Afropolitan Journals

This open-access article is distributed under Creative Commons Attribution 4.0 license

ISSN: 3027-2882 www.afropolitanjournals.com

# Rewiring the Brain: A Critical Review of Neuroplasticity in Language Development and Recovery from Language Disorders

**Mercy Omolola, Olukoya [1]; Daniel Nwokwu [2]; Sadare Joy Deborah [3]; Akindele Olalekan Abdulqayyum [4]; Haris Muhammad [5]; and Adegbite O. Tobalase [6]**

*[1]Department of Biochemistry, Adeleke University, Ede. [2]Department of Linguistics and African Languages, University of Ibadan, Nigeria. [3]Abiola Ajimobi Technical University, Natural and Applied Science, Microbiology and Biotechnology, Nigeria. [4]Department of Linguistics, University of Florida, USA. [5]Department of Physiotherapy, Allied Health Sciences, Federal University of Health Sciences Azare, Bauchi, Nigeria. [6]Department of Languages and Literary Studies, Adeleke University Ede, Nigeria.*

*Corresponding author: danielnwokwu28@gmail.com*

***DOI***: *https://doi.org/10.62154/ajastr.2025.023.01026*

## Abstract

Language is one of the most experience-dependent human abilities, but 'neuroplasticity' is often used as a slogan or assumed to be a mechanism. Research in the developmental, bilingual, clinical and neuromodulation fields has developed in parallel, with few syntheses that critically address methodology. This critical review asks which neural principles link plasticity to language and how reliably they can be measured, what the evidence shows for language growth and disorder recovery, and how strong the evidence is for interventions that harness plasticity. Studies were identified through keyword searches prioritising meta-analyses, randomised trials and longitudinal studies, and appraised for sample size, design, controls, measurement reliability and replication. The dual-stream model that has superseded the classical Broca-Wernicke model, and network-based accounts emphasising flexible redistribution across language-selective and domain-general areas offer the best theoretical basis, though neuroimaging inference is limited by small samples, poor reliability and reverse inference. In language growth, conversational experience is related to left inferior frontal activity in children; grammatical learning declines gradually after late adolescence; bilingualism is associated to structural changes while the behavioural bilingual advantage is less robust; and ageing involves maintenance, reserve and compensation. Post-stroke aphasia shows most recovery in the first year; evidence of plasticity in dyslexia, developmental language disorder and primary progressive aphasia remains limited. Intensive speech-language therapy has the strongest support; transcranial stimulation shows low-certainty effects; and speech neuroprostheses involve few participants with paralysis rather than aphasia. The review recommends preregistered, longitudinal trials, individualised functional mapping, and early, intensive rehabilitation and language-rich environments.

**Keywords:** Critical Review, Language Development, Aphasia Recovery, Bilingualism, Neuromodulation, Speech-Language Therapy.

## Introduction

### Language as an Experience-Dependent System

Language is a signature human ability, and the neural processes involved in language have been one of the most intensely studied problems in cognitive neuroscience. The network of frontal and temporal regions is selectively activated by language inputs and can be dissociated from a network involved in general reasoning even in healthy subjects (Fedorenko et al., 2024). Selectivity is not rigid, however; the network can be modified by experiences from the past, modified by acquiring new language, modified in response to being older, and modified in response to injury. Knowing this is at the heart of theories about language and is at the core of rehabilitation.

Typically, this is attributed to the concept of neuroplasticity, or the ability of the nervous system to adapt to experience, injury or intervention (Kiran & Thompson, 2019). It is hypothesized to play a role in partial recovery that most post-stroke aphasics experience (mostly within the first year of stroke; Wilson et al., 2023), in age-related compensation in cognition generally (Cabeza et al., 2018), and in second language learning (Pliatsikas, 2020). Although common, the use of the term "rewiring" can be misleading because plasticity is often not directly assessed in humans, but rather its presence is often surmised based on noisy changes in activation, connectivity or behaviour. The purpose of this review is to synthesize the varied developmental, bilingual, clinical and neuromodulation literature and to make a clear and critical appraisal of it.

### Statement of the Problem

Neuroplasticity is a term used in language studies, with conflicting findings. The studies on developmental, bilingual, clinical, and neuromodulation approaches have mostly been conducted separately, with different samples, vocabulary, and outcome measures, and with no reviews to compare them with methodological considerations. Although there are studies that focus on reorganisation in perilesional, contralesional, and domain-general regions (Hartwigsen & Saur, 2019; Kiran & Thompson, 2019), this reorganisation is not specifically linked to language network reorganisation in typical development and adulthood. On the other hand, the early input/bilingualism literature (Pliatsikas, 2020; Romeo et al., 2018) rarely addresses clinical recovery.

A second problem is critical. Often, plasticity is treated as an explanation, but it is actually assumed from poorly reliable and noisy measures (Elliott et al., 2020). Unresolved questions such as whether compensation or maladaptation occurs when the right hemisphere is recruited, the operation of the sensitive periods, and whether a bilingual advantage exists are rarely appraised together. Finally, intervention evidence, ranging from behavioural interventions to brain stimulation and speech neuroprostheses, is seldom assessed against the claims of mechanism upon which it is justified.

There are some integrative reviews. Kiran and Thompson (2019) reviewed the plasticity of language networks in post-stroke aphasia, and Aghaz et al. (2018) systematically reviewed the types of neuroplasticity and factors affecting language recovery in adults with acquired

aphasia. Both are limited to aphasia and do not relate recovery to typical development or bilingualism. Birdsong (2018) reviewed plasticity, variability and age in second language acquisition and bilingualism, but this work centres on language learning and does not cover clinical recovery or interventions in any depth. None of these appraises the evidence across development, bilingualism, disorder recovery and interventions against common methodological criteria. To our knowledge, few syntheses combine language growth and recovery with a critical appraisal of methodological quality across these strands.

Unless attention is paid to this issue, research will continue to rely on claims of plasticity that are impossible to test, and results from one stream of research will not inform the work in another. Rehabilitation, therapies, stimulation protocols and devices can be adopted based on evidence that does not yet support the mechanism, and resources can be used for approaches that have not been shown to result in meaningful and lasting language gains.

