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A longitudinal study of auditory comprehension in post-stroke aphasia

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Abstract

Objective: Most studies documenting the longitudinal recovery of auditory comprehension in post-stroke aphasia begin in the subacute phase. The present study aimed to address this gap by exploring the longitudinal changes in auditory comprehension from the acute to the chronic phase and their neural correlates.

Method: Twenty-one Laurentian French persons with aphasia (PWA) following a first left middle cerebral artery stroke underwent three language assessments (acute, 0–72 h; subacute, 7–14 days; chronic, 6–12 months post-onset). Auditory comprehension was assessed at each time point using two tasks, sentence picture matching and sequential commands. From the sentence-picture matching task, four measures were extracted: single-word, subject-verb, canonical subject-verb-object, and noncanonical subject-verb-object comprehension, while one measure was derived from the sequential commands task, totaling five measures. Lesion-symptom mapping (LSM) was used to identify the brain regions associated with comprehension impairments.

Results: All five auditory comprehension measures showed significant positive changes between acute and chronic phases. Persistent comprehension impairments with canonical sentences and sequential commands were more likely to occur in the chronic phase. LSM analyses revealed that comprehension of noncanonical sentences was associated with lesions in the supramarginal gyrus and extended to the superior temporal gyrus (STG) and middle temporal gyrus (MTG). Similarly, the comprehension of sequential commands was associated with lesions in the MTG, extending to the STG and insula.

Conclusions: The current findings suggest that PWA with more severe impairments in the acute phase reach a similar performance in the chronic phase than people with milder aphasia, and suggest a critical role for the left MTG in the recovery of auditory comprehension, especially with complex stimuli.

Word count: 6,819 words, excluding references.

Keywords: aphasia, auditory comprehension, voxel-symptom lesion mapping

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Introduction

Aphasia is one of the most devastating cognitive impairments associated with strokes. One-third of stroke survivors present with aphasia (Dickey et al., 2010; Laska et al., 2001; Pedersen et al., 1995, 2004), an acquired communication disorder that affects language expression and comprehension (El Hachioui et al., 2013). A key challenge that clinicians face in the early stages after stroke is determining the extent of recovery. A common concern among stroke survivors and their families is understanding how much recovery will occur and how quickly. Predicting individual recovery remains a challenge. However, research suggests that most persons with aphasia (PWA) experience gradual improvement in communication abilities in the days or months following stroke (Hillis, 2007). While the degree of spontaneous recovery varies, studies have consistently shown that the most significant progress occurs within the first two weeks post-stroke (Laska et al., 2001; Pedersen et al., 1995, 2004; Wade et al., 1986). This period aligns with the hyperacute, acute, or early subacute phases outlined by Bernhardt et al. (2017).

Although spontaneous recovery from aphasia is a well-documented phenomenon during the acute and subacute phases post-stroke, the specific trajectory of auditory comprehension within this critical period remains relatively unexplored (Stefaniak et al., 2020). In general, studies investigating the recovery from aphasia tend to use more global measures of aphasia rather than more specific aspects of aphasia, such as auditory comprehension. Because auditory comprehension is central to recovery from aphasia, understanding how it progresses early is essential for accurately predicting long-term outcomes and informing targeted therapeutic interventions. While auditory comprehension assessment is routine in clinical practice (e.g., Sheppard & Sebastian, 2021; Teasell et al., 2020), our current knowledge of its evolution over time following stroke remains limited. Indeed, most studies focusing on auditory comprehension have been conducted at least a few months after stroke, when the recovery curve is less prominent (e.g., Crinion & Price, 2005; Lwi et al., 2021; Pickersgill & Lincoln, 1983; Prins et al., 1978; Tyler et al., 2010, 2011). The lack of literature on auditory comprehension deficits induced by left unilateral post-stroke aphasia and its long-term recovery is problematic when considering the clinical importance of comprehension impairments. Indeed, a large majority of PWA present with comprehension impairments in the early post-stroke period. For instance, Selnes et al. (1984) investigated the longitudinal recovery of a group of 37 PWA at 1-month and 6-month post-onset. At 1-month post-stroke, 86% (32 out of 37 persons) presented single-word comprehension impairments compared to those without brain damage, which suggests that comprehension impairments are common in the early phases of post-stroke aphasia recovery. At 6-month post-stroke, only 40% (15 out of 37) still presented with persistent single-word comprehension impairments, and striking improvements were also observed in persons with persistent impairments. In contrast to single-word comprehension, the longitudinal recovery trajectory with the Token Test (i.e., auditory comprehension of commands to execute) was less pronounced. Similarly, Sheppard et al. (2022) assessed 15 patients with unilateral left hemisphere infarct at the acute (average of 2.5 days post-onset) and chronic phases (average of 21.4 months post-onset) using the subject-relative, object-relative, active, and passive tests of comprehension (SOAP; Love & Oster, 2002). Unsurprisingly, impairment in noncanonical sentences was more important than impairment in canonical sentences. The comprehension of canonical sentences improved between the acute and chronic phases, while the changes were not significant in noncanonical sentence comprehension. Despite these improvements, compared with the performance of healthy controls, most PWA were still impaired in both canonical and noncanonical sentences in the chronic phase. These results highlight the value of examining auditory comprehension through a range of tasks to gain a more comprehensive understanding of longitudinal recovery.

