., 2010; A Flöel et al., 2005; Groen et al., 2012; Rosch et al., 2012; Whitehouse & Bishop, 2009). After a focal brain lesion, language and visuospatial functions can share the same hemisphere (Bryden et al., 1983). This is perhaps unsurprising because in the small proportion of healthy, typically developing individuals who have right hemisphere language dominance, language and visuospatial function can share the same hemisphere (Flöel et al., 2001). In these rare cases where

language is right-lateralized, a unilateral lesion can produce both aphasia and spatial neglect (De Witte et al., 2008).

In summary, we begin life with a brain that is innately slightly asymmetrical and has a leftward bias for linguistic information. As our learning systems and language abilities mature, left hemisphere dominance for language processing strengthens, partly through a reduction in use of the right hemisphere for language, and the engagement of specific regions becomes more focused and less diffuse. However, strong lateralization may not be required for normal language development. Atypical lateralization may sometimes lead to normal language outcomes, but it may in some cases play a role, albeit undetermined, in developmental language impairments (Bishop, 2013).

C. LANGUAGE PLASTICITY AFTER DEVELOPMENTAL BRAIN INJURY

Plasticity after brain injury or dysfunction in the language network plays out differently depending on the age of the individual and the nature of their injury. It is generally accepted that injury-induced plasticity has a monotonic relationship with age, which relates to the critical period plasticity processes discussed previously: the younger a person is, the more flexibility the brain has to remap processes onto alternative brain structures. The relationship between the nature of the neural injury and the outcome of language network plasticity is more complicated, and also interacts with age. This section discusses commonly studied examples of neural injuries that impact the language network in children (stroke, epilepsy, hemispherectomy), and the general conclusions from this research about the plasticity that supports language recovery.

Perinatal Stroke

A perinatal stroke occurs around the time of birth, in a window between 28 gestational weeks and 28 postnatal days. A stroke occurring earlier than 28 weeks is considered a neonatal stroke and has a different profile of presentation, and a stroke after 28 postnatal days is considered a childhood stroke (Ferriero et al., 2019). It is estimated to be six times more likely for a newborn to have a stroke than an older child (DeVeber et al., 2017). During the perinatal window, the most common type of stroke (approximately 80%) is arterial ischemic. The remainder are either hemorrhagic or a cerebral sinovenous thrombosis. Some infants (estimated around 1/3) present with symptoms in the first few days of life, most commonly seizures, changes in muscle tone (hemiparesis, hypotony, hypertony), and disturbed level of alertness (irritability, lethargy; Laugesaar et al., 2007). More often, symptoms present several months later (8 months on average): most commonly, hemiparesis is observed (early hand preference before handedness is typically apparent), and occasionally seizures (Laugesaar et al., 2007). For uncertain reasons, the majority of perinatal strokes impact the left hemisphere (Golomb et al., 2001; Laugesaar et al., 2007; Nelson & Lynch, 2004), perhaps as many as 80% (Grunt et al., 2015).

Left middle cerebral artery (MCA) perinatal strokes without other comorbid or congenital conditions (e.g., cardiovascular disease, epilepsy) are an important model for understanding language network plasticity. In these individuals, language develops successfully despite the loss of left hemisphere cortical regions that are critical for a full range of language abilities

in typical adults (Newport et al., 2017; Stiles et al., 2012). Behavioral studies with perinatal stroke survivors suggest that language shows a delayed developmental trajectory compared to neurologically typical children, but by the end of development, language abilities are normal (Bates, 2004; Trauner et al., 2013). For example, a study performed by Ballantyne and colleagues (2007) found that school-age perinatal stroke participants with either a left or right hemisphere stroke performed worse than controls on receptive and expressive language (both groups were below the fourteenth percentile; Ballantyne et al., 2007). The lesion side and location were not predictive of language outcomes. The presence of seizures, however, significantly related to poorer performance in the stroke groups. This finding has been replicated in a number of studies (Ballantyne et al., 2008; Bosenbark et al., 2017; Williams et al., 2017). When tested in adolescence or adulthood, perinatal stroke survivors without chronic seizures perform the same as their neurotypical peers on language tests (Fair et al., 2010; Ilves et al., 2014; Newport et al., 2017).

When language develops successfully after a left hemisphere perinatal stroke, it organizes in the right hemisphere. Dichotic listening experiments provided the earliest evidence of right-lateralization of language in this population (Brizzolara et al., 2002; Bulgheroni et al., 2004; Carlsson et al., 1992; Chilosi et al., 2005). More recently, fMRI studies have specified that language organizes in right hemisphere regions that are a mirror image of typical left hemisphere language regions, including inferior frontal gyrus, superior temporal gyrus and sulcus, and middle temporal gyrus (François et al., 2019; Guzzetta et al., 2008; Newport et al., 2017; Tillema et al., 2008). There is no conclusive evidence from these studies that lesion size relates to right hemisphere organization of language (Guzzetta et al., 2008; Tillema et al., 2008), which suggests that even when only part of the left hemisphere cortical territory that typically processes language is impacted, the network still becomes right-lateralized. In fact, Staudt and colleagues (2002) found that even in the case of small periventricular white matter strokes, which leave the majority of left hemisphere cortex intact, language processing can be right-lateralized to regions that mirror the left hemisphere activation patterns in controls (Staudt et al., 2002). Right-hemisphere language organization may also be more likely if the perinatal stroke encompasses Broca’s area (Guzzetta et al., 2008). The organization of language in the healthy right hemisphere after a left hemisphere perinatal stroke exemplifies the extreme plasticity available in the brain at the start of life, and demonstrates that successful language development can occur in the absence of left hemisphere brain structures that typically support language.

A few studies have suggested that the left hemisphere may still play a role in language processing after a left hemisphere perinatal stroke. Raja Beharelle and colleagues (2010) found that in left hemisphere perinatal stroke survivors, behavioral language scores positively correlated with left-lateralized frontal activation and bilateral posterior temporal and parietal activation evoked by a category fluency fMRI task (Raja Beharelle et al., 2010). Fair and colleagues (2010) argued that methodological decisions can bias our interpretations of right hemisphere language activation. In particular, they demonstrated that when only correct trials were investigated for their word generation fMRI task, there were few differences in right hemisphere language activation between patients and controls, and the differences that were present seemed to be idiosyncratic across individuals (Fair et al., 2010). However, studies that have taken these methodological considerations into account,

such as those using an easy sentence processing task that produces few to no errors, continue to demonstrate robust right hemisphere language activation in left hemisphere perinatal stroke participants (Newport et al., 2017). And critically, young children who have lost most of—or in rare cases, all of—the left hemisphere cortical language network can still achieve normal language outcomes (Lenneberg, 1967; Stiles et al., 2005, 2012).

It is remarkable that the right hemisphere is able to support language processing after a perinatal stroke, considering how limited it is in its ability to recover language functions after a left MCA stroke in adulthood. Elissa Newport's "Developmental Origins Hypothesis" suggests that because the representations of cognitive functions are more widely distributed in the young child's brain, functions like language can be preserved after unilateral injury through engagement of these additional representations (Newport et al., 2017). Because language is processed bilaterally in early childhood (Olulade et al., 2020), children may successfully make use of the available language processors in the right hemisphere when an early stroke damages the left hemisphere. However, over the course of development, the language network consolidates in the left hemisphere, and this alternative set of language processors in the right hemisphere is no longer able to support language. An important question raised by this hypothesis is whether the right hemisphere language regions that are capable of supporting language early in life can be functionally resurrected after left hemisphere injury in an adult. Further investigation is needed into how these more diffuse areas are used during language processing by children, and the mechanisms of plasticity that make these regions less involved in language processing later in life.

Overall, this work has concluded that language organization in the brain is highly plastic early in life: language abilities can develop successfully even if typical left hemisphere language regions are unavailable by recruiting frontal and temporal regions in the intact right hemisphere. Seizures are disruptive to successful language development, and further investigation is needed to conclude whether the site of the lesion and the residual left hemisphere tissue are important features in language plasticity after perinatal stroke.

Childhood Stroke

Strokes occur far less often in childhood after the perinatal period (DeVeber et al., 2017). Generally, after a left hemisphere stroke in childhood, language is more likely to remain lateralized to the left hemisphere, and language outcomes are worse. These outcomes further demonstrate that there is a window of plasticity early in life, after which—even in later childhood—there is much less plasticity available for atypical language mapping and successful language development. Ilves and colleagues (2014) found that in childhood stroke survivors (age at stroke ranging from 1.5 months to 11.25 years) language activation was strongly left-lateralized regardless of age at stroke – however, in those who suffered a stroke after age 2, behavioral scores on receptive and expressive language tasks were significantly lower compared to those who were younger than 2 at the time of stroke (Ilves et al., 2014). Everts and colleagues (2010) examined left and right hemisphere childhood stroke survivors, and found left-lateralized language in 3/5 left hemisphere and 3/5 right hemisphere stroke survivors. Among those with atypical lateralization, one left hemisphere stroke survivor showed left-lateralization for vowel detection and right-lateralization for synonym judgment,

and one right hemisphere stroke survivor showed the opposite dissociation (Everts et al., 2010). Elkana and colleagues (2011) found greater right-lateralization of language activation in childhood stroke survivors compared to healthy controls, but that linguistic proficiency correlated positively with left-lateralization in the stroke group. In one patient studied longitudinally, left-lateralization of frontal activity increased with age, and linguistic proficiency also improved (Elkana et al., 2011). There have been fewer studies investigating language organization after childhood stroke than after perinatal stroke, but these results indicate that language recruits typical left hemisphere regions with variable success, and idiosyncrasies in organization may relate to the degree of developmental plasticity still available at the age the stroke occurred. However, age and stroke severity are not the only factors that impact functional recovery. Environmental influences (family, sociodemographic factors, interventions) also contribute to the “recovery continuum” of cognitive outcomes after neural injury in development (Anderson et al., 2011).