**Aim, Objectives and Research Questions**

This review should critically evaluate the evidence related to neuroplasticity in language development and recovery from language disorders and assess the extent to which the concept of 'rewiring' is supported.

The objectives are to:

1. describe the neural architecture of language and the mechanisms by which it is thought to change;
2. examine how reliably plasticity can be measured in humans;
3. appraise the evidence for plasticity in language growth (early development, bilingualism, adult learning and ageing) and in recovery from developmental and acquired language disorders;
4. evaluate the evidence for interventions that aim to harness plasticity; and
5. identify areas of agreement, disagreement, and methodological limitations that limit inferences.

The review is guided by four questions. First, what are the neural mechanisms that underlie language plasticity? Second, are these mechanisms measurable in human beings? Third, what is the evidence for plasticity in language growth and in recovery from developmental and acquired language disorders? Fourth, is there sufficient evidence of meaningful and lasting language gains following interventions that take advantage of plasticity?

**Contribution to Knowledge**

This review contributes to knowledge in four ways. First, it integrates development, bilingualism, ageing and disorder recovery into a unified system and demonstrates that flexible redistribution of activity within language-selective and domain-general networks and experience dependence of windows to interventions occur, but they are not mutually exclusive and may be present in various combinations depending on the starting conditions. Second, explicit appraisal criteria (e.g., sample size, design, controls, measurement reliability, and replication) are used for each strand. This helps identify well-supported

claims, including that aphasia recovery tends to be concentrated in the first year, from weakly supported claims like a general bilingual executive advantage or the relevance of speech neuroprostheses to aphasia.

## Gap in Literature

The concept of neuroplasticity is often used in language studies, but the studies are conflicting. Most studies on developmental, bilingual, clinical, and neuromodulation approaches have been conducted independently of each other, with their own samples, outcome measures, and vocabulary, and there is a lack of reviews that compare them using common methodological criteria. Studies on aphasia recovery focus on reorganisation in perilesional, contralesional, and domain-general regions (Hartwigsen & Saur, 2019; Kiran & Thompson, 2019), but do not generally relate this to the language network reorganisation in typical development and adulthood. Conversely, work on early input and bilingualism (Pliatsikas, 2020; Romeo et al., 2018) seldom engages with clinical recovery. A second gap is critical. Often, plasticity is treated as an explanation, but it is actually assumed from poorly reliable and noisy measures (Elliott et al., 2020). Unresolved questions such as whether compensation or maladaptation occurs when the right hemisphere is recruited, the operation of the sensitive periods, and whether a bilingual advantage exists are rarely appraised together. Finally, intervention evidence, ranging from behavioural interventions to brain stimulation and speech neuroprostheses, is seldom assessed against the claims of mechanism upon which it is justified. Few syntheses combine language growth/recovery with a critical appraisal of methodological quality across these strands.

### Review Questions and Approach

This review is guided by three questions. First, what neural mechanisms are involved in language, and can these mechanisms be measured reliably in humans? Second, what does current evidence reveal about plasticity in language growth (early development, bilingualism, and adult learning) and in recovery from developmental and acquired language disorders? Third, is there sufficient evidence of meaningful and lasting language gains following interventions that take advantage of plasticity? In addition to these questions, the review aims to determine where there is consensus, where there is disagreement, and which methodological limitations most constrain the inferences.

To address these questions, the literature was retrieved through searches that combined the following terms: neuroplasticity, language development, bilingualism, aphasia, developmental language disorder, primary progressive aphasia, brain stimulation, and brain-computer interfaces. Meta-analyses, systematic reviews, randomised controlled trials and large or longitudinal empirical studies were given priority as these designs offer the most reliable foundation for the inference of change over time. The review does not delve deeply into traumatic brain injury, pharmacological interventions, or virtual-reality approaches.

Five criteria—sample size and statistical power, study design, adequacy of experimental controls, reliability of outcome measures, and evidence of replication—were used to evaluate each study. By consistently applying these criteria to the implementation of developmental, bilingual, clinical and interventional research claims, it becomes possible to separate claims based on converging, well-powered evidence from claims based on small correlational or unreplicated evidence.

The rest of the paper is based on the same principles. The architecture of the language network, the ways in which it can change, and the limits of the inferences available to the methods of study are laid out in Section 2. Section 3 examines plasticity in typical language growth, and Section 4 addresses developmental and acquired language disorders and the predictors of recovery. Section 5 evaluates interventions that aim to harness plasticity, and Section 6 integrates these strands and sets out directions for research and practice.

**Contributions to Knowledge**

This review contributes to knowledge in four ways. First, it integrates development, bilingualism, ageing and disorder recovery into a unified system and demonstrates that flexible redistribution of activity within language-selective and domain-general networks and experience dependence of windows to interventions occur, but they are not mutually exclusive and may be present in various combinations depending on the starting conditions. Second, it uses explicit appraisal criteria—sample size, design, controls, measurement reliability, and replication—for each strand. This helps identify well-supported claims, including that aphasia recovery tends to be concentrated in the first year, from weakly supported claims like a general bilingual executive advantage or the relevance of speech neuroprostheses to aphasia. Third, it clarifies unresolved debates by identifying the evidence on which to base the decision on, such as the unsettled bilingualism issue of whether or not children experience a sensitive period, or whether perturbation designs can resolve the issue of whether there is an optimal window for learning a second language. Fourth, it "moves these appraisals into practice: timely and sufficient intensity of therapy; careful use of stimulation and neuroprostheses; individualised functional mapping and multimodal prediction; and larger preregistered trials with wider eligibility. These contributions together bring the notion of "rewiring" from metaphor to testable, clinically relevant hypotheses.

**Theoretical and Conceptual Framework**

This review is based on two theoretical accounts of the organisation of the language network and change in it, and on one contested idea that is not assumed but rather proposed as a hypothesis. Table 1 associates each of these with the review questions and the appraisal criteria used to test them.