While comprehension impairments are prevalent, auditory comprehension tends to demonstrate a higher recovery rate than oral expression (Mazzoni et al., 1992; Prins et al., 1978), and even faster (Pickersgill & Lincoln, 1983; Wilson et al., 2023). For instance, Pickersgill and Lincoln studied 56 individuals with moderate and severe aphasia. Nearly half of the participants attended therapy for eight weeks, while the other half did not. Most improvements were observed in the treated group and within the first month post-stroke (1- and 4-months post-onset). Interestingly, people with severe aphasia recovered more on tasks involving comprehension, whereas people with moderate aphasia recovered mostly on expressive tasks. The authors suggest that the recovery of comprehension occurred before the recovery of expression.

Considering that initial severity has been identified as one of the most important predictors of outcome (Osa García et al., 2020), there is a crucial need to explore the role of severity when investigating the longitudinal trajectory starting from the acute phase. Among the few studies conducted in the subacute phase, Mazzoni et al. (1992) studied 45 individuals with left unilateral stroke who had aphasia but did not receive therapy. An assessment was first conducted in the early subacute phase (i.e., starting on the fifteenth day following the stroke) and repeated monthly up to the chronic phase (i.e., six–seven months post-stroke). Participants completed single-word comprehension (word-picture matching), sentence comprehension (commands), and a composite score of auditory comprehension was calculated. Spontaneous recovery in auditory comprehension was more pronounced than in oral and written expressions, as well as reading comprehension. Interestingly, improvement in auditory comprehension was independent of lesion size, aphasia type, and severity, which was not the case with the other modalities. These findings highlight the need for further exploration of auditory comprehension during different recovery phases. Investigating the neural mechanisms underlying these processes could provide valuable insights into the evolution of auditory comprehension over time, an area that remains largely unexplored.

Neural correlates of auditory comprehension

Comprehension is traditionally linked to Wernicke's and Broca's areas (Binder et al., 1997; Friederici, 2002; Zhang et al., 2023). Language comprehension is a broad and complex system within the brain that is characterized by a bilateral network connecting the temporal and frontal regions (Dronkers et al., 2004; Hickok & Poeppel, 2007; Lee et al., 2022). The left temporal regions are responsible for identifying phonetic, lexical, and structural elements, whereas the left frontal cortex is responsible for sequencing and the formation of structural, semantic, and thematic relations (Butler et al., 2023). Historically, the right temporal region has been strongly associated with prosody processing. However, a recent meta-analysis of 403 neuroimaging studies showed that prosody relies on a bilateral frontotemporal network and the right amygdala. Historically, prosody processing has been thought to depend primarily on the right hemisphere. However, a recent meta-analysis of 403 neuroimaging studies (Turker et al., 2023) revealed that prosody relies on the bilateral frontotemporal network and the right amygdala.

Understanding the neural basis of language comprehension has been a major focus of cognitive neuroscience. Several methods have been developed to map brain-behavior relationships, particularly in individuals with brain lesions. Regarding auditory comprehension, Naeser et al. (1987) conducted a pioneering study that employed computer analysis to quantify the percentage of tissue lost and visual analysis of specific regions. They reported a significant correlation between the extent of lesions in Wernicke's area and the BDAE auditory comprehension *z*-scores, Token test, word discrimination, and body-part identification. Other approaches have been used to investigate brain behavior mapping, such as Lesion-Symptom Mapping (LSM; e.g., Dronkers et al., 2004; Geva et al., 2012; Lwi et al., 2021; Shahid et al., 2017) and regions of interest (ROIs; e.g., Den Ouden et al., 2019; Fridriksson et al., 2018; Kristinsson et al., 2020). LSM correlates behavioral data across a group of individuals with brain lesions, such as stroke patients in the present case, on a voxel-by-voxel basis over the whole brain, whereas ROIs approaches have specific hypotheses and examine specific regions based on literature. LSM is a robust and widely used method; however, only a few studies have specifically focused on identifying the brain structures associated with comprehension impairments, especially starting in the acute phase. Shahid et al. (2017) conducted an LSM analysis on a group of 191 individuals with acute left hemisphere stroke who performed a yes/no word-picture verification task. Their results showed that the left posterior superior temporal gyrus (STG) was correlated with spoken word comprehension. Lwi et al. (2021) also recently conducted LSM with three auditory comprehension tasks, namely single-word comprehension, yes/no questions, and sequential commands, on a group of 168 persons with chronic aphasia (i.e., at least 12 months post-onset). When looking at the three tasks combined, a small area in the most posterior part of the left middle temporal gyrus (MTG) was associated with comprehension impairment. Impairments in single-word auditory comprehension and in parts of the angular gyrus and inferior middle occipital gyri were associated with lesions in the left posterior MTG. In contrast, impairments in yes/no sentence comprehension were linked to lesions in the left mid-posterior MTG, consistent with previous findings (e.g., Dronkers et al., 2004; Geva et al., 2012). The MTG, along with the mid-posterior superior temporal sulcus, superior temporal gyrus, and inferior temporal gyrus, has been associated with general sentence comprehension based on the LSM (Biondo et al., 2024). Additionally, damage to the MTG has been linked to auditory comprehension impairments using an ROI approach (e.g., Den Ouden et al., 2019; Fridriksson et al., 2018; Kristinsson et al., 2020). For sequential commands, Lwi et al. (2021) showed that comprehension impairments are linked to lesions in the left posterior MTG. In contrast, Harrington et al. (2024) found that poorer performance in the auditory comprehension of commands was associated with damage to the posterior insula. Overall, these findings highlight the role of the left middle and posterior temporal regions in auditory comprehension and underscore the complexity of brain-behavior relationships across different linguistic tasks and complexities and lesion mapping approaches.