Epilepsy

When a child has severe left hemisphere epilepsy, language can organize atypically in a few ways. In a relatively large fMRI study of patients with focal epilepsy (n=220) and healthy controls (n=118), Berl, Gaillard and colleagues (2014) identified atypical language organization in 2.5% of controls and 24.5% of patients that presented as either symmetrically bilateral, right-lateralized, or incongruent lateralization of frontal and temporal regions (“unilateral crossed”; Berl, Zimmaro, et al., 2014). In agreement with previous work by their group and others, atypical language organization was related to early onset of seizures (before age 6), atypical handedness (left or ambidextrous), and vascular pathology (stroke, cavernomas, and arteriovenous malformations; Berl, Zimmaro, et al., 2014; Gaillard et al., 2007). Other fMRI studies have shown that when language reorganizes to the right hemisphere in patients with left hemisphere foci, the regions recruited are the right hemisphere homologues of typical left hemisphere language regions (Mbwana et al., 2008; Rosenberger et al., 2009)—the same overall pattern that is observed after left hemisphere perinatal stroke. When language remains left-lateralized, activation localizes to typical frontal regions, while the location of activation in temporal regions is more variable —likely due to the high prevalence of temporal lobe seizure foci in these participants (Rosenberger et al., 2009). Surprisingly, Liégeois and colleagues (2004) found that when a left hemisphere lesion occurred in cases of severe epilepsy, lesions remote from language regions resulted in atypical language organization in 4/5 cases, the same proportion that was observed when lesions were proximal to Broca’s area (Liégeois et al., 2004). The findings of Berl, Gaillard and colleagues (2014) may explain some of this nuance. Their results demonstrate that frontal and temporal regions can lateralize differently, and the different lateralization profiles that arise have systematic relationships with some of the common variables that have been identified as predictors of general atypical language lateralization in previous work: the frontal region was right-lateralized more often in patients with atypical handedness, the temporal region was right-lateralized more often in patients with early seizure onset, and both frontal and temporal regions were right-lateralization more often in patients with left hemisphere seizure foci (though some patients with right hemisphere seizure foci also showed this right-lateralized organization). In summary, language can become atypically organized in childhood epilepsy by recruiting structures bilaterally, in

the right hemisphere, or with the frontal and temporal regions oppositely lateralized. The common variables implicated in atypical language organization in developmental epilepsy are handedness, age of seizure onset, and vascular pathology.

Hemispherectomy

Rasmussen's syndrome, or Rasmussen's encephalitis, causes severe epilepsy in children who are often otherwise neurodevelopmentally typical. The surgical removal of the hemisphere with the primary epileptogenic center, while an extreme procedure, is highly successful in eradicating seizures in these individuals (Moosa et al., 2013). Language outcomes in these children—who developed language normally for some number of years and then in some cases had the left hemisphere removed after the disease began—can elucidate which language processes can be supported by the non-dominant right hemisphere.

Boatman and colleagues (1999) studied language outcomes in a group of right-handed Rasmussen's syndrome patients who had at least 5 years of normal language development before they acquired epilepsy and underwent a left hemispherectomy. Five of the six patients were impaired on phoneme discrimination prior to surgery, but after 5–6 months of recovery post-surgery, these 5 patients were no longer impaired. Most patients were completely mute in the days to weeks immediately following surgery, and while repetition recovered and picture-naming eventually improved, their spontaneous speech was largely telegraphic even after 5–6 months of recovery. The authors interpret that the right hemisphere may have been innately capable of supporting phoneme discrimination, since this ability recovered successfully in only a few months (Boatman et al., 1999). Similarly, Bulteau and colleagues (2015) found that phoneme discrimination was fully supported by the right hemisphere after left hemispherectomy in the 6 Rasmussen's syndrome patients they studied. Verbal comprehension also recovered after surgery, although other speech abilities, particularly those that required producing speech or judging speech segments longer than a single word, remained impaired. Many of these impaired processes correlated with working memory scores measured by forward and backward digit span. The authors conclude that both hemispheres may have equal potential for comprehending word meaning (lexicosemantic knowledge), but the left hemisphere may develop early specialization for speech production, syntax, and perhaps complex aspects of phonological analysis (Bulteau et al., 2015).

Hemispherectomies are also performed in children with intractable epilepsy that begins at the onset of life, for example due to a prenatal stroke. In these cases, epilepsy is concurrent with early cognitive and linguistic development. Case studies performed by Basser led to the conclusion that if seizure pathology onset was in infancy, language would lateralize to whichever hemisphere was healthy, and aphasia would be rare when the pathological hemisphere was removed later (Basser, 1962; Lenneberg, 1967). Interestingly, Curtiss, de Bode, and Mathern (2001) found that better spoken language outcomes related to seizure onset (and surgery) at an older age in children with right hemispherectomies, but not left. They interpret this finding to suggest that the right hemisphere supports the maturation of the left hemisphere language network, such that early onset of seizures in the right hemisphere disrupts normal early language network development (Curtiss et al., 2001).

Curtiss and colleagues (2001) also found that children with a surviving left hemisphere after hemispherectomy showed higher language scores than those with a surviving right hemisphere (Curtiss et al., 2001). In a sample with mixed congenital and acquired epilepsy, Liégeois, Cross and colleagues (2008) found that receptive vocabulary could develop successfully after the removal of either the left or right hemisphere (Liégeois, Cross, et al., 2008). They also found that damage to the left hemisphere and early-life pathology in either hemisphere related to deficits in verbal working memory and verbal intelligence. These results converge with the findings of Bulteau et al (2015) previously discussed, that the right hemisphere can support verbal comprehension in the absence of the left hemisphere, and that post-surgical working memory outcomes were weak and related to deficits in complex speech processing. For speech production, Liégeois, Connelly and colleagues (2008) found using task-related fMRI that recruitment of pars triangularis and pars orbitalis in either the left or right inferior frontal cortex related to better outcomes than pars opercularis alone (Liégeois, Connelly, et al., 2008).

In summary, the extent to which language is able to reorganize to the right hemisphere after early left hemisphere injury is multifaceted. In the case of stroke, age is a key factor. In the case of epilepsy, outcomes are more variable, but age and pathology of seizure onset play an important role. Studies on hemispherectomy patients have found that the non-dominant right hemisphere can support some language processes, particularly receptive language functions, even if the left hemisphere is removed after years of typical language development. Further investigation is needed into the primary effects of epilepsy on the development of language and other cognitive systems.

D. LANGUAGE PLASTICITY AFTER INJURY IN ADULTS

Behavioral effects of language network injury and course of recovery

Plasticity of language networks is more limited and less successful in terms of behavioral outcomes in adults than in children. Any type of brain injury or disorder affecting the left cerebral hemisphere can cause aphasia in adults. The most common cause of aphasia is stroke (Simmons-Mackie & Cherney, 2018), which serves as the main model of brain injury for studying language network plasticity in adults. About one third of all stroke survivors experience aphasia acutely, and about one in five continue to have aphasia chronically after stroke (Pedersen et al., 1995). Like other deficits caused by stroke, improvement of aphasia is fastest early after the injury and slows down over time, typically over a period of several months (Lendrem & Lincoln, 1985). The clinical presentations of aphasia are protean, depending primarily on the specific brain structures damaged by the stroke. The aphasia profile may also change over the first several months, with stroke survivors often evolving from one syndromic diagnosis into a less severe diagnosis over time (e.g., Wernicke’s Aphasia evolving into Conduction Aphasia; Kertesz & McCabe, 1977). These changes help to illustrate that language is actually composed of many subprocesses that rely on somewhat distinct brain networks, and may follow different patterns of recovery, both in the brain and in behavior. Early longitudinal studies measuring aphasia outcomes suggested that there was little significant improvement on standardized measures after the first year of recovery (Kertesz & McCabe, 1977). While many neurologists are still taught

that aphasia recovery ends after one year based on these findings, it is now clear that improvement often continues for many years after stroke (Holland et al., 2017; Smania et al., 2010). While some have interpreted the rapid early improvement in aphasia as reflecting a critical or sensitive period for plasticity after injury, this interpretation is not supported by evidence. A critical or sensitive period should be marked by a time window during which language relearning is most effective, but no studies to date have demonstrated that the effectiveness of speech-language therapy for aphasia depends on its timing after stroke. Further, multi-center randomized trial data has demonstrated that intensive aphasia therapy can improve language abilities even years after stroke (Breitenstein et al., 2017). Thus, while improvement of aphasia may be fastest early after the stroke, there is no clear evidence of a sensitive period for relearning of language skills in adults.

Topology and timing of language network reorganization

Early improvement in aphasia after adult stroke likely reflects resolution of cerebral edema, reperfusion of tissue, and improvements of so-called diaschisis, remote brain dysfunction of networks connected to the lesioned tissue (Carrera & Tononi, 2014). Further recovery from aphasia is supported by explicit behavioral compensation strategies, and plastic changes in the brain's networks for speech and language. Our understanding of how language networks reorganize after stroke is still evolving. Most of the research on this topic has focused on describing where changes occur in the brain, and to a lesser extent, when they occur after stroke (Hartwigsen & Saur, 2017). In terms of where, i.e., the topology, changes in language-related brain activity, as measured using task-related PET or fMRI, tend to occur in left hemisphere perilesional brain regions surrounding the stroke, in right hemisphere regions that mirror the typical left hemisphere language network (the same right hemisphere regions that support successful language development in children with perinatal stroke), and in alternate processing areas in both hemispheres thought to be involved in "domain general" processes such as attention and executive function (Geranmayeh et al., 2014; Turkeltaub et al., 2011). Of note, the involvement of right hemisphere language regions in adults with aphasia is qualitatively different from that observed in children with perinatal stroke. Whereas children with perinatal stroke are able to develop a fully formed right hemisphere language network that supports normal language, adults with aphasia typically only weakly recruit right hemisphere regions, and this activity is not typically associated with recovery of normal language ability. In aphasia caused by brain tumors in adults, the right hemisphere may be somewhat better able to compensate for disruption of left hemisphere language structures in slowly growing tumors as compared to rapidly growing tumors (Thiel et al., 2006). This suggests that age is not the sole factor limiting the plasticity needed to successfully recruit right hemisphere language homologs in adults, and that the rapid onset of damage may further limit the degree of plasticity available for successful right hemisphere recruitment.