The dual-stream model is a description of the architecture that influences what can change. A ventral stream supports sound-to-meaning mapping and a dorsal stream supports sound-to-articulatory representation and these are dissociable in speech processing following

stroke (Fridriksson et al., 2016; Hickok 2022). The flexible-redistribution account is a model of how change occurs: processing may be shifted to surviving language regions, shifted to right hemisphere homologues, and/or shifted to domain-general control networks (Hartwigsen, 2018). This is the principal account of reorganisation in language growth and in the recovery from language disorder.

**The Conceptual Model**

Figure 1 collates these accounts. Triggers of change (language input, second-language learning, adult training and ageing, brain injury, and intervention) act on the language network. The network reorganizes at the structural, functional and behavioural levels, and the phenomena observed at each level are understood within the limits of the inference, discussed in Section 4.2: reverse inference, poor test-retest reliability, small samples, correlational designs and short follow up. The appraisal criteria will be the mechanism for addressing these restrictions. Sample size deals with small samples, design deals with correlation versus causation, controls deal with spontaneous recovery as a confound, and measurement reliability deals with test-retest problems, and replication deals with unstable findings.

**Linking the Framework to the Review Questions**

The framework is applied in the same order throughout. Section 4 uses the dual-stream and flexible-redistribution accounts to answer the first two questions (mechanisms and measurability). In Section 5 and 6, the third question is examined with reference to language growth and disorder recovery. Section 7 assesses 4 on evidence on interventions. For each strand, the studies are rated on the five criteria, and the ratings are reflected in the evidence labels provided in the synthesis.

**Neural and Mechanistic Foundations of Language Plasticity**

**The Language Network Architecture and Mechanisms of Plasticity**

Modern theories of speech and language processing have been framed in the context of partially separate processing streams. The dual-stream model proposes that a ventral stream maps sound to meaning and a dorsal stream maps sound to articulatory representations, with both streams held together by white matter tracts along the perisylvian cortex (Hickok, 2022). Evidence for the separability of these routes comes from studies of stroke, which have shown, in chronic stroke patients, that dorsal and ventral pathways contribute dissociably to speech processing (Fridriksson et al., 2016). Poeppel and Assaneo (2020) also note that the coincidence of rhythmic neural activity with speech timing links perception and production.

The classic Broca-Wernicke model, which assumes that language is produced in the anterior part of the brain and understood in the posterior part, is now accepted as being too simplistic. It cannot support a distributed, network-based organisation that modern imaging and lesion studies have revealed, and Fedorenko and Blank (2020) demonstrate

that there are subregions within Broca's area that respond to many demanding tasks and language-selective regions within the same area. Beyond the word level, Hagoort (2019) suggests that sentence and discourse comprehension rely on memory, unification, and control processes.

This architecture is important for plasticity because it determines what changes. Language reorganisation can take place at multiple locations and via multiple pathways, such as strengthening of remaining language regions, recruitment of homologous regions in the opposite hemisphere, and activation of domain-general control networks (Fedorenko et al., 2024; Hartwigsen, 2018).

Plasticity at the cellular level is typically linked to strengthening and weakening of synapses as a result of activity and to structural remodelling of connections. In human language studies, these mechanisms are inferred, not observed, and therefore studies necessarily operate at the level of systems: changes in regional activation, functional connectivity, grey matter, and white matter. Kiran and Thompson (2019) note that change in aphasia involves both perilesional and contralesional regions.

**Measuring Plasticity and Its Limits: A Critical Appraisal**

Plasticity is studied with structural and diffusion imaging, functional imaging, electrophysiology, and non-invasive stimulation, each capturing a different aspect of change with characteristic limitations. Meta-analysis is an effective antidote to the power problem of the individual study: Stefaniak et al. (2021) combined functional imaging data across 481 patients with post-stroke aphasia and 530 healthy controls—which is far greater than any single study.

Three problems limit what neuroimaging can currently say about plasticity. The first is reverse inference: activation in a region does not indicate which process is engaged, especially if there are functionally heterogeneous subregions within the region (e.g., Broca's area; Fedorenko & Blank, 2020; Tremblay & Dick, 2016). The second is reliability. Elliott et al. (2020) reported that many widely used task-based functional MRI measures lack test-retest reliability, which is problematic for plasticity studies because change is computed as the difference between two noisy measurements.

The third problem is sample size. Many influential studies are based on a few dozen participants, as in the study by Romeo et al. (2018), which used 36 children. However, lesion-based work presents a partial remedy: Thye and Mirman (2018) demonstrated that lesion location and lesion size make distinctly different contributions to predictions of varied language deficits. As with all small samples, estimates are unstable, and correlational neuroimaging alone is unable to demonstrate that neural change produces behavioural change, a problem which is encountered throughout this review.

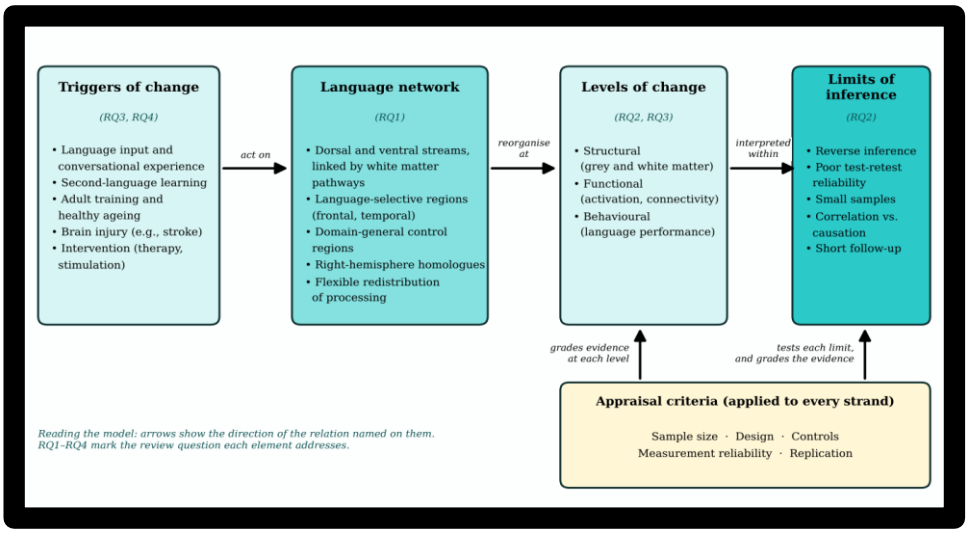



**Figure 1:** The Conceptual Model of Language Plasticity

This is an original figure, based on the dual-stream model (Hickok, 2022), flexible redistribution (Hartwigsen, 2018) and the measurement limits described by Elliott et al. (2020) and Fedorenko and Blank (2020).