Examining different sentence structures is crucial because canonical and noncanonical sentences impose distinct cognitive demands on language processing. Research on PWA has demonstrated that sentence comprehension deficits vary depending on the type of sentence structure and the location of brain damage. For instance, PWA with posterior MTG damage exhibit greater deficits in comprehending noncanonical sentences (Kristinsson et al., 2020), whereas damage to the temporoparietal cortex is associated with impairments in both canonical and noncanonical sentence comprehension (Caplan et al., 2016; Thothathiri et al., 2012). These findings underscore the need to examine how different syntactic structures engage distinct neural and cognitive mechanisms.

Noncanonical sentences, which deviate from the default subject-verb-object (SVO) order, impose greater cognitive demands due to increased syntactic complexity and working memory requirements (Thothathiri et al., 2012). Unlike canonical sentences, which facilitate efficient parsing, noncanonical structures involve syntactic reordering, such as object-relative clauses and passive constructions, requiring listeners to track non-adjacent dependencies and rely on syntactic cues beyond semantics (Poulin et al., 2022). These structures are more taxing because they disrupt default word-order expectations and require additional reanalysis and memory retrieval (Gordon et al., 2001). As a result, noncanonical sentences demand greater cognitive resources for real-time processing, particularly in spoken language, where listeners cannot visually revisit sentence elements.

Neurophysiological evidence supports these claims, as processing noncanonical sentences elicits greater neural activity, reflecting increased cognitive load (Osterhout & Holcomb, 1992; Vogelzang et al., 2020). These sentences require listeners to maintain and integrate non-adjacent dependencies, increasing the burden on working memory (Friederici, 2002; Swinney, 1979). These demands are further amplified in individuals with agrammatic aphasia, who struggle with syntactic reanalysis and working memory limitations (Cho-Reyes & Thompson, 2012; Thompson et al., 2013). Additionally, cross-linguistic studies indicate that the challenges posed by noncanonical structures are not merely language-specific but reflect universal constraints on sentence processing (Friederici, 2002). These findings highlight the necessity of examining sentence structures across languages to gain a comprehensive understanding of the cognitive and neural mechanisms underlying language processing, particularly in populations with aphasia and other language impairments.

Significance of investigating different languages

Although auditory comprehension recovery is critically important, most studies have focused on English-speaking populations (e.g., Lwi et al., 2021; Selnes et al., 1984; Sheppard et al., 2022). Limiting aphasia research to English constrains our understanding of how language-specific characteristics influence recovery trajectories. Languages differ in syntactic, morphological, and phonological structures, shaping the cognitive demands of auditory comprehension and impacting recovery processes. Investigating non-English languages is essential to distinguish universal recovery mechanisms from those that are language-specific. French, for instance, presents distinct linguistic features that may uniquely affect auditory comprehension recovery. Unlike English, French permits greater syntactic flexibility, including stylistic inversions in subject-verb order used for emphasis or formality, which adds complexity to sentence processing (Rigalleau et al., 1997). Additionally, French has a richer inflectional morphology, requiring listeners to process verb conjugations and grammatical agreements that differ significantly from English, potentially influencing comprehension in different ways (Prévost, 2009). Another key distinction is phonology: frequent phonological liaisons in French obscure word boundaries, increasing processing demands and making real-time auditory comprehension more challenging (Gustafson & Bradlow, 2016). These linguistic characteristics suggest that auditory sentence processing in French may rely on different cognitive strategies than in English, underscoring the need for research in this linguistic context. Studies suggest that languages with richer inflectional morphology, such as French, may provide more cues for sentence interpretation, potentially aiding recovery in some contexts while increasing processing challenges in others (Bastiaanse et al., 2011). Similarly, languages with flexible word order may require additional working memory resources, which could influence the severity of comprehension deficits (Menn & Obler, 1990). Given these factors, the trajectory of auditory comprehension recovery in Laurentian French remains an open question, necessitating further research to determine whether findings from English-centric studies generalize to this linguistic context.