The timing of language network changes after stroke is not as well characterized as the topology because only a few longitudinal imaging studies of aphasia have been performed. The most rigorous of these studies examined individuals with relatively mild aphasia using an fMRI sentence comprehension task and found a global decrease in language network activity immediately after stroke, which was thought to reflect diaschisis (Saur, 2006). This

was followed by right hemisphere activity that mirrored typical left hemisphere language areas, which peaked weeks after stroke and decreased over time, with normalization of activation patterns into a typical left-dominant pattern several months later. It remains unclear if individuals with more severe strokes and worse aphasia follow a similar time course of changes over time, although presumably with less successful normalization of activity. It is also unclear if this pattern of change over time is specific to sentence comprehension or would generalize to other language processes as well.

Some longitudinal studies in acute aphasia (Heiss et al., 1999; Stockert et al., 2020) and other studies in chronic aphasia (Skipper-Kallal et al., 2017a, 2017b) have demonstrated that patterns of reorganization are partly determined by lesion location and size. For example, while left frontal lesions are associated with recruitment of right frontal cortex for language (Blank et al., 2003; Heiss et al., 1999; Skipper-Kallal et al., 2017a; Turkeltaub et al., 2011), left temporal lesions may prevent the recruitment of right temporal cortex (Skipper-Kallal et al., 2017b; Stockert et al., 2020). It is often assumed that recruitment of right hemisphere regions for language is greater for large than small lesions. Only one study has assessed this relationship systematically, finding that lesion size was indeed correlated with right hemisphere activity (Skipper-Kallal et al., 2017a). However, a similar relationship between lesion size and visual cortex activity suggested that an artifactual increase in activity due to increased effort explained the effect, rather than true plastic reorganization of the language network. These complex relationships between lesion attributes and reorganization make developing a full picture of language network reorganization in aphasia challenging, leading to inconsistent findings across the literature (Wilson & Schneck, 2021). A better understanding of the biological and behavioral mechanisms of plasticity underlying observed changes may help to constrain hypotheses and develop more focused studies of language recovery (Turkeltaub, 2019).

Brain changes associated with behavioral language outcomes

Speech-language therapy for aphasia can improve aphasia outcomes, and several studies have examined brain changes associated with treatment-induced improvements. These changes follow the same patterns as described above, including residual left hemisphere tissue, mirror-image right hemisphere language regions, and alternate “domain general” regions (Schevenels et al., 2020). There is little clear evidence to date that the type of therapy systematically relates to the pattern of brain changes observed, with the possible exception that melodic or rhythmic therapies seem to preferentially impact right hemisphere structures (Schevenels et al., 2020). Good aphasia outcomes, whether considered in the context of treatment or not, are often associated with preserved left hemisphere language activity (Fridriksson et al., 2010; Heiss & Thiel, 2006; Saur, 2006), an association that may in part simply reflect the greater availability of left hemisphere tissue in less severe strokes. Right hemisphere involvement in recovery has sometimes been considered to be inefficient or maladaptive for recovery, although other work has suggested the opposite (for review, see Turkeltaub, 2015). The relative effectiveness of right hemisphere incorporation into a reorganized network may differ depending on individual characteristics of the stroke survivor, including lesion size (Anglade et al., 2014) and premorbid degree of language lateralization (Knecht et al., 2002). Specific right hemisphere brain structures may also

play different roles in recovery, with some better able to compensate and some perhaps having a net negative role in language performance. For example, TMS studies have demonstrated that inhibition of the right pars triangularis of the inferior frontal gyrus can improve picture naming performance in people with aphasia, whereas inhibiting other nearby structures can sometimes impair naming (Naeser et al., 2011). In one illustrative case, a woman with chronic nonfluent aphasia improved on measures of word production after TMS inhibition of right pars triangularis, but worsened on the same measures after a subsequent right hemisphere watershed ischemic stroke, which affected language even more than prototypical right hemisphere functions (Turkeltaub et al., 2012). Given that different language abilities rely on somewhat different brain structures (Mirman et al., 2015) and have varying degrees of native lateralization (Gazzaniga, 2000), it seems likely that the ability of the right hemisphere to compensate in aphasia varies by the specific language ability under consideration; this, however, has not been investigated thoroughly. Overall, it remains unclear whether there is an optimal topological pattern of reorganization for successful aphasia recovery; if so, this likely differs from person to person based on several factors, including at minimum the location and size of stroke and the specific language abilities under consideration.

Network-level descriptions of language recovery

Recent research has focused on changes in brain network properties during language recovery. Aphasia is now understood to be caused by not only focal damage to established language-associated regions, but also disruption of distributed brain networks (Hartwigsen & Saur, 2019; Siegel et al., 2016). These networks have an optimized premorbid organization that supports efficient transfer of information required for language functions (Baldassarre et al., 2019; Bullmore & Sporns, 2009; Geranmayeh et al., 2014; Hartwigsen & Saur, 2019; Rubinov & Sporns, 2010; Siegel et al., 2016). Under this framework, critical disruptions of this organization result in aphasia, and recovery of function is dependent on network-level plasticity that reconstitutes these premorbid patterns with the remaining intact tissue (Geranmayeh et al., 2014; Hartwigsen & Saur, 2019).

Characterizing network-level plasticity is performed by measuring changes in the connections between brain regions. Neuroimaging studies of connectivity most commonly use one of two approaches: diffusion imaging, which takes advantage of the coherent diffusion of water along white matter tracts to estimate structural connectivity (SC) between gray matter regions (Bullmore & Sporns, 2009; Sporns, 2013; Wang et al., 2015); and functional MRI – often in the absence of a task (resting state) – which allows for the estimation of functional connectivity (FC), or correlations in the fMRI signal between gray matter regions that may process similar information (Fox & Raichle, 2007; Fox et al., 2005; Gordon et al., 2016; Wang et al., 2015; Yeo et al., 2011). Fewer studies have used a combination of these approaches, but a growing body of evidence supports the hypothesis that structural (white matter) disconnections underlie functional network dysfunction in stroke (Griffis et al., 2019). Network approaches to studying plasticity primarily aim to identify properties of individual brain regions that make them particularly important to network function as a whole, or to identify properties of the entire large-scale network that are important to recovery.

Regarding network properties of individual brain regions, it has been proposed that aphasia is associated with damage to highly-connected “hub regions” within the language network, because damage to these regions would hypothetically cause severe disruption of information flow through the network (Carrera & Tononi, 2014; Griffis et al., 2019; Sporns, 2013). There is some disagreement as to the precise location of these language hub regions and evidence relating aphasia deficits to hub damage is limited (Chen et al., 2020; Dick et al., 2014; Fuertinger et al., 2015; Muller & Meyer, 2014; Vandenberghe et al., 2013; Zhao et al., 2017). Other studies look beyond the influence of individual hub regions to the so-called “rich club network” of interconnected hubs (van den Heuvel & Sporns, 2011), finding that damage to the rich club as a whole is associated with worse aphasia and widespread network dysfunction (Gleichgerrcht et al., 2015; Marebwa et al., 2017). These studies collectively support the idea that although some brain processors may play key roles within the language network, processing is distributed enough that the system is somewhat resilient in the long term even when some hubs are damaged (Blank & Fedorenko, 2020; Fridriksson et al., 2018).

More commonly, network studies take a broader perspective to consider global network properties rather than the contributions of individual regions. The brain has been shown to be intrinsically organized in discrete networks (Fox et al., 2005) with a “small-world” organization (Liao et al., 2017), defined by dense connections within networks and sparse but efficient connections between networks. Thus, brain networks are said to be both highly segregated and highly integrated (Rubinov & Sporns, 2010; Sporns & Betzel, 2016). Acute strokes that cause aphasia are associated with a global reduction in functional connectivity within the left hemisphere and between the hemispheres, particularly between homotopic or mirror-image regions (Sandberg, 2017; Siegel et al., 2016; Warren et al., 2009). Decreases in segregation (regions within the language network become less connected) and increases in integration (language regions become more connected to other networks) lead to a language network that is dysfunctional and less discrete (Baldassarre et al., 2019; Geranmayeh et al., 2016; Siegel et al., 2016).

Longitudinal network connectivity studies suggest that aphasia recovery may in part be related to restoration of network segregation which is observable as early as the subacute phase (Siegel et al., 2016). One prominent longitudinal FC study (Siegel et al., 2018) examined changes in modularity, a summary measure of the relative ratio of network segregation to integration (Rubinov & Sporns, 2010; Sporns & Betzel, 2016). This study found significantly lower whole-brain modularity in stroke survivors acutely, but no significant difference from controls in the subacute phase, a change that paralleled recovery of higher-level cognitive functions including verbal and semantic memory and language (Siegel et al., 2018). Critically, this increase in modularity from the acute to subacute phase was driven by an increase in a measure of segregation (clustering) with no change in a measure of integration (path length). This suggests that successful recovery is associated with tuning of existing within-network connections, with minimal contribution from new cross-network connections (Rubinov & Sporns, 2010; Siegel et al., 2018), consistent with observations in cross-sectional studies of subacute-to-chronic stroke (Duncan & Small, 2016; Duncan & Small, 2018).

Summary of language plasticity after injury in adults

In summary, recovery from left hemisphere injury is generally not as successful in adults as in children, and many adults with left hemisphere injury experience chronic aphasia. The brain basis of aphasia recovery is complex and not completely understood. The topology and to a lesser extent the timing of these changes has been documented, although the specific patterns observed in individuals depend on lesion attributes and likely other individual differences which have not been sufficiently accounted for by previous studies. Recovery seems to be associated with increasing network modularity, which occurs through tuning within-network connections. As a future direction, a better description of the relationships between changes in large-scale network organization and changes in individual brain regions within the language network may be critical to gain a full understanding of how brain plasticity supports aphasia recovery.