## Neuroplasticity in Language Growth

### Early Development, Sensitive Periods and the Critical-Periods Debate

The most direct evidence from humans is found in research correlating naturalistic input with brain function. Romeo et al. (2018) analysed home audio recordings from 36 socioeconomically diverse children aged 4 to 6 years. Left inferior frontal activation during story listening, independent of socioeconomic status, IQ, and total amount of adult speech, statistically explained the correlation between conversational exposure and verbal skill, with children who engaged in more conversational turns with adults showing greater activation in this area. Bergelson et al. (2019), analysing a large collection of home recordings, documented considerable variability in infants' speech environments.

Newport (2020) summarises evidence indicating that children and adults learn the structure of language in systematically different ways, which is consistent with maturational change in learning mechanisms. The capacity to learn grammar, however, has been shown to persist through late adolescence and to decline only after that point, according to a large online sample of English speakers studied by Hartshorne et al. (2018).

The concept of a critical period itself is hard to reconcile with evidence of gradual change. The findings of Hartshorne et al. (2018) suggest that the learning of grammar does not close abruptly but rather declines gradually and that the online, self-selected data set cannot rule out the influence of motivation, education, or task familiarity. The possibility of a biological "closure" of a language window is also an inferential claim, since human neuroimaging cannot identify the molecular mechanisms that are hypothesised to open and close

sensitive periods in animals. The results of Romeo et al. (2018) are also correlative and do not distinguish between input and genetic/family-level effects.

**Bilingualism, Adult Learning and Healthy Ageing**

Pliatsikas (2020) put forward the Dynamic Restructuring Model, in which the structure of the bilingual brain adapts to prolonged exposure, from early gains in grey matter in the cortex to later gains or reorganisation of subcortical and white matter structures. Grundy et al. (2017) suggest that bilingual experience is linked to neural engagement patterns that differ from those of unimodal experience, even if performance is comparable, and Bialystok (2017) views bilingualism as an experience to which minds adapt, with effects of bilingual experience depending on the demands of the language experience.

Plasticity continues throughout adulthood but is manifested in different ways at different ages. Cabeza et al. (2018) review studies that show that older adults compensate for reduced neural resources, use cognitive reserve, and preserve performance through compensatory recruitment, and they stress the need for longitudinal studies to test these possibilities. Lövdén et al. (2020) reviewed evidence on education and cognitive functioning across the lifespan and concluded that education is more clearly linked to higher levels of cognitive performance than to slower rates of decline.

Second, there is some controversy regarding the bilingual advantage in executive function. In a meta-analytical review of studies conducted in adults, Lehtonen et al. (2018) concluded that most of the small and inconsistent benefits were largely affected by publication bias and confounding. In a population sample of approximately 11,000 participants, Nichols et al. (2020) found no general executive-function benefits, and Antoniou (2019) suggests that the question is now when, not whether, bilingual experience affects cognition.

Much of this evidence is also cross-sectional (bilingual-monolingual or older-younger adults), and such studies combine factors like age of acquisition, proficiency, immersion, and self-selection.

**Neuroplasticity in Language Disorder Recovery**

**Post-Stroke Aphasia, Developmental and Neurodegenerative Language Disorders**

Post-stroke aphasia has been the most extensively studied model of language recovery. Wilson et al. (2023) recruited 334 patients with acute left-hemisphere stroke and assessed 218 of these patients as aphasic within days of stroke using the Quick Aphasia Battery and followed them at 1 month, 3 months, and 1 year. The greatest improvement was in the first year, and the authors found no support for the traditional aphasia subtypes or for binary concepts like fluency, and they arrived at the conclusion that aphasia is dynamic, multidimensional and graded, with traditional aphasia types and binary terms like fluency having little explanatory power.

There are conflicting views about which patterns of reorganisation are conducive to recovery. Classical descriptions focus on recruitment of areas that have not been used before for language, either via quiescent homologues in the other hemisphere or by

invasion of the non-language cortex. The most recent accounts suggest that recovery is based on underused parts of the normal language network that would typically be suppressed in order to conserve resources, known as variable neurodisplacement; the pooled analysis of Stefaniak et al. (2021) was intended to resolve this issue. Both Hartwigsen and Saur (2019) and Kiran and Thompson (2019) highlight how the contribution of ipsilesional, contralesional and domain-general regions may be different across time since stroke, lesion characteristics and task type, respectively, as well as for treatment-induced change.

The concept of plasticity also plays a key role in the disorders that occur in development or degeneration. Ozernov-Palchik and Gaab (2016) reviewed behavioural and neural markers that can be identified prior to formal reading instruction, lending support to the notion that dyslexia are a consequence of abnormal brain function rather than the cause. Studies by Perrachione et al. (2016) suggest that dyslexics have impaired neural adaptation to repeated speech and other stimuli, suggesting a more general problem in the use of recent experience to modulate perceptual processing.

Developmental language disorder (DLD) refers to persistent language problems, for which there is no biomedical explanation. An international consensus established new terminology (Bishop et al., 2017), and population-based studies give indications of a prevalence of 7% to 10% at school entry (Norbury et al., 2016). In PPA (primary progressive aphasia), Tsapkini et al. (2018) examined whether the effects of transcranial direct current stimulation (DCS) could be enhanced by combining it with language therapy in a randomised trial, an approach that attempts to capitalise on the remaining plasticity in PPA.