Beyond theoretical insights, expanding research beyond English-speaking populations has critical clinical implications. Many rehabilitation approaches and assessment tools are designed based on English-language models, which may not fully capture the needs of individuals speaking languages with different syntactic and phonological characteristics. Cross-linguistic research is therefore essential for developing language-appropriate assessment tools and evidence-based interventions that account for linguistic diversity (García et al., 2023). Investigating auditory comprehension recovery in languages such as Laurentian French will not only enhance clinical outcomes for Laurentian French-speaking individuals but also contribute to a more comprehensive, inclusive model of aphasia recovery.

Purpose

The aims of this study are twofold. First, we aimed to assess changes in auditory comprehension of various complexities in persons speaking Laurentian (Quebec) French with acute post-stroke aphasia. Based on previous longitudinal studies (e.g., Bernhardt et al., 2017; Pedersen et al., 2004), we expected positive changes over the course of time for all tasks. More specifically, we predict that auditory comprehension will improve between the acute and chronic phases, with a significant improvement in individuals with moderate-to-severe aphasia. We also expect that comprehension of noncanonical sentences will be more impaired than that of canonical sentences in the chronic phase. The second aim of this study was to explore the neural correlates of different auditory comprehension complexities using outcome scores in the chronic phase. Given that recovery fluctuates in the acute and subacute phases, lesion-symptom mapping at these stages could introduce variability unrelated to stable lesion-deficit associations. Therefore, we focused on outcome scores in the chronic phase to ensure a more reliable identification of the brain regions that are critical for auditory comprehension. We predicted that auditory comprehension impairments for all five measures would be associated with lesions in the left posterior MTG (Lwi et al., 2021 Dronkers et al., 2004). In addition, the performance of noncanonical sentences and sequential commands is mediated by the posterior insula (Harrington et al., 2024).

Materials and Methods

Participants

This study was approved by the ethics review board of the *Centre intégré universitaire de santé et de services sociaux du Nord-de-l'Ile-de Montréal* (Project #MP-32-2018-1478), and written informed consent was obtained from all participants. PWA were recruited from a stroke unit of the *Centre intégré universitaire de santé et de services sociaux du Nord-de-l'île-de-Montréal* between May 2015 and February 2021. A research team member reviewed the patient lists from the emergency department and stroke unit daily at each site to identify potential participants.

Twenty-one Laurentian French speakers (ten women, mean age: 71.8 ± 12.6 years old; mean education: 12.5 ± 4.1 years) with various types of post-stroke aphasia participated in the present study. The inclusion criteria were as follows: 1) a first cortical ischemic stroke in the territory of the left middle cerebral artery with symptom onset within 24 hours, 2) French as the language of use, 3) 18 years of age and older, and 4) right-handed. No criteria were applied regarding aphasia severity or lesion size at the time of the study. Exclusion criteria were as follows: 1) awake state or medical condition that does not allow for assessment, 2) major psychiatric or developmental disorders, 3) severe perceptual deficits, as identified by the on-call physician, or 4) other major neurological conditions.

All participants used Laurentian (Quebec) French as their dominant language, and the assessment was conducted in Laurentian French. Five were monolinguals (Laurentian-French only), 13 were bilinguals (Laurentian-French and another language, mainly English), and three spoke three languages. The clinical and sociodemographic data of all the participants are presented in Table 1.

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Table 1. Demographic and clinical variables of participants with post-stroke aphasia

Participant	Sex	Age	Educ.	Language status	Initial NIHSS score	Lesion vol corrected	rTPA	Days post-stroke T1	Days post-stroke T2	Days post-stroke T3	CS_{acute} (T1)	$CS_{subacute}$ (T2)	CS_{chron} (T3)
1	M	52	9	Monolingual	n/a	0.0226	Yes	1	7	387	8.20	24.78	27.87
2	M	74	6	Monolingual	9	0.0277	Yes	3	8	365	10.24	13.81	24.02
3	M	73	19	Bilingual	18	0.0199	No	3	10	224	7.71	14.02	27.11
4	F	70	14	Trilingual	16	0.0657	No	3	12	249	1.87	1.69	5.39
5	M	83	9	Bilingual	9	0.0133	No	3	10	366	3.90	14.39	18.17
6	F	47	18	Trilingual	26	0.0456	No	0	10	218	0.00	0.00	18.13
7	F	73	7	Trilingual	n/a	0.0077	No	3	13	217	14.36	17.23	16.74
8	M	65	11	Bilingual	6	0.0080	Yes	3	14	196	28.53	28.88	29.11
9	M	72	15	Bilingual	11	0.0030	Yes	1	9	188	21.33	28.11	28.69
10	M	73	11	Monolingual	n/a	0.0010	Yes	1	8	231	12.76	14.79	24.50
11	M	64	15	Bilingual	n/a	0.0049	Yes	1	11	277	27.46	28.90	28.87
12	F	95	6	Bilingual	1	0.0240	No	2	9	251	16.27	22.86	23.03