E. CONCLUSIONS

Language is a uniquely human ability. It is the prototypical lateralized brain function, and so serves as a model system for understanding neuroplasticity in lateralized networks. Disorders of language cause suffering and loss of productivity in our society, and understanding plasticity of language networks may lead to new treatments for aphasia and childhood language disorders. At the time of birth, the language network is essentially bilateral, albeit with a subtle left bias, and is plastic. Even when the entire left hemisphere is lost due to perinatal stroke, language can successfully develop in the remaining right hemisphere, appearing as a mirror image of the typical left hemisphere language network (Newport et al., 2017). There is a sensitive period for learning new languages early in life that closes over the course of childhood (Newport, 1990), and similarly, potential for plasticity in the face of brain injury diminishes over the course of childhood (Ilves et al., 2014). The effects of epilepsy on language network development are complex and relate at least in part to the age of seizure onset, although other factors likely contribute to altered language network development (Gaillard et al., 2007). By adulthood, the plasticity available to support recovery from aphasia is limited, and most individuals who acquire aphasia after stroke are left with at least mild language deficits permanently. Reorganization in the adult brain utilizes the same mirror image right hemisphere language network that children with perinatal stroke can use to acquire language (Turkeltaub et al., 2011), but recruitment is weak, variable, and not effective enough to support normal language. Language plasticity in adults also relies on left hemisphere language processors spared by injury, nearby tissue surrounding the lesion, and non-language processors that may support compensatory strategies. Our understanding of the architecture of large-scale brain networks is rapidly evolving, and new methods to combine information about global network structure and changes in local processors in the brain will lead to new insights about language plasticity. In addition, studies that move beyond descriptions of neuroplastic changes in language networks to test specific hypotheses regarding the mechanisms that drive these changes could lead to new treatments to enhance plasticity and improve recovery from aphasia and other language disorders (Turkeltaub, 2019).

Acknowledgments

This work was supported by NIH/NIDCD (R01DC014960 to P.E.T.) and NIH/NINDS (NIH NINDS 5T32NS041218 to K.M. through the Center for Neural Injury and Recovery).

REFERENCES

Albareda-Castellot B, Pons F, & Sebastián-Gallés N (2011). The acquisition of phonetic categories in bilingual infants: New data from an anticipatory eye movement paradigm. Developmental Science, 14(2), 395–401. [PubMed: 22213908]

Anderson V, Spencer-Smith M, & Wood A (2011). Do children really recover better? Neurobehavioural plasticity after early brain insult. Brain, 134(8), 2197–2221. [PubMed: 21784775]

Anglade C, Thiel A, & Ansaldo AI (2014). The complementary role of the cerebral hemispheres in recovery from aphasia after stroke: A critical review of literature. Brain Inj, 28(2), 138–145. 10.3109/02699052.2013.859734 [PubMed: 24456053]

Badcock NA, Bishop DVM, Hardiman MJ, Barry JG, & Watkins KE (2012). Co-localisation of abnormal brain structure and function in specific language impairment. Brain and Language, 120(3), 310–320. 10.1016/j.bandl.2011.10.006 [PubMed: 22137677]

Badzakova-Trajkov G, Häberling IS, Roberts RP, & Corballis MC (2010). Cerebral Asymmetries: Complementary and Independent Processes. PLOS ONE, 5(3), e9682–e9682. [PubMed: 20300635]

Baldassarre A, Metcalf NV, Shulman GL, & Corbetta M (2019). Brain networks' functional connectivity separates aphasic deficits in stroke. Neurology, 92(2), e125–e135. [PubMed: 30518552]

Ballantyne AO, Spilkin AM, Hesselink J, & Trauner DA (2008). Plasticity in the developing brain: Intellectual, language and academic functions in children with ischaemic perinatal stroke. Brain, 131(11), 2975–2985. 10.1093/brain/awn176 [PubMed: 18697910]

Ballantyne AO, Spilkin AM, & Trauner DA (2007). Language Outcome After Perinatal Stroke: Does Side Matter? Child Neuropsychology, 13(6), 494–509. 10.1080/09297040601114878 [PubMed: 17852133]

Basser LS (1962). Hemiplegia of early onset and the faculty of speech with special reference to the effects of hemispherectomy. Brain, 85(3), 427–460. [PubMed: 13969875]

Bates EA (2004). Explaining and interpreting deficits in language development across clinical groups: Where do we go from here? Brain and Language, 88(2), 248–253. [PubMed: 14965545]

Berl MM, Mayo J, Parks EN, Rosenberger LR, VanMeter J, Ratner NB, Vaidya CJ, & Gaillard WD (2014). Regional differences in the developmental trajectory of lateralization of the language network. Human Brain Mapping, 35(1), 270–284. 10.1002/hbm.22179 [PubMed: 23033058]

Berl MM, Zimmaro LA, Khan OI, Dustin I, Ritzl E, Duke ES, Sepeta LN, Sato S, Theodore WH, & Gaillard WD (2014). Characterization of atypical language activation patterns in focal epilepsy. Annals of Neurology, 75(1), 33–42. [PubMed: 24038442]

Bishop DVM, Hardiman MJ, & Barry JG (2012). Auditory deficit as a consequence rather than endophenotype of specific language impairment: Electrophysiological evidence. PLoS One, 7(5), e35851–e35851. [PubMed: 22662112]

Bishop Dorothy V M. (2013). Cerebral Asymmetry and Language Development: Cause, Correlate, or Consequence? Science, 340(6138), 1230531–1230531. 10.1126/science.1230531 [PubMed: 23766329]

Blank IA, & Fedorenko E (2020). No evidence for differences among language regions in their temporal receptive windows. NeuroImage, 219, 116925. 10.1016/j.neuroimage.2020.116925 [PubMed: 32407994]

Blank SC, Bird H, Turkheimer F, & Wise RJS (2003). Speech production after stroke: The role of the right pars opercularis. Annals of Neurology, 54, 310–320. 10.1002/ana.10656 [PubMed: 12953263]

Boatman D, Freeman J, Vining E, Pulsifer M, Miglioretti D, Minahan R, Carson B, Brandt J, & McKhann G (1999). Language recovery after left hemispherectomy in children with late-onset

seizures. Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society, 46(4), 579–586.

Bosenbark DD, Krivitzky L, Ichord R, Vossough A, Bhatia A, Jastrzab LE, & Billinghurst L (2017). Clinical Predictors of Attention and Executive Functioning Outcomes in Children After Perinatal Arterial Ischemic Stroke. Pediatric Neurology, 69, 79–86. 10.1016/j.pediatrneurol.2017.01.014 [PubMed: 28274640]

Breitenstein C, Grewe T, Flöel A, Ziegler W, Springer L, Martus P, Huber W, Willmes K, Ringelstein EB, Haeusler KG, Abel S, Glindemann R, Domahs F, Regenbrecht F, Schlenck K-J, Thomas M, Obrig H, de Langen E, Rocker R, … Bamborschke S (2017). Intensive speech and language therapy in patients with chronic aphasia after stroke: A randomised, open-label, blinded-endpoint, controlled trial in a health-care setting. The Lancet, 389(10078), 1528–1538. 10.1016/s0140-6736(17)30067-3

Brizzolara D, Pecini C, Brovedani P, Ferretti G, Cipriani P, & Cioni G (2002). Timing and type of congenital brain lesion determine different patterns of language lateralization in hemiplegic children. Neuropsychologia, 40(6), 620–632. 10.1016/S0028-3932(01)00158-0 [PubMed: 11792403]

Brown TT, Petersen SE, & Schlaggar BL (2006). Does human functional brain organization shift from diffuse to focal with development? Developmental Science, 9(1), 9–11. [PubMed: 16445388]

Bryden MP, Hécaen H, & DeAgostini M (1983). Patterns of cerebral organization. Brain and Language, 20(2), 249–262. 10.1016/0093-934X(83)90044-5 [PubMed: 6196080]

Bulgheroni S, Nichelli F, Erbetta A, Bagnasco I, & Riva D (2004). Verbal Dichotic Listening and Manual Performance in Children With Congenital Unilateral Brain Lesions. Neuropsychology, 18(4), 748–755. [PubMed: 15506843]

Bullmore E, & Sporns O (2009). Complex brain networks: Graph theoretical analysis of structural and functional systems. Nature Reviews Neuroscience, 10(3), 186–198. [PubMed: 19190637]

Bulteau C, Grosmaitre C, Save-Pédebos J, Leunen D, Delalande O, Dorfmüller G, Dulac O, & Jambaqué I (2015). Language recovery after left hemispherotomy for Rasmussen encephalitis. Epilepsy & Behavior, 53, 51–57. [PubMed: 26519666]

Burns TC, Yoshida KA, Hill K, & Werker JF (2007). The development of phonetic representation in bilingual and monolingual infants. Applied Psycholinguistics, 28(3), 455–474.