**Contexts of Language Plasticity: Mechanisms, Evidence, and Limits**

**Table 1: summarises the mechanisms, evidence, and limitations across the contexts reviewed.**

| Context | Key mechanism | Main evidence | Main limitation |
|---|---|---|---|
| Early development | Input-driven network tuning | Conversation linked to frontal activity | Correlational, small samples |
| Bilingualism | Time-dependent structural adaptation | Brain differences, weak behavioural advantage | Cross-sectional comparisons |
| Adult learning and ageing | Maintenance, reserve, compensation | Performance preserved through added recruitment | Few longitudinal designs |
| Post-stroke aphasia | Flexible redistribution across the network | Most gains in first year; lesion-driven | Heterogeneity; spontaneous recovery |
| Developmental and degenerative disorders | Atypical or declining plasticity | Early markers; adaptation deficits; stimulation trials | Small samples; limited evidence |

**Predictors of Recovery and Critical Appraisal of the Evidence**

Planning for recovery and interpreting trials depends on recovery predictions. Wilson et al. (2023) was able to determine that location and extent of stroke lesions were important factors in determining outcome after stroke, and Thye and Mirman (2018) demonstrated that lesion location and size accounted for distinct deficits. In the study by Kristinsson et al. (2021), machine learning was applied to a combination of imaging, demographic, and behavioural data to predict language outcomes in individuals with chronic aphasia. Intensity of therapy is a variable that may be modified: Breitenstein et al. (2017) compared at least 3 weeks of intensive therapy (10 or more hours per week) to deferred treatment in chronic aphasia, finding that verbal communication in everyday life situations was improved.

The big issue that remains is whether right hemisphere recruitment is compensatory or maladaptive. In some studies, activation of the right hemisphere is correlated with recovery, and in other studies, with worse outcomes, and correlation does not necessarily imply that the activation helps or harms performance (Stefaniak et al., 2021; Hartwigsen & Saur, 2019). Right-hemisphere therapies are based on the premise that it is maladaptive. There is a need for careful behavioural and lesion stratification of perturbation designs to address the question.

Confounding and heterogeneity exacerbate the issue. Studies tend to combine patients into small groups because of differences in lesion size and location, time since stroke, and treatment history, but spontaneous recovery, which is greatest early after stroke (Wilson et al., 2023), can be confused with treatment effects if proper controls are not used. Generalisability is also constrained by eligibility – Breitenstein et al. (2017) limited the age range of people to minimise the contribution of age-related neurodegenerative processes, enhancing internal validity but excluding many older adults.

**Interventions That Harness Plasticity**

**Behavioural Therapies: Dosage, Timing, and Evidence**

Behavioural speech and language therapy is the most researched therapy. Brady et al. (2016) completed a Cochrane Review which found that speech and language therapy (SALT) is beneficial for individuals with aphasia following stroke and that greater intensity, dosage, and duration of therapy improve outcomes, although higher intensity may not be tolerated by all individuals. Breitenstein et al. (2017) tested intensity in a rigorous design with routine clinical conditions for chronic aphasia across 19 rehabilitation centres using a randomised, blinded-endpoint design.

Most spontaneous recovery happens in the early phase (Wilson et al., 2023), so the timing of intervention is an important factor, but trials tend to include chronic phase patients, which means little can be concluded about early intervention.

**Neuromodulation, Speech Neuroprostheses and Critical Appraisal**

The goal of non-invasive brain stimulation is to modulate cortical excitability during or before therapy to improve plasticity. Elsner et al. (2019) conducted a Cochrane review of transcranial direct current stimulation for aphasia following stroke, which noted the small samples and heterogeneous protocols. The field needs sham-controlled designs, such as that used by Fridriksson et al. (2018) to test stimulation as an adjunct to computerised speech therapy. Fisicaro et al. (2019) also raised concerns about the use of different stimulation parameters and patient selection.

Speech neuroprostheses are designed to work around the damaged output pathways by transforming neural activity into text or synthetic speech. Moses et al. (2021) have reported decoding of attempted speech in a person with anarthria following a brainstem stroke, and Willett et al. (2023) report large-vocabulary decoding of speech-to-text using intracortical arrays. In less than 2 weeks of decoder training, Metzger et al. (2023) reached a median rate of 78 words per minute and a median word error rate of 25% for speech audio synthesis and control of a facial avatar.

The certainty of evidence is low for brain stimulation; protocols vary greatly with respect to montage, dose, and timing, and the interhemispheric-inhibition rationale in many protocols depends on the unresolved question of whether right-hemisphere activity is maladaptive (Elsner et al., 2019; Fisicaro et al., 2019). Follow-up is often limited or not performed, and the durability is unknown.

Neuroprostheses studies conducted so far have one or very few individuals who are paralysed or anarthric but not aphasic (Metzger et al., 2023; Moses et al., 2021; Willett et al., 2023). These devices are used to restore motor output; they have not been shown to repair the language representations that are impaired in aphasia, so their usefulness to most people with aphasia is not certain.

**Interventions That Harness Plasticity: Aims, Evidence, and Implications**

**Table 2: compares the intervention approaches discussed in Section 5 in terms of aims, evidence strength, limitations, and clinical implications.**

| Approach | Aim | Evidence strength | Main limitation | Implication |
|---|---|---|---|---|
| Intensive speech-language therapy | Strengthen language through dose | Strongest | Tolerability; chronic-phase trial | Offer at adequate intensity |
| tDCS | Boost excitability during therapy | Low certainty | Small samples; varied protocols | Adjunct only |
| rTMS | Rebalance hemispheric activity. | Emerging, inconsistent | Parameter variation; unresolved rationale | Use cautiously |

| Approach | Aim | Evidence strength | Main limitation | Implication |
|---|---|---|---|---|
| Speech neuroprostheses | Bypass damaged motor output | Proof of concept | Few participants; not aphasia | Promising, not yet clinical |
| Individualised rehabilitation | Match treatment to patient profile | Early | Needs validation | Priority for future trials |

## Critical Synthesis, Future Directions, and Conclusion

### Integrating Development and Recovery: Convergence, Divergence, and Gaps

Several mechanisms recur. Language networks are experience-dependent: interactive conversation (Romeo et al., 2018), sustained bilingual use (Pliatsikas, 2020), and intensive therapy (Breitenstein et al., 2017) all involve structured, repeated experiences that lead to neural and behavioural change. Growth and recovery seem to rely on flexible modulation between language-selective and domain-general components (Cabeza et al., 2018; Hartwigsen, 2018; Stefaniak et al., 2021). In both, time is the critical factor, either as the window that influences learning (Hartshorne et al., 2018; Newport, 2020) or as the initial time post-stroke when there is the most recovery (Wilson et al., 2023).