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Particip ant	Sex	Age	Educ.	Langu age status	Initial NIHSS score	Lesion vol corrected	rTPA	Days post-stroke T1	Days post-stroke T2	Days post-stroke T3	CS_{acute} (T1)	$CS_{subacute}$ (T2)	CS_{chron} (T3)
13	F	60	12	Bilingu al	7	0.0009	Yes	3	13	232	23.60	21.73	21.97
14	M	91	19	Bilingu al	7	0.0008	No	3	15	383	20.09	25.08	25.73
15	F	85	16	Bilingu al	n/a	0.0089	No	2	8	227	26.79	27.70	27.12
16	F	81	15	Monoli ngual	17	0.0086	Yes	2	11	222	26.79	27.70	28.26
17	F	68	12	Bilingu al	4	0.0009	Yes	3	8	217	26.73	28.78	20.85
18	F	77	7	Bilingu al	n/a	0.0661	No	3	8	479	2.05	9.65	11.63
19	M	54	18	Bilingu al	4	0.0324	No	2	9	357	3.31	10.58	21.16
20	M	52	15	Bilingu al	n/a	0.0113	Yes	2	10	557	21.24	29.55	29.38
21	M	84	15	Monoli ngual	3	0.0318	Yes	2	11	485	10.72	16.47	24.67
group Mean (*SD*)		71.09 (13.13)	12.81 (4.26)		9.86 (7.40)	0.0197 (0.0195)		2.19 (0.92)	10.19 (2.20)	301.33 (108.29)	14.95 (9.75)	19.37 (9.07)	22.97 (6.23)

NIHSS= National Institute of Health Stroke Scale; n/a= non-available in the medical chart; BDAE= Boston Diagnostic Aphasia Examin

Procedure

Language Assessments

The participants underwent three language assessments over time. The first assessment (T1; acute phase) occurred within the first 3 days post-onset (*range* = 1–3 days, *M* = 2.2 days, *SD* = 1.0). The second assessment (T2; subacute phase) took place at least seven days post-onset (*range* = 7–15 days, *M* = 10.5 days, *SD* = 2.2). The third assessment (T3; chronic phase) was conducted at least 180 days post-stroke (*range* = 188–557 days, *M* = 283.6 days, *SD* = 99.3). The specific timing for each assessment was reported for each PWA in Table 1. All participants were admitted to the public health care system in Quebec and received speech-language therapy between T2 and T3, as recommended by the Canadian Stroke Guidelines (Boulanger et al., 2018) . The therapy ranged from a few sessions to several months. At the time of the third assessment (T3), no participant was actively involved in speech-language therapy.

All PWA completed language assessments of several language domains at each time point. Auditory comprehension was assessed using the Word/Sentence Comprehension Task (max = 47 points) of the Montreal-Toulouse test (Nespoulous et al., 1992), which can be divided into four different categories: single words (*n* = 9), simple subject-verb sentences (*n* = 6), canonical subject-verb-object sentences (*n* = 16), and matched noncanonical sentences (i.e., relatives, passives, etc.). The revised (short) version of the Token Test (De Renzi & Faglioni, 1978) (max = 36 points) was administered.

To obtain a more comprehensive measure of aphasia, we calculated composite scores (CS) based on three subscores: comprehension, repetition, and naming, following previous studies (Lazar et al., 2010; Osa García et al., 2020). The comprehension sub-score combines the word-sentence comprehension score from the MT-86 (Nespoulous et al., 1992) and the revised Token Test (De Renzi & Faglioni, 1978). The repetition sub-score included word and sentence repetition tasks from MT-86. The naming sub-score comprised the semantic fluency score from the Protocol Montréal d'Évaluation de la Communication (Joanette et al., 2004), along with the Dénomination Orale d'Images (Deloche & Hannequin, 1997). Each subscore was scaled to 10, yielding a maximum CS of 30. The individual and mean composite scores of the three time points are reported in Table 1. Initial severity scoring and aphasia type were based on the results obtained from these tasks, clinical judgement, and overall rating on the severity scale of the Boston Diagnostic Aphasia Examination-3 (BDAE-3; Goodglass et al., 2001). Participants were also asked to produce an oral description of the picture of the Western Aphasia Battery – Revised (Kertesz, 2006) and the results have already been reported longitudinally (Brisebois et al., 2021).