Cai Q, Van der Haegen L, & Brysbaert M (2013). Complementary hemispheric specialization for language production and visuospatial attention. Proceedings of the National Academy of Sciences, 110(4), E322 LP–E330. 10.1073/pnas.1212956110

Carlsson G, Hugdahl K, Uvebrant P, Wiklund L-M, & von Wendt L (1992). Pathological left-handedness revisited: Dichotic listening in children with left vs right congenital hemiplegia. Neuropsychologia, 30(5), 471–481. 10.1016/0028-3932(92)90094-3 [PubMed: 1620327]

Carrera E, & Tononi G (2014). Diaschisis: Past, present, future. Brain, 137(Pt 9), 2408–2422. 10.1093/brain/awu101 [PubMed: 24871646]

Chen Y, Huang L, Chen K, Ding J, Zhang Y, Yang Q, Lv Y, Han Z, & Guo Q (2020). White matter basis for the hub-and-spoke semantic representation: evidence from semantic dementia. Brain : a journal of neurology, 143(4), 1206–1219. 10.1093/brain/awaa057 [PubMed: 32155237]

Chilosi AM, Pecini C, Cipriani P, Brovedani P, Brizzolara D, Ferretti G, Pfanner L, & Cioni G (2005). Atypical language lateralization and early linguistic development in children with focal brain lesions. Developmental Medicine & Child Neurology, 47(11), 725–730. [PubMed: 16225734]

Costa A, & Sebastián-Gallés N (2014). How does the bilingual experience sculpt the brain? Nature Reviews Neuroscience, 15(5), 336–345. [PubMed: 24739788]

Curtiss S (2014). Genie: A psycholinguistic study of a modern-day wild child. Academic Press.

Curtiss S, de Bode S, & Mathern GW (2001). Spoken language outcomes after hemispherectomy: Factoring in etiology. Brain and Language, 79(3), 379–396. [PubMed: 11781049]

Darki F, Peyrard-Janvid M, Matsson H, Kere J, & Klingberg T (2012). Three dyslexia susceptibility genes, DYX1C1, DCDC2, and KIAA0319, affect temporo-parietal white matter structure. Biological Psychiatry, 72(8), 671–676. [PubMed: 22683091]

de Guibert C, Maumet C, Jannin P, Ferré J-C, Tréguier C, Barillot C, Le Rumeur E, Allaire C, & Biraben A (2011). Abnormal functional lateralization and activity of language brain areas

in typical specific language impairment (developmental dysphasia). Brain, 134(10), 3044–3058. 10.1093/brain/awr141 [PubMed: 21719430]

De Witte L, Verhoeven J, Engelborghs S, De Deyn PP, & Mariën P (2008). Crossed aphasia and visuo-spatial neglect following a right thalamic stroke: A case study and review of the literature. Behavioural Neurology, 19, 177–194. [PubMed: 19096142]

DeVeber GA, Kirton A, Booth FA, Yager JY, Wirrell EC, Wood E, Shevell M, Surmava A-M, McCusker P, & Massicotte MP (2017). Epidemiology and outcomes of arterial ischemic stroke in children: The Canadian Pediatric Ischemic Stroke Registry. Pediatric Neurology, 69, 58–70. [PubMed: 28254555]

Dick AS, Bernal B, & Tremblay P (2014). The Language Connectome: New Pathways, New Concepts. The Neuroscientist, 20(5), 453–467. 10.1177/1073858413513502 (The Neuroscientist) [PubMed: 24342910]

Dorsaint-Pierre R, Penhune VB, Watkins KE, Neelin P, Lerch JP, Bouffard M, & Zatorre RJ (2006). Asymmetries of the planum temporale and Heschl's gyrus: Relationship to language lateralization. Brain, 129(5), 1164–1176. 10.1093/brain/awl055 [PubMed: 16537567]

Dubois J, Hertz-Pannier L, Cachia A, Mangin JF, Le Bihan D, & Dehaene-Lambertz G (2008). Structural Asymmetries in the Infant Language and Sensori-Motor Networks. Cerebral Cortex, 19(2), 414–423. 10.1093/cercor/bhn097 [PubMed: 18562332]

Duncan ES, & Small SL (2016). Increased Modularity of Resting State Networks Supports Improved Narrative Production in Aphasia Recovery. Brain connectivity, 6(7), 524–529. 10.1089/brain.2016.0437 [PubMed: 27345466]

Duncan ES, & Small SL (2018). Changes in dynamic resting state network connectivity following aphasia therapy. Brain Imaging Behav, 12(4), 1141–1149. 10.1007/s11682-017-9771-2 [PubMed: 29064020]

Durston S, Davidson MC, Tottenham N, Galvan A, Spicer J, Fossella JA, & Casey BJ (2006). A shift from diffuse to focal cortical activity with development. Developmental Science, 9(1), 1–8. [PubMed: 16445387]

Eckert MA, & Leonard CM (2000). Structural imaging in dyslexia: The planum temporale. Mental Retardation and Developmental Disabilities Research Reviews, 6(3), 198–206. 10.1002/1098-2779(2000)6:3<198::AID-MRDD7>3.0.CO;2-1 [PubMed: 10982497]

Elkana O, Frost R, Kramer U, Ben-Bashat D, Hendler T, Schmidt D, & Schweiger A (2011). Cerebral reorganization as a function of linguistic recovery in children: An fMRI study. Cortex, 47(2), 202–216. [PubMed: 20138262]

Everts R, Lidzba K, Wilke M, Kiefer C, Wingeier K, Schroth G, Perrig W, & Steinlin M (2010). Lateralization of cognitive functions after stroke in childhood. Brain Injury, 24(6), 859–870. [PubMed: 20377346]

Fair DA, Choi AH, Dosenbach YBL, Coalson RS, Miezin FM, Petersen SE, & Schlaggar BL (2010). The functional organization of trial-related activity in lexical processing after early left hemispheric brain lesions: An event-related fMRI study. Brain and Language, 114(2), 135–146. 10.1016/j.bandl.2009.09.001 [PubMed: 19819000]

Ferriero DM, Fullerton HJ, Bernard TJ, Billinghurst L, Daniels SR, Debaun MR, Deveber G, Ichord RN, Jordan LC, Massicotte P, Meldau J, Roach ES, & Smith ER (2019). Management of stroke in neonates and children: A scientific statement from the American Heart Association/American stroke association. Stroke. 10.1161/STR.0000000000000183

Flöel A, Buyx A, Breitenstein C, Lohmann H, & Knecht S (2005). Hemispheric lateralization of spatial attention in right- and left-hemispheric language dominance. Behavioural Brain Research, 158(2), 269–275. 10.1016/j.bbr.2004.09.016 [PubMed: 15698893]

Flöel Agnes, Knecht S, Lohmann H, Deppe M, Sommer J, Dräger B, Ringelstein EB, & Henningsen H (2001). Language and spatial attention can lateralize to the same hemispdhere in healthy humans. Neurology. 10.1212/WNL.57.6.1018

Fox MD, & Raichle ME (2007). Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging. Nature reviews neuroscience, 8(9), 700–711. 10.1038/nrn2201 [PubMed: 17704812]

Fox MD, Snyder AZ, Vincent JL, Corbetta M, Van Essen DC, & Raichle ME (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. Proceedings of the National Academy of Sciences of the United States of America, 102(27), 9673–9678. 10.1073/pnas.0504136102 [PubMed: 15976020]

François C, Ripollés P, Ferreri L, Muchart J, Sierpowska J, Fons C, Solé J, Rebollo M, Zatorre RJ, & Garcia-Alix A (2019). Right Structural and Functional Reorganization in Four-Year-Old Children with Perinatal Arterial Ischemic Stroke Predict Language Production. ENeuro, 6(4).

Fridriksson J, Bonilha L, Baker JM, Moser D, & Rorden C (2010). Activity in preserved left hemisphere regions predicts anomia severity in aphasia. Cereb Cortex, 20(5), 1013–1019. [PubMed: 19687294]

Fridriksson J, den Ouden DB, Hillis AE, Hickok G, Rorden C, Basilakos A, Yourganov G, & Bonilha L (2018). Anatomy of aphasia revisited. Brain, 141(3), 848–862. 10.1093/brain/awx363 [PubMed: 29360947]

Friederici AD (2017). Language in our brain: The origins of a uniquely human capacity. MIT Press.

Fuertinger S, Horwitz B, & Simonyan K (2015). The Functional Connectome of Speech Control. PLoS Biol, 13(7), e1002209. 10.1371/journal.pbio.1002209 [PubMed: 26204475]

Gaillard WD, Berl MM, Moore EN, Ritzl EK, Rosenberger LR, Weinstein SL, Conry JA, Pearl PL, Ritter FF, & Sato S (2007). Atypical language in lesional and nonlesional complex partial epilepsy. Neurology, 69(18), 1761–1771. [PubMed: 17967992]

Gandour J, Wong D, Lowe M, Dzemidzic M, Satthamnuwong N, long Y, & Lurito J (2002). Neural circuitry underlying perception of duration depends on language experience. Brain and Language, 83(2), 268–290. 10.1016/S0093-934X(02)00033-0 [PubMed: 12387798]

Gazzaniga MS (2000). Cerebral specialization and interhemispheric communication. Brain, 123(7), 1293–1326. [PubMed: 10869045]

Geranmayeh F, Brownsett SLE, & Wise RJS (2014). Task-induced brain activity in aphasic stroke patients: What is driving recovery? Brain. 10.1093/brain/awu163

Geranmayeh F, Leech R, & Wise R (2016). Network dysfunction predicts speech production after left hemisphere stroke. Neurology, 86(14), 1296–1305. 10.1212/WNL.0000000000002537 [PubMed: 26962070]

Gleichgerrcht E, Kocher M, Nesland T, Rorden C, Fridriksson J, & Bonilha L (2016). Preservation of structural brain network hubs is associated with less severe post-stroke aphasia. Restorative Neurology and Neuroscience, 34(1), 19–28. [PubMed: 26599472]

Golomb MR, MacGregor DL, Domi T, Armstrong DC, McCrindle BW, Mayank S, & DeVeber GA (2001). Presumed pre-or perinatal arterial ischemic stroke: Risk factors and outcomes. Annals of Neurology, 50(2), 163–168. [PubMed: 11506398]

Gordon EM, Laumann TO, Adeyemo B, Huckins JF, Kelley WM, & Petersen SE (2016). Generation and evaluation of a cortical area parcellation from resting-state correlations. Cerebral Cortex, 26(1), 288–303. 10.1093/cercor/bhu239 [PubMed: 25316338]

Graham SA, & Fisher SE (2013). Decoding the genetics of speech and language. Current Opinion in Neurobiology, 23(1), 43–51. [PubMed: 23228431]