The contexts are also different: development creates a system that is at an early stage, while recovery reconfigures a damaged system. The most important theoretical deficit is that "plasticity" is a catch-all term for any observed change, and, if not for the mechanism, interval, and behavioural consequence, it is hard to falsify. Methodologically, the same weaknesses are repeated: small and heterogeneous samples, cross-sectional designs, unreliable imaging measures (Elliott et al., 2020), reverse inference, publication bias and brief follow-up.

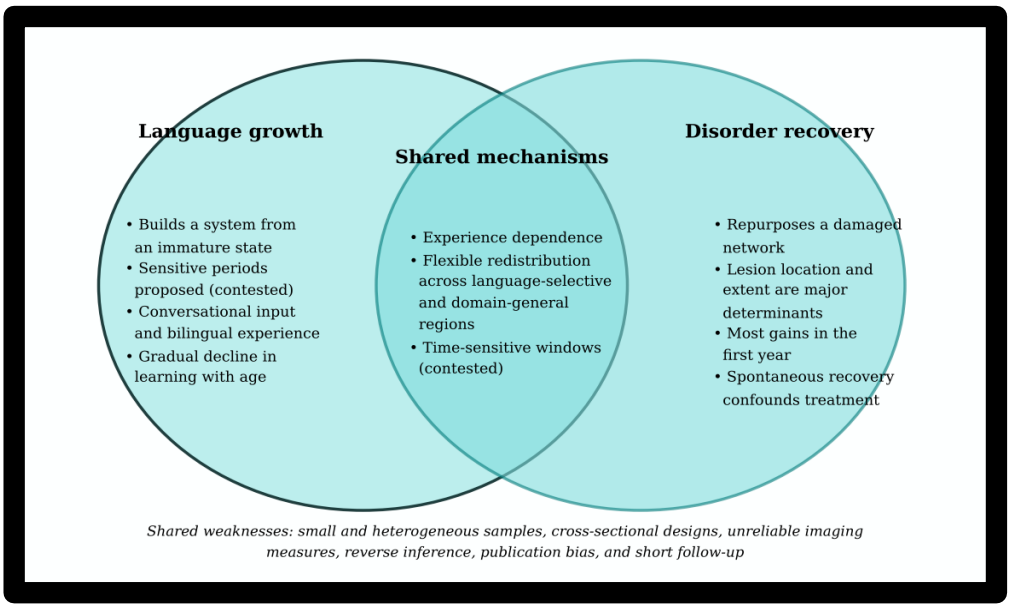



**Figure 2:** Convergence and Divergence Between Language Growth and Disorder Recovery

Original figure synthesised by the authors from the evidence reviewed in Sections 5 and 6, drawing on Hartshorne et al. (2018), Newport (2020), Romeo et al. (2018), Hartwigsen (2018) and Wilson et al. (2023). Sensitive-period items are shown as contested (see Section 5.1).

## Future Directions, Implications, and Conclusion

Larger, preregistered, longitudinal studies measuring neural, behavioural, and functional outcomes behaviour simultaneously at multiple time points will be necessary to make progress. To minimise reverse inference, the language network can be localised individually based on the functional properties of each region for each person (Fedorenko et al., 2024). Multimodal predictive models (Kristinsson et al., 2021) along with stratification by lesion characteristics (Thye & Mirman, 2018) may aid in personalised rehabilitation by determining who may be likely to benefit from which intervention and when. There also needs to be a wider range of participants in trials, including older people and those who speak multiple languages.

In clinical practice, the evidence indicates that speech and language therapy (SALT) should be delivered at an adequate intensity (Brady et al., 2016; Breitenstein et al., 2017), whereas brain stimulation and neuroprostheses are promising but not yet proven. Findings from conversational exposure (Romeo et al., 2018) studies in the education field support interactive, early language experience, although these findings are correlational. Recovery in the first year (Wilson et al., 2023) suggests the need for policies that ensure timely access to rehabilitation.

Neuroplasticity is a real and important property of the language system, but "rewiring the brain" runs ahead of the evidence. Language networks are formed by experience, and recovery from aphasia is significant but uneven, dynamic and only partially predictable. The issue of sensitive periods, the bilingual advantage and the role of the right hemisphere remain unsettled, partly because of small samples, correlational designs, lack of reliable measures and limited follow-up. Some interventions that harness plasticity hold promise, but the evidence varies considerably, and the most remarkable technologies focus on motor output rather than language deficits. The most plausible way to achieve consistent improvements for individuals with language disorders is through a more intense, mechanistically articulated, and personalised research programme.

**Acknowledgements**

The authors sincerely thank all collaborating scholars and colleagues who contributed to the authorship and editing of this review paper. There was no external funding or organisation involved in this work; it was only the intellectual and academic endeavours of the author team.

**Declaration of Competing Interests**

The authors assert that there are no financial or personal relationships that might have influenced or appeared to influence the findings reported in this paper.