Neuroimaging acquisition

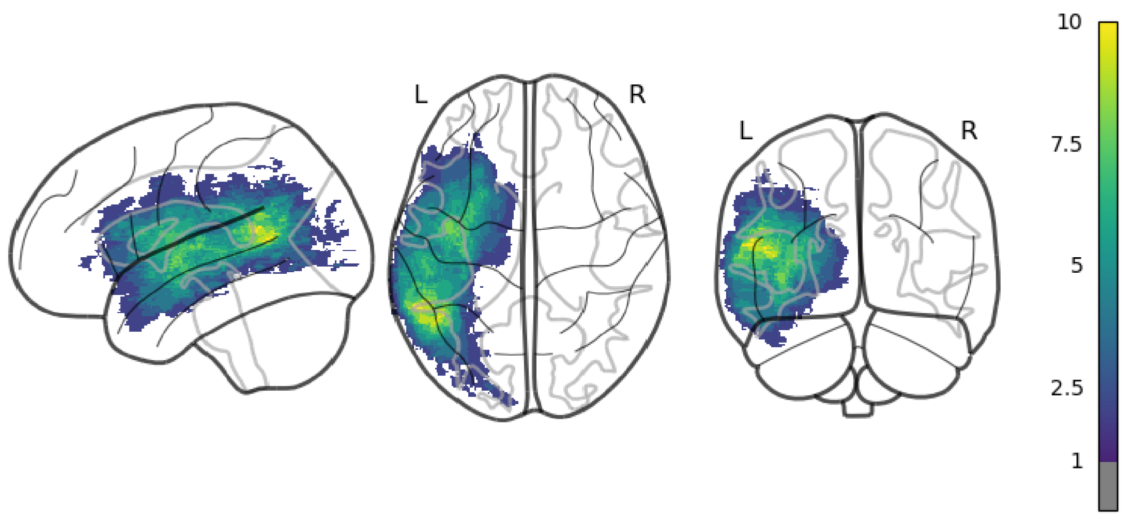
The participants underwent magnetic resonance imaging (MRI) on the same day as each language assessment. MRI images were acquired with a Skyra 3T scanner (Siemens Healthcare, USA) at the Radiology Department of the acute care hospital. A high-resolution 3D T1-weighted image was acquired (TR = 2200 ms, TE = 2.96 ms, TI = 900 ms, FOV = 250 mm, voxel size = 1 × 1 × 1 mm3, matrix = 256 × 256, 192 slices, flip angle = 8 °) in a Magnetization Prepared Rapid Gradient Echo (MP-RAGE) sequence. The MRI diffusion-weighted images had the following parameters: 65 images with non-collinear diffusion direction at b = 1000 s/mm2, posterior-anterior acquisition (TR = 11000 ms, TE = 86 ms, field of view = 230 mm, voxel resolution = 2 × 2 × 2 mm3, flip angle = 90°, bandwidth = 1700, EPI factor = 67), and two T2-weighted images with b = 0 s/mm2, one being a posterior-anterior acquisition and the other an anterior-posterior acquisition (time of acquisition = 12 min 30 s).

Lesion demarcation

Semi-automated segmentation of each brain lesion was conducted with the imaging data from the acute phase using *Clusterize* (Clas et al., 2012) by two team members (BH and SMB), blinded to the participant's identification and experience in lesion delineation. Briefly, hypo-intensity clusters of voxels were first identified on mean diffusivity (MD) maps (set with default parameters), manually selected and adjusted to fit the lesion in each slice, counter-verified, and adjusted (if needed) using MD and b0 diffusion-weighted imaging maps with MI-brain software (Imeka Solutions Inc.). For more details, please refer to our complete methodology of Boucher et al. (2023). The brain templates were then digitized and nonlinearly transformed into the MNI space using SPM12. This transformation was achieved using 50 control-point pairs to match the anatomical features of the two templates. The slices were then aligned using a local weighted mean transformation implemented using cpselect, cp2tform, and imtransform MATLAB imaging toolbox functions.

An overlay map of the patients' lesions is shown in Figure 1. Considering the inclusion criterion, it is not surprising that the extent of lesion coverage is predominantly located in the middle cerebral artery territory, including the white matter. The area of maximal overlay across all patients was centered around the left insula and more posteriorly around the left angular gyrus. The corrected average lesion volume in the sample was 0.0197 cc.

Figure 1. Lesion overlay map of participants. The color bar indicates the minimum number of participants with lesion present in each voxel.