Griffis JC, Metcalf NV, Corbetta M, & Shulman GL (2019). Structural Disconnections Explain Brain Network Dysfunction after Stroke. Cell Reports, 28(10), 2527–2540.e2529. 10.1016/j.celrep.2019.07.100 [PubMed: 31484066]

Groen MA, Whitehouse AJO, Badcock NA, & Bishop DVM (2012). Does cerebral lateralization develop? A study using functional transcranial Doppler ultrasound assessing lateralization for language production and visuospatial memory. Brain and Behavior, 2(3), 256–269. 10.1002/brb3.56 [PubMed: 22741100]

Grunt S, Mazenauer L, Buerki SE, Boltshauser E, Mori AC, Datta AN, Fluss J, Mercati D, Keller E, & Maier O (2015). Incidence and outcomes of symptomatic neonatal arterial ischemic stroke. Pediatrics, 135(5), e1220–e1228. [PubMed: 25896840]

Guzzetta A, Pecini C, Biagi L, Tosetti M, Brizzolara D, Chilosi A, Cipriani P, Petacchi E, & Cioni G (2008). Language organisation in left perinatal stroke. Neuropediatrics, 39(03), 157–163. [PubMed: 18991195]

Habas PA, Scott JA, Roosta A, Rajagopalan V, Kim K, Rousseau F, Barkovich AJ, Glenn OA, & Studholme C (2011). Early Folding Patterns and Asymmetries of the Normal Human Brain Detected from in Utero MRI. Cerebral Cortex, 22(1), 13–25. 10.1093/cercor/bhr053 [PubMed: 21571694]

Hartwigsen G, & Saur D (2017). Neuroimaging of stroke recovery from aphasia—Insights into plasticity of the human language network. Neuroimage. 10.1016/j.neuroimage.2017.11.056

Hartwigsen G, & Saur D (2019). Neuroimaging of stroke recovery from aphasia–Insights into plasticity of the human language network. Neuroimage, 190, 14–31. [PubMed: 29175498]

Heiss WD, Kessler J, Thiel A, Ghaemi M, & Karbe H (1999). Differential capacity of left and right hemispheric areas for compensation of poststroke aphasia. Annals of Neurology, 45(4), 430–438. [PubMed: 10211466]

Heiss WD, & Thiel A (2006). A proposed regional hierarchy in recovery of post-stroke aphasia. Brain Lang, 98(1), 118–123. 10.1016/j.bandl.2006.02.002 [PubMed: 16564566]

Hensch TK (2005). Critical period plasticity in local cortical circuits. Nature Reviews Neuroscience, 6(11), 877–888. [PubMed: 16261181]

Hofer SB, Mrsic-Flogel TD, Bonhoeffer T, & Hübener M (2006). Prior experience enhances plasticity in adult visual cortex. Nature Neuroscience, 9(1), 127–132. [PubMed: 16327785]

Höhle B, Bijeljac-Babic R, & Nazzi T (2020). Variability and stability in early language acquisition: Comparing monolingual and bilingual infants' speech perception and word recognition. Bilingualism: Language and Cognition, 23(1), 56–71.

Holland A, Fromm D, Forbes M, & MacWhinney B (2017). Long-term Recovery in Stroke Accompanied by Aphasia: A Reconsideration. Aphasiology, 31(2), 152–165. 10.1080/02687038.2016.1184221 [PubMed: 28713191]

Houston DM, Stewart J, Moberly A, Hollich G, & Miyamoto RT (2012). Word learning in deaf children with cochlear implants: Effects of early auditory experience. Developmental Science, 15(3), 448–461. [PubMed: 22490184]

Houston DM, Ying EA, Pisoni DB, & Kirk KI (2001). Development of pre-word-learning skills in infants with cochlear implants. The Volta Review, 103(4), 303–303. [PubMed: 21643556]

Hubel DH, & Wiesel TN (1964). Effects of monocular deprivation in kittens. Naunyn-Schmiedebergs Archiv Für Experimentelle Pathologie Und Pharmakologie, 248(6), 492–497. [PubMed: 14316385]

Illingworth S, & Bishop DVM (2009). Atypical cerebral lateralisation in adults with compensated developmental dyslexia demonstrated using functional transcranial Doppler ultrasound. Brain and Language, 111(1), 61–65. 10.1016/j.bandl.2009.05.002 [PubMed: 19525003]

Ilves P, Tomberg T, Kepler J, Laugesaar R, Kaldoja M-L, Kepler K, & Kolk A (2014). Different plasticity patterns of language function in children with perinatal and childhood stroke. Journal of Child Neurology, 29(6), 756–764. [PubMed: 23748202]

James SD (2008). Wild child speechless after tortured life. URL: Https://Abcnews.Go.Com/Health/Story.

Jansson-Verkasalo E, Ruusuvirta T, Huotilainen M, Alku P, Kushnerenko E, Suominen K, Rytky S, Luotonen M, Kaukola T, & Tolonen U (2010). Atypical perceptual narrowing in prematurely born infants is associated with compromised language acquisition at 2 years of age. BMC Neuroscience, 11(1), 1–7.

Johnson JS, & Newport EL (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. Cognitive Psychology, 21(1), 60–99. [PubMed: 2920538]

Kasprian G, Langs G, Brugger PC, Bittner M, Weber M, Arantes M, & Prayer D (2010). The Prenatal Origin of Hemispheric Asymmetry: An In Utero Neuroimaging Study. Cerebral Cortex, 21(5), 1076–1083. 10.1093/cercor/bhq179 [PubMed: 20851852]

Keller SS, Roberts N, García-Fiñana M, Mohammadi S, Ringelstein EB, Knecht S, & Deppe M (2010). Can the Language-dominant Hemisphere Be Predicted by Brain Anatomy? Journal of Cognitive Neuroscience, 23(8), 2013–2029. 10.1162/jocn.2010.21563 [PubMed: 20807056]

Kertesz A, & McCabe P (1977). Recovery patterns and prognosis in aphasia. Brain, 100 Pt 1, 1–18. [PubMed: 861709]

Kivilevitch Z, Achiron R, & Zalel Y (2010). Fetal brain asymmetry: In utero sonographic study of normal fetuses. American Journal of Obstetrics and Gynecology, 202(4), 359.e1–359.e8. 10.1016/j.ajog.2009.11.001

Knecht S, Floel A, Drager B, Breitenstein C, Sommer J, Henningsen H, Ringelstein EB, & Pascual-Leone A (2002). Degree of language lateralization determines susceptibility to unilateral brain lesions. Nature Neuroscience, 5(7), 695–699. 10.1038/nn868 [PubMed: 12055632]

Knecht Stefan, Deppe M, Dräger B, Bobe L, Lohmann H, Ringelstein EB, & Henningsen H (2000). Language lateralization in healthy right-handers. Brain. 10.1093/brain/123.1.74

Knecht Stefan, Dräger B, Deppe M, Bobe L, Lohmann H, Flöel A, Ringelstein E-B, & Henningsen H (2000). Handedness and hemispheric language dominance in healthy humans. Brain, 123(12), 2512–2518. [PubMed: 11099452]

Knudsen EI (1998). Capacity for plasticity in the adult owl auditory system expanded by juvenile experience. Science, 279(5356), 1531–1533. [PubMed: 9488651]

Kral A, Dorman MF, & Wilson BS (2019). Neuronal development of hearing and language: Cochlear implants and critical periods. Annual Review of Neuroscience, 42, 47–65.

Kral A, & Sharma A (2012). Developmental neuroplasticity after cochlear implantation. Trends in Neurosciences, 35(2), 111–122. [PubMed: 22104561]

Krentz UC, & Corina DP (2008). Preference for language in early infancy: The human language bias is not speech specific. Developmental Science, 11(1), 1–9. [PubMed: 18171360]

Krishnan S, Watkins KE, & Bishop DVM (2016). Neurobiological Basis of Language Learning Difficulties. Trends in Cognitive Sciences, 20(9), 701–714. 10.1016/j.tics.2016.06.012 [PubMed: 27422443]

Laugesaar R, Kolk A, Tomberg T, Metsvaht T, Lintrop M, Varendi H, & Talvik T (2007). Acutely and retrospectively diagnosed perinatal stroke: A population-based study. Stroke, 38(8), 2234–2240. [PubMed: 17585082]

Lebel C, & Beaulieu C (2009). Lateralization of the arcuate fasciculus from childhood to adulthood and its relation to cognitive abilities in children. Human Brain Mapping, 30(11), 3563–3573. 10.1002/hbm.20779 [PubMed: 19365801]

Lendrem W, & Lincoln NB (1985). Spontaneous recovery of language in patients with aphasia between 4 and 34 weeks after stroke. Journal of Neurology, Neurosurgery & Psychiatry, 48(8), 743–748. [PubMed: 2411876]

Lenneberg EH (1967). The Biological Foundations of Language. Hospital Practice, 2(12), 59–67. 10.1080/21548331.1967.11707799

Lenneberg EH (1969). On Explaining Language: The development of language in children can best be understood in the context of developmental biology. Science, 164(3880), 635–643. [PubMed: 5813477]

Leonard CM, Lombardino LJ, Walsh K, Eckert MA, Mockler JL, Rowe LA, Williams S, & DeBose CB (2002). Anatomical risk factors that distinguish dyslexia from SLI predict reading skill in normal children. Journal of Communication Disorders, 35(6), 501–531. 10.1016/S0021-9924(02)00120-X [PubMed: 12443050]

Liao X, Vasilakos AV, & He Y (2017). Small-world human brain networks: Perspectives and challenges. Neurosci Biobehav Rev, 77, 286–300. 10.1016/j.neubiorev.2017.03.018 [PubMed: 28389343]

Liégeois F, Connelly A, Baldeweg T, & Vargha-Khadem F (2008). Speaking with a single cerebral hemisphere: FMRI language organization after hemispherectomy in childhood. Brain and Language, 106(3), 195–203. [PubMed: 18329093]