## References


Aghaz, A., Hemmati, E., & Ghasisin, L. (2018). Types of neuroplasticity and factors affecting language recovery in patients with aphasia: A systematic review. Archives of Neuroscience, 5(3), Article e62265. https://doi.org/10.5812/ans.622

Antoniou, M. (2019). The advantages of bilingualism debate. *Annual Review of Linguistics, 5*, 395–415. https://doi.org/10.1146/annurev-linguistics-011718-011820

Bergelson, E., Casillas, M., Soderstrom, M., Seidl, A., Warlaumont, A. S., & Amatuni, A. (2019). What do North American babies hear? A large-scale cross-corpus analysis. *Developmental Science, 22*(1), Article e12724. https://doi.org/10.1111/desc.12724

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin, 143*(3), 233–262. https://doi.org/10.1037/bul0000099

Birdsong, D. (2018). Plasticity, variability and age in second language acquisition and bilingualism. Frontiers in Psychology, 9, Article 81. https://doi.org/10.3389/fpsyg.2018.00081

Bishop, D. V. M., Snowling, M. J., Thompson, P. A., Greenhalgh, T., & the CATALISE-2 consortium. (2017). Phase 2 of CATALISE: A multinational and multidisciplinary Delphi consensus study of problems with language development. *Journal of Child Psychology and Psychiatry, 58*(10), 1068–1080. https://doi.org/10.1111/jcpp.12721

Brady, M. C., Kelly, H., Godwin, J., Enderby, P., & Campbell, P. (2016). Speech and language therapy for aphasia following stroke. *Cochrane Database of Systematic Reviews, 2016*(6), Article CD000425. https://doi.org/10.1002/14651858.CD000425.pub4

Breitenstein, C., Grewe, T., Flöel, A., Ziegler, W., Springer, L., Martus, P., Huber, W., Willmes, K., Ringelstein, E. B., Haeusler, K. G., Abel, S., Glindemann, R., Domahs, F., Regenbrecht, F., Schlenck, K.-J., Thomas, M., Obrig, H., de Langen, E., Rocker, R., … Baumgaertner, A. (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. https://doi.org/10.1016/S0140-6736(17)30067-3

Cabeza, R., Albert, M., Belleville, S., Craik, F. I. M., Duarte, A., Grady, C. L., Lindenberger, U., Nyberg, L., Park, D. C., Reuter-Lorenz, P. A., Rugg, M. D., Steffener, J., & Rajah, M. N. (2018). Maintenance, reserve and compensation: The cognitive neuroscience of healthy ageing. *Nature Reviews Neuroscience, 19*(11), 701–710. https://doi.org/10.1038/s41583-018-0068-2

Elliott, M. L., Knodt, A. R., Ireland, D., Morris, M. L., Poulton, R., Ramrakha, S., Sison, M. L., Moffitt, T. E., Caspi, A., & Hariri, A. R. (2020). What is the test-retest reliability of common task-functional MRI measures? New empirical evidence and a meta-analysis. *Psychological Science, 31*(7), 792–806. https://doi.org/10.1177/0956797620916786

Elsner, B., Kugler, J., Pohl, M., & Mehrholz, J. (2019). Transcranial direct current stimulation (tDCS) for improving aphasia in adults with aphasia after stroke. *Cochrane Database of Systematic Reviews, 2019*(5), Article CD009760. https://doi.org/10.1002/14651858.CD009760.pub4

Fedorenko, E., & Blank, I. A. (2020). Broca's area is not a natural kind. *Trends in Cognitive Sciences, 24*(4), 270–284. https://doi.org/10.1016/j.tics.2020.01.001

Fedorenko, E., Piantadosi, S. T., & Gibson, E. A. F. (2024). Language is primarily a tool for communication rather than thought. *Nature, 630*(8017), 575–586. https://doi.org/10.1038/s41586-024-07522-w

Fisicaro, F., Lanza, G., Grasso, A. A., Pennisi, G., Bella, R., Paulus, W., & Pennisi, M. (2019). Repetitive transcranial magnetic stimulation in stroke rehabilitation: Review of the current evidence and

pitfalls. *Therapeutic Advances in Neurological Disorders, 12*, Article 1756286419878317. https://doi.org/10.1177/1756286419878317

Fridriksson, J., Rorden, C., Elm, J., Sen, S., George, M. S., & Bonilha, L. (2018). Transcranial direct current stimulation vs sham stimulation to treat aphasia after stroke: A randomised clinical trial. *JAMA Neurology, 75*(12), 1470–1476. https://doi.org/10.1001/jamaneurol.2018.2287

Fridriksson, J., Yourganov, G., Bonilha, L., Basilakos, A., Den Ouden, D.-B., & Rorden, C. (2016). Revealing the dual streams of speech processing. *Proceedings of the National Academy of Sciences, 113*(52), 15108–15113. https://doi.org/10.1073/pnas.1614038114

Grundy, J. G., Anderson, J. A. E., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences, 1396*(1), 183–201. https://doi.org/10.1111/nyas.13333

Hagoort, P. (2019). The neurobiology of language beyond single-word processing. *Science, 366*(6461), 55–58. https://doi.org/10.1126/science.aax0289

Hartshorne, J. K., Tenenbaum, J. B., & Pinker, S. (2018). A critical period for second language acquisition: Evidence from 2/3 million English speakers. *Cognition, 177*, 263–277. https://doi.org/10.1016/j.cognition.2018.04.007

Hartwigsen, G. (2018). Flexible redistribution in cognitive networks. *Trends in Cognitive Sciences, 22*(8), 687–698. https://doi.org/10.1016/j.tics.2018.05.008

Hartwigsen, G., & Saur, D. (2019). Neuroimaging of stroke recovery from aphasia: Insights into plasticity of the human language network. *NeuroImage, 190*, 14–31. https://doi.org/10.1016/j.neuroimage.2017.11.056

Hickok, G. (2022). The dual stream model of speech and language processing. In G. Hickok & S. L. Small (Eds.), *Handbook of clinical neurology* (Vol. 185, pp. 45–58). Elsevier. https://doi.org/10.1016/B978-0-12-823384-9.00003-7

Kiran, S., & Thompson, C. K. (2019). Neuroplasticity of language networks in aphasia: Advances, updates, and future challenges. *Frontiers in Neurology, 10*, Article 295. https://doi.org/10.3389/fneur.2019.00295