Data analysis

Longitudinal changes

First, we measured auditory comprehension changes over time. Thus, separate analyses were conducted on the five dependent variables of auditory comprehension (i.e., single words, simple subject-verb sentences, canonical subject-verb-object sentences, matched noncanonical subject-verb-object sentences, and sequential commands), with time as a repeated measure. All variables showed a non-normal distribution (Shapiro-Wilk normality test, $p < .05$ for these variables). A non-parametric Friedman test with

Bonferroni-adjusted post hoc comparisons for paired samples was conducted on all five variables using SPSS® v29.0, with the significance level set at $p < .05$ after Bonferroni correction for multiple comparisons. To assess the effect size, Kendall's *W* was calculated as recommended for non-parametric tests (Tomczack & Tomczak, M., 2014). Kendall's *W* was computed using the *boot* (Canty & Ripley, 2022) and *irr* (Gamer et al., 2019) packages in RStudio [version 2024.12.0+467] (R Core Team, 2024; RStudio Team., 2024). The effect size interpretation follows Cohen's (Cohen, 1988) benchmarks, where *d* values of 0.2 indicate a small effect, 0.5 a medium effect, and 0.8 a large effect.

Additionally, we conducted two exploratory analyses. First, a visual analysis of preserved and impaired performance was conducted. To do so, impaired performance was defined as an accuracy lower than two standard deviations below the mean of persons without brain injury. Second, we explored the impact of the initial severity of aphasia on the outcome of all five variables of auditory comprehension, as it has been identified as one of the most important predictors of outcome (Osa García et al., 2020). To do so, the participants were separated into two groups based on their initial severity (i.e., mild-to-moderate and moderate-to-severe).

Lesion-symptom mapping

Voxel lesion symptom mapping (VLSM) was conducted to identify the gray and white matter correlates of the auditory comprehension outcome scores. Voxel-wise analyses were performed using NiiStat (https://www.nitrc.org/projects/niistat/). The results were adjusted for multiple comparisons using False Discovery Rate (FDR) corrections ($\alpha = 0.05$). Z-statistic significance is reported, with negative *z*-scores representing an association with impairment. The lesion anatomy was evaluated using Automated Anatomical Labeling (Tzourio-Mazoyer et al., 2002) and John Hopkins University White Matter atlases (Mori et al., 2005) in MRIcroGL (https://www.nitrc.org/projects/mricrogl).

Results

Longitudinal changes

The non-parametric Friedman test demonstrated a significant effect of time on all the variables. The results of these analyses are presented in Table 2. In summary, a moderate effect of time was found for single words (χ^2 (2) = 11.607, p = .003, W = .538, 95% CI [.362,.683], canonical sentences (χ^2 (2) = 21.562, $p < .001$, Kendall's W = .610 95% CI [.405,.741], noncanonical subject-verb-object sentences (χ^2 (2) = 12.028, p = .002, W = .673, 95% CI [.457, .800]) and sequential commands (χ^2 (2) = 17.410, $p < .001$, W = .782, 95% CI [.619, .851]). The effect of time was small for subject-verb sentences (Kendall's W = .471, 95% CI [.300, .618]. As reported in Table 2, the Bonferroni post-hoc test for paired comparisons demonstrated a significant improvement in all variables only between T1 and T3.

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Table 2. Mean scores (SD) of comprehension measures at each assessment timepoint and the effect of time.

				Repeated measure mixed ANOVA Non parametrical Friedman test * Post-hoc multiple comparisons		
				Time effect		
Variables	**T1 (acute) MEAN (*SD*)**	**T2 (subacute) MEAN (*SD*)**	**T3 (chronic) MEAN (*SD*)**	**T1-T2**	**T2-T3**	**T1-T3**
Words	69.31 (34.23)	83.33 (25.45)	94.18 (10.32)	χ^2 (2) = 11.607, p = .003, Kendall's W = .538, 95% CI [.362,.683]		
				p = .161	p = 1.000	p = .021
Subject-verb sentences	64.29 (37.74)	76.19 (33.57)	96.03 (8.98)	χ^2 (2) = 14.727, p = .001, Kendall's W = .471, 95% CI [.300, .618]		
				p = .495	p = .495	p = .016
Canonical sentences	51.96 (31.19)	67.86 (25.39)	86.86 (18.07)	χ^2 (2) = 21.562, p < .001, Kendall's W = .610 95% CI [.405,.741]		
				p = .161	p = .050	p < .001
Noncanonical sentences	54.07 (28.78)	63.21 (26.23)	80.38 (21.11)	χ^2 (2) = 12.028, p = .002, Kendall's W = .673, 95% CI [.457, .800]		
				p =.651	p = .161	p = .005
	39.75 (36.81)	55.27 (32.47)	77.36 (25.91)	χ^2 (2) = 17.410, p < .001, Kendall's W = .782, 95% CI [.619, .851]		