Liégeois F, Connelly A, Cross JH, Boyd SG, Gadian DG, Vargha-Khadem F, & Baldeweg T (2004). Language reorganization in children with early-onset lesions of the left hemisphere: An fMRI study. Brain, 127(6), 1229–1236. [PubMed: 15069021]

Liégeois F, Cross JH, Polkey C, Harkness W, & Vargha-Khadem F (2008). Language after hemispherectomy in childhood: Contributions from memory and intelligence. Neuropsychologia, 46(13), 3101–3107. [PubMed: 18657558]

Locke JL (1997). A Theory of Neurolinguistic Development. Brain and Language, 58(2), 265–326. 10.1006/brln.1997.1791 [PubMed: 9182750]

MacSweeney M, Capek CM, Campbell R, & Woll B (2008). The signing brain: The neurobiology of sign language. Trends in Cognitive Sciences, 12(11), 432–440. [PubMed: 18805728]

Marebwa BK, Fridriksson J, Yourganov G, Feenaughty L, Rorden C, & Bonilha L (2017). Chronic post-stroke aphasia severity is determined by fragmentation of residual white matter networks. Scientific Reports, 7(1), 1–13. [PubMed: 28127051]

Maurer D, & Werker JF (2014). Perceptual narrowing during infancy: A comparison of language and faces. Developmental Psychobiology, 56(2), 154–178. [PubMed: 24519366]

Mayberry RI (1998). The critical period for language acquisition and the deaf child's language comprehension: A psycholinguistic approach. BULLETIN D AUDIOPHONOLOGIE, 14, 349–360.

Mayberry RI, Davenport T, Roth A, & Halgren E (2018). Neurolinguistic processing when the brain matures without language. Cortex, 99, 390–403. 10.1016/j.cortex.2017.12.011 [PubMed: 29406150]

Mbwana J, Berl MM, Ritzl EK, Rosenberger L, Mayo J, Weinstein S, Conry JA, Pearl PL, Shamim S, Moore EN, Sato S, Vezina LG, Theodore WH, & Gaillard WD (2008). Limitations to plasticity of language network reorganization in localization related epilepsy. Brain, 132(2), 347–356. 10.1093/brain/awn329 [PubMed: 19059978]

Mirman D, Chen Q, Zhang Y, Wang Z, Faseyitan OK, Coslett HB, & Schwartz MF (2015). Neural organization of spoken language revealed by lesion-symptom mapping. Nat Commun, 6, 6762. 10.1038/ncomms7762 [PubMed: 25879574]

Moosa ANV, Gupta A, Jehi L, Marashly A, Cosmo G, Lachhwani D, Wyllie E, Kotagal P, & Bingaman W (2013). Longitudinal seizure outcome and prognostic predictors after hemispherectomy in 170 children. Neurology, 80(3), 253–260. [PubMed: 23223541]

Mower GD (1991). The effect of dark rearing on the time course of the critical period in cat visual cortex. Developmental Brain Research, 58(2), 151–158. [PubMed: 2029762]

Muller AM, & Meyer M (2014). Language in the brain at rest: new insights from resting state data and graph theoretical analysis. Front Hum Neurosci, 8, 228. 10.3389/fnhum.2014.00228 [PubMed: 24808843]

Naeser MA, Martin PI, Theoret H, Kobayashi M, Fregni F, Nicholas M, Tormos JM, Steven MS, Baker EH, & Pascual-Leone A (2011). TMS suppression of right pars triangularis, but not pars opercularis, improves naming in aphasia. Brain Lang, 119(3), 206–213. 10.1016/j.bandl.2011.07.005 [PubMed: 21864891]

Nelson KB, & Lynch JK (2004). Stroke in newborn infants. The Lancet Neurology, 3(3), 150–158. 10.1016/S1474-4422(04)00679-9 [PubMed: 14980530]

Newbury DF, & Monaco AP (2010). Genetic advances in the study of speech and language disorders. Neuron, 68(2), 309–320. [PubMed: 20955937]

Newman AJ, Supalla T, Fernandez N, Newport EL, & Bavelier D (2015). Neural systems supporting linguistic structure, linguistic experience, and symbolic communication in sign language and gesture. Proceedings of the National Academy of Sciences, 112(37), 11684 LP–11689. 10.1073/pnas.1510527112

Newport EL (1990). Maturational constraints on language learning. Cognitive Science, 14(1), 11–28.

Newport EL, Bavelier D, & Neville HJ (2001). Critical thinking about critical periods: Perspectives on a critical period for language acquisition. Language, Brain and Cognitive Development: Essays in Honor of Jacques Mehler, 481–502.

Newport EL, Landau B, Seydell-Greenwald A, Turkeltaub PE, Chambers CE, Dromerick AW, Carpenter J, Berl MM, & Gaillard WD (2017). Revisiting Lenneberg's Hypotheses About Early Developmental Plasticity: Language Organization After Left-Hemisphere Perinatal Stroke. Biolinguistics, 11, 407–422. [PubMed: 30556058]

Newport EL, & Meier RP (1985). The acquisition of american sign language. Lawrence Erlbaum Associates, Inc.

Ocklenburg S, Beste C, Arning L, Peterburs J, & Güntürkün O (2014). The ontogenesis of language lateralization and its relation to handedness. Neuroscience & Biobehavioral Reviews, 43, 191–198. [PubMed: 24769292]

Oh JS, Au TK, & Jun SA (2010). Early childhood language memory in the speech perception of international adoptees. Journal of Child Language, 37(5), 1123–1123. [PubMed: 19951452]

Olulade OA, Seydell-Greenwald A, Chambers CE, Turkeltaub PE, Dromerick AW, Berl MM, Gaillard WD, & Newport EL (2020). The neural basis of language development: Changes in lateralization over age. Proceedings of the National Academy of Sciences, 117(38), 23477–23483.

Pallier C, Dehaene S, Poline J-B, LeBihan D, Argenti A-M, Dupoux E, & Mehler J (2003). Brain imaging of language plasticity in adopted adults: Can a second language replace the first? Cerebral Cortex, 13(2), 155–161. [PubMed: 12507946]

Palmer SB, Fais L, Golinkoff RM, & Werker JF (2012). Perceptual narrowing of linguistic sign occurs in the 1st year of life. Child Development, 83(2), 543–553. [PubMed: 22277043]

Pedersen PM, Jorgensen HS, Nakayama H, Raaschou HO, & Olsen TS (1995). Aphasia in acute stroke: Incidence, determinants, and recovery. Annals of Neurology, 38(4), 659–666. 10.1002/ana.410380416 [PubMed: 7574464]

Peña M, Pittaluga E, & Mehler J (2010). Language acquisition in premature and full-term infants. Proceedings of the National Academy of Sciences, 107(8), 3823–3828.

Petitto LA, Zatorre RJ, Gauna K, Nikelski EJ, Dostie D, & Evans AC (2000). Speech-like cerebral activity in profoundly deaf people processing signed languages: Implications for the neural basis of human language. Proceedings of the National Academy of Sciences, 97(25), 13961–13966.

Price CJ (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. Neuroimage, 62(2), 816–847. [PubMed: 22584224]

Raja Beharelle A, Dick AS, Josse G, Solodkin A, Huttenlocher PR, Levine SC, & Small SL (2010). Left hemisphere regions are critical for language in the face of early left focal brain injury. Brain, 133(6), 1707–1716. [PubMed: 20466762]

Rasmussen T, & Milner B (1977). The role of early left-brain injury in determining lateralization of cerebral speech functions. Annals of the New York Academy of Sciences, 299(1), 355–369. [PubMed: 101116]

Rosch RE, Bishop DVM, & Badcock NA (2012). Lateralised visual attention is unrelated to language lateralisation, and not influenced by task difficulty – A functional transcranial Doppler study. Neuropsychologia, 50(5), 810–815. 10.1016/j.neuropsychologia.2012.01.015 [PubMed: 22285903]

Rosenberger LR, Zeck J, Berl MM, Moore EN, Ritzl EK, Shamim S, Weinstein SL, Conry JA, Pearl PL, & Sato S (2009). Interhemispheric and intrahemispheric language reorganization in complex partial epilepsy. Neurology, 72(21), 1830–1836. [PubMed: 19470965]

Rubinov M, & Sporns O (2010). Complex network measures of brain connectivity: Uses and interpretations. NeuroImage, 52(3), 1059–1069. 10.1016/j.neuroimage.2009.10.003 [PubMed: 19819337]

Sandberg CW (2017). Hypoconnectivity of Resting-State Networks in Persons with Aphasia Compared with Healthy Age-Matched Adults. Frontiers in Human Neuroscience, 11, 91. 10.3389/fnhum.2017.00091 [PubMed: 28293185]

Saur D (2006). Dynamics of language reorganization after stroke. Brain : A Journal of Neurology, 129(6), 1371–1384. 10.1093/brain/awl090 [PubMed: 16638796]

Schevenels K, Price CJ, Zink I, De Smedt B, & Vandermosten M (2020). A review on treatment-related brain changes in aphasia. Neurobiology of Language, 1–102. 10.1162/nol_a_00019

Siegel JS, Seitzman BA, Ramsey LE, Ortega M, Gordon EM, Dosenbach NU, Petersen SE, Shulman GL, & Corbetta M (2018). Re-emergence of modular brain networks in stroke recovery. Cortex, 101, 44–59. [PubMed: 29414460]

Siegel JS, Ramsey LE, Snyder AZ, Metcalf NV, Chacko RV, Weinberger K, Baldassarre A, Hacker CD, Shulman GL, & Corbetta M (2016). Disruptions of network connectivity predict impairment in multiple behavioral domains after stroke. Proceedings of the National Academy of Sciences, 113(30), E4367–E4376.