Kristinsson, S., Zhang, W., Rorden, C., Newman-Norlund, R., Basilakos, A., Bonilha, L., Yourganov, G., Xiao, F., Hillis, A., & Fridriksson, J. (2021). Machine learning-based multimodal prediction of language outcomes in chronic aphasia. *Human Brain Mapping, 42*(6), 1682–1698. https://doi.org/10.1002/hbm.25321

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin, 144*(4), 394–425. https://doi.org/10.1037/bul0000142

Lövdén, M., Fratiglioni, L., Glymour, M. M., Lindenberger, U., & Tucker-Drob, E. M. (2020). Education and cognitive functioning across the lifespan. *Psychological Science in the Public Interest, 21*(1), 6–41. https://doi.org/10.1177/1529100620920576

Metzger, S. L., Littlejohn, K. T., Silva, A. B., Moses, D. A., Seaton, M. P., Wang, R., Dougherty, M. E., Liu, J. R., Wu, P., Berger, M. A., Zhuravleva, I., Tu-Chan, A., Ganguly, K., Anumanchipalli, G. K., & Chang, E. F. (2023). A high-performance neuroprosthesis for speech decoding and avatar control. *Nature, 620*(7976), 1037–1046. https://doi.org/10.1038/s41586-023-06443-4

Moses, D. A., Metzger, S. L., Liu, J. R., Anumanchipalli, G. K., Makin, J. G., Sun, P. F., Chartier, J., Dougherty, M. E., Liu, P. M., Abrams, G. M., Tu-Chan, A., Ganguly, K., & Chang, E. F. (2021). Neuroprosthesis for decoding speech in a paralysed person with anarthria. *New England Journal of Medicine, 385*(3), 217–227. https://doi.org/10.1056/NEJMoa2027540

Newport, E. L. (2020). Children and adults as language learners: rules, variation, and maturational change. *Topics in Cognitive Science, 12*(1), 153–169. https://doi.org/10.1111/tops.12416

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., & Owen, A. M. (2020). Bilingualism affords no general cognitive advantages: a population study of executive function in 11,000 children. *Psychological Science, 31*(5), 548–567. https://doi.org/10.1177/0956797620903113

Norbury, C. F., Gooch, D., Wray, C., Baird, G., Charman, T., Simonoff, E., Vamvakas, G., & Pickles, A. (2016). The impact of nonverbal ability on prevalence and clinical presentation of language disorder: Evidence from a population study. *Journal of Child Psychology and Psychiatry, 57*(11), 1247–1257. https://doi.org/10.1111/jcpp.12573

Ozernov-Palchik, O., & Gaab, N. (2016). Tackling the "dyslexia paradox": Reading brain and behaviour for early markers of developmental dyslexia. *WIREs Cognitive Science, 7*(2), 156–176. https://doi.org/10.1002/wcs.1383

Perrachione, T. K., Del Tufo, S. N., Winter, R., Murtagh, J., Cyr, A., Chang, P., Halverson, K., Ghosh, S. S., Christodoulou, J. A., & Gabrieli, J. D. E. (2016). Dysfunction of rapid neural adaptation in dyslexia. *Neurone, 92*(6), 1383–1397. https://doi.org/10.1016/j.neuron.2016.11.020

Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. *Bilingualism: Language and Cognition, 23*(2), 459–471. https://doi.org/10.1017/S1366728919000130

Poeppel, D., & Assaneo, M. F. (2020). Speech rhythms and their neural foundations. *Nature Reviews Neuroscience, 21*(6), 322–334. https://doi.org/10.1038/s41583-020-0304-4

Romeo, R. R., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., Rowe, M. L., & Gabrieli, J. D. E. (2018). Beyond the 30-million-word gap: Children's conversational exposure is associated with language-related brain function. *Psychological Science, 29*(5), 700–710. https://doi.org/10.1177/0956797617742725

Stefaniak, J. D., Alyahya, R. S. W., & Lambon Ralph, M. A. (2021). Language networks in aphasia and health: A 1000-participant activation likelihood estimation meta-analysis. *NeuroImage, 233*, Article 117960. https://doi.org/10.1016/j.neuroimage.2021.117960

Thye, M., & Mirman, D. (2018). Relative contributions of lesion location and lesion size to predictions of varied language deficits in post-stroke aphasia. *NeuroImage: Clinical, 20*, 1129–1138. https://doi.org/10.1016/j.nicl.2018.10.017

Tremblay, P., & Dick, A. S. (2016). Broca and Wernicke are dead, or moving past the classic model of language neurobiology. *Brain and Language, 162*, 60–71. https://doi.org/10.1016/j.bandl.2016.08.004

Tsapkini, K., Webster, K. T., Ficek, B. N., Desmond, J. E., Onyike, C. U., Rapp, B., Frangakis, C. E., & Hillis, A. E. (2018). Electrical brain stimulation in different variants of primary progressive aphasia: A randomised clinical trial. *Alzheimer's & Dementia: Translational Research & Clinical Interventions, 4*, 461–472. https://doi.org/10.1016/j.trci.2018.08.002

Willett, F. R., Kunz, E. M., Fan, C., Avansino, D. T., Wilson, G. H., Choi, E. Y., Kamdar, F., Glasser, M. F., Hochberg, L. R., Druckmann, S., Shenoy, K. V., & Henderson, J. M. (2023). A high-performance speech neuroprosthesis. *Nature, 620*(7976), 1031–1036. https://doi.org/10.1038/s41586-023-06377-x

Wilson, S. M., Entrup, J. L., Schneck, S. M., Onuscheck, C. F., Levy, D. F., Rahman, M., Willey, E., Casilio, M., Yen, M., Brito, A. C., Kam, W., Davis, L. T., de Riesthal, M., & Kirshner, H. S. (2023). Recovery from aphasia in the first year after stroke. *Brain, 146*(3), 1021–1039. https://doi.org/10.1093/brain/awac129