Simmons-Mackie N, & Cherney L (2018). Aphasia in North America: Highlights of a White Paper. Archives of Physical Medicine and Rehabilitation, 99(10), e117.

Skipper-Kallal LM, Lacey EH, Xing S, & Turkeltaub PE (2017a). Right Hemisphere Remapping of Naming Functions Depends on Lesion Size and Location in Poststroke Aphasia. Neural Plast, Article ID 8740353, 1–17.

Skipper-Kallal LM, Lacey EH, Xing S, & Turkeltaub PE (2017b). Functional activation independently contributes to naming ability and relates to lesion site in post-stroke aphasia. Human Brain Mapping. 10.1002/hbm.23504

Smania N, Gandolfi M, Aglioti SM, Girardi P, Fiaschi A, & Girardi F (2010). How long is the recovery of global aphasia? Twenty-five years of follow-up in a patient with left hemisphere stroke. Neurorehabilitation and Neural Repair, 24(9), 871–875. 10.1177/1545968310368962 [PubMed: 20829410]

Sporns O (2013). Structure and function of complex brain networks. Dialogues in Clinical Neuroscience, 15(3), 247–262. [PubMed: 24174898]

Sporns O, & Betzel RF (2016). Modular Brain Networks. Annual review of psychology, 67, 613–640. 10.1146/annurev-psych-122414-033634

Staudt M, Lidzba K, Grodd W, Wildgruber D, Erb M, & Krägeloh-Mann I (2002). Right-Hemispheric Organization of Language Following Early Left-Sided Brain Lesions: Functional MRI Topography. NeuroImage, 16(4), 954–967. 10.1006/nimg.2002.1108 [PubMed: 12202083]

Stiles J, Reilly J, Paul B, & Moses P (2005). Cognitive development following early brain injury: Evidence for neural adaptation. Trends in Cognitive Sciences, 9(3), 136–143. [PubMed: 15737822]

Stiles J, Reilly JS, Levine SC, Trauner DA, & Nass R (2012). Neural plasticity and cognitive development: Insights from children with perinatal brain injury. Oxford University Press.

Stockert A, Wawrzyniak M, Klingbeil J, Wrede K, Kummerer D, Hartwigsen G, Kaller CP, Weiller C, & Saur D (2020). Dynamics of language reorganization after left temporo-parietal and frontal stroke. Brain, 143(3), 844–861. 10.1093/brain/awaa023 [PubMed: 32068789]

Sun Y-F, Lee J-S, & Kirby R (2010). Brain Imaging Findings in Dyslexia. Pediatrics & Neonatology, 51(2), 89–96. 10.1016/S1875-9572(10)60017-4 [PubMed: 20417459]

Sundara M, Polka L, & Molnar M (2008). Development of coronal stop perception: Bilingual infants keep pace with their monolingual peers. Cognition, 108(1), 232–242. [PubMed: 18281027]

Szaflarski JP, Binder JR, Possing ET, McKiernan KA, Ward BD, & Hammeke TA (2002). Language lateralization in left-handed and ambidextrous people: FMRI data. Neurology. 10.1212/WNL.59.2.238

Thiel A, Habedank B, Herholz K, Kessler J, Winhuisen L, Haupt WF, & Heiss W-D (2006). From the left to the right: How the brain compensates progressive loss of language function. Brain and Language, 98(1), 57–65. 10.1016/j.bandl.2006.01.007 [PubMed: 16519926]

Tillema JM, Byars AW, Jacola LM, Schapiro MB, Schmithorst VJ, Szaflarski JP, & Holland SK (2008). Reprint of “Cortical reorganization of language functioning following perinatal left MCA stroke” [Brain and Language 105 (2008) 99–111]. Brain and Language. 10.1016/j.bandl.2008.08.001

Trauner DA, Eshagh K, Ballantyne AO, & Bates E (2013). Early language development after peri-natal stroke. Brain and Language, 127(3), 399–403. 10.1016/j.bandl.2013.04.006 [PubMed: 23711573]

Turkeltaub PE (2015). Brain Stimulation and the Role of the Right Hemisphere in Aphasia Recovery. Curr Neurol Neurosci Rep, 15(11), 72. 10.1007/s11910-015-0593-6 [PubMed: 26396038]

Turkeltaub PE (2019). A Taxonomy of Brain-Behavior Relationships After Stroke. Journal of Speech, Language, and Hearing Research : JSLHR, 62(11), 3907–3922. 10.1044/2019_JSLHR-L-RSNP-19-0032 [PubMed: 31756155]

Turkeltaub PE, Coslett HB, Thomas AL, Faseyitan O, Benson J, Norise C, & Hamilton RH (2012). The right hemisphere is not unitary in its role in aphasia recovery. Cortex, 48(9), 1179–1186. 10.1016/j.cortex.2011.06.010 [PubMed: 21794852]

Turkeltaub PE, Messing S, Norise C, & Hamilton RH (2011). Are networks for residual language function and recovery consistent across aphasic patients? Neurology, 76(20), 1726–1734. 10.1212/WNL.0b013e31821a44c1 [PubMed: 21576689]

van den Heuvel MP, & Sporns O (2011). Rich-Club Organization of the Human Connectome. The Journal of Neuroscience, 31(44), 15775–15786. 10.1523/jneurosci.3539-11.2011 [PubMed: 22049421]

Vandenberghe R, Wang Y, Nelissen N, Vandenbulcke M, Dhollander T, Sunaert S, & Dupont P (2013). The associative-semantic network for words and pictures: effective connectivity and graph analysis. Brain Lang, 127(2), 264–272. 10.1016/j.bandl.2012.09.005 [PubMed: 23084460]

Ventureyra VAG, Pallier C, & Yoo H-Y (2004). The loss of first language phonetic perception in adopted Koreans. Journal of Neurolinguistics, 17(1), 79–91.

Wada J, & Rasmussen T (1960). Intracarotid Injection of Sodium Amytal for the Lateralization of Cerebral Speech Dominance. Journal of Neurosurgery, 17(2), 266–282. 10.3171/jns.1960.17.2.0266

Wang LE, Tittgemeyer M, Imperati D, Diekhoff S, Ameli M, Fink GR, & Grefkes C (2012). Degeneration of corpus callosum and recovery of motor function after stroke: A multimodal magnetic resonance imaging study. Human Brain Mapping. 10.1002/hbm.21417

Wang Z, Dai Z, Gong G, Zhou C, & He Y (2015). Understanding structural-functional relationships in the human brain: a large-scale network perspective. The Neuroscientist : a review journal bringing neurobiology, neurology and psychiatry, 21(3), 290–305. 10.1177/1073858414537560 [PubMed: 24962094]

Warren JE, Crinion JT, Lambon Ralph MA, & Wise RJS (2009). Anterior temporal lobe connectivity correlates with functional outcome after aphasic stroke. Brain, 132(12), 3428–3442. 10.1093/brain/awp270 [PubMed: 19903736]

Werker JF, & Hensch TK (2015). Critical periods in speech perception: New directions. Annual Review of Psychology, 66, 173–196.

Werker JF, & Tees RC (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. Infant Behavior and Development, 7(1), 49–63.

Werker JF, & Tees RC (2005). Speech perception as a window for understanding plasticity and commitment in language systems of the brain. Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology, 46(3), 233–251.

Whitehouse AJO, & Bishop DVM (2008). Cerebral dominance for language function in adults with specific language impairment or autism. Brain, 131(12), 3193–3200. 10.1093/brain/awn266 [PubMed: 18953053]

Whitehouse AJO, & Bishop DVM (2009). Hemispheric division of function is the result of independent probabilistic biases. Neuropsychologia, 47(8), 1938–1943. 10.1016/j.neuropsychologia.2009.03.005 [PubMed: 19428426]

Wiesel TN, & Hubel DH (1965). Extent of recovery from the effects of visual deprivation in kittens. Journal of Neurophysiology, 28(6), 1060–1072. [PubMed: 5883732]

Williams TS, McDonald KP, Roberts SD, Dlamini N, deVeber G, & Westmacott R (2017). Prevalence and Predictors of Learning and Psychological Diagnoses Following Pediatric Arterial Ischemic Stroke. Developmental Neuropsychology, 42(5), 309–322. 10.1080/87565641.2017.1353093 [PubMed: 28805445]

Wilson SM, & Schneck SM (2021). Neuroplasticity in post-stroke aphasia: A systematic review and meta-analysis of functional imaging studies of reorganization of language processing. Neurobiol Lang (Camb), 2(1), 22–82. 10.1162/nol_a_00025 [PubMed: 33884373]

Xu Y, Gandour J, Talavage T, Wong D, Dzemidzic M, Tong Y, Li X, & Lowe M (2006). Activation of the left planum temporale in pitch processing is shaped by language experience. Human Brain Mapping, 27(2), 173–183. 10.1002/hbm.20176 [PubMed: 16035045]

Zhang Z, Liu S, Lin X, Teng G, Yu T, Fang F, & Zang F (2011). Development of fetal brain of 20 weeks gestational age: Assessment with post-mortem Magnetic Resonance Imaging. European Journal of Radiology, 80(3), e432–e439. 10.1016/j.ejrad.2010.11.024 [PubMed: 21146341]

Yeo BTT, Krienen FM, Sepulcre J, Sabuncu MR, Lashkari D, Hollinshead M, Roffman JL, Smoller JW, Zöllei L, Polimeni JR, Fischl B, Liu H, & Buckner RL (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. Journal of neurophysiology, 106(3), 1125–1165. 10.1152/jn.00338.2011 [PubMed: 21653723]

Zhao Y, Song L, Ding J, Lin N, Wang Q, Du X, Sun R, & Han Z (2017). Left Anterior Temporal Lobe and Bilateral Anterior Cingulate Cortex Are Semantic Hub Regions: Evidence from Behavior-Nodal Degree Mapping in Brain-Damaged Patients. J Neurosci, 37(1), 141–151. 10.1523/jneurosci.1946-16.2016 [PubMed: 28053037]