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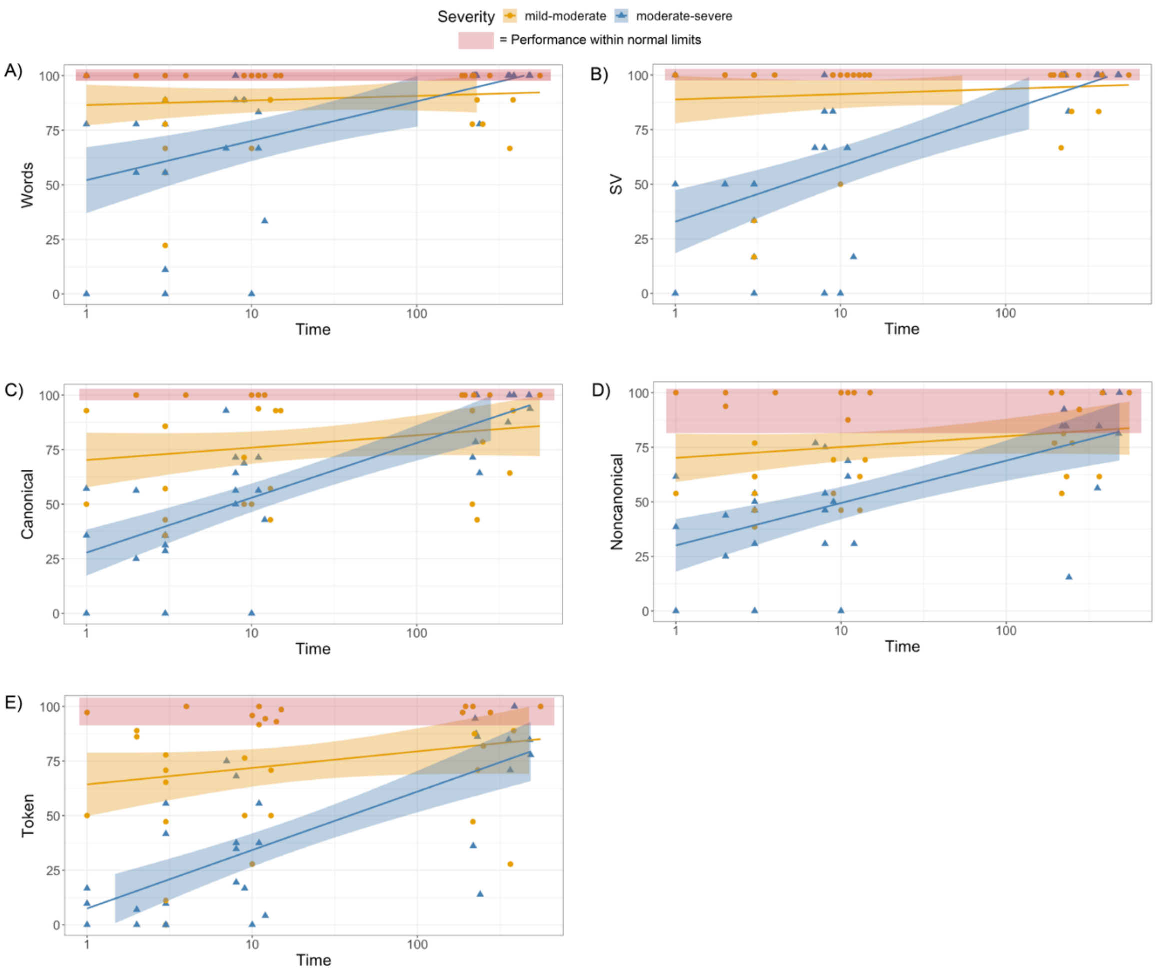
Sequential commandes (Token Test)				$p = .228$	$p = .076$	$p < .001$

*p values of the post-hoc comparisons adjusted with the Bonferroni correction

The visual analysis of preserved versus impaired performance is shown in Figure 2. In comparison with the performance of persons without brain injury, visual inspection of the data showed that the most persistent impairments were found with canonical sentences and sequential commands. Specifically, performance with canonical sentences in the chronic phase was below the typical limits for 52% of our group (11 out of 21 PWA). For the token test, 62% of the group (13 out of 21 PWA) exhibited performance below the typical range in the chronic phase. In comparison, only 33% of PWAs (seven out of 21) exhibited a performance below the typical range with noncanonical sentences, 30% (six out of 21) with words, and 19% (four out of 21) with subject-verb sentences.

Figure 2. Scatterplot of the longitudinal recovery of comprehension abilities for (a) words, (b) subject-verb sentences thematic, (c) canonical sentences, (d) noncanonical sentences and (e) sequential commands of the Token test. The three timepoints are represented on the x-axis by the log (number of days post-stroke). The performance of PWA with initial mild-moderate aphasia is represented in yellow and the performance of PWA with moderate-to-severe aphasia is represented in blue. The normal performance range of participants without brain damage is represented is red.



Regarding the effect of severity, Figure 2 also shows that over time, there was a decreasing difference between individuals with milder aphasia and those with more severe aphasia. In addition, the mean performance of the group of persons with more severe aphasia was similar to that of the group of persons with milder aphasia for all five auditory comprehension tasks.

Voxel symptom lesion mapping

The VSLM analysis yielded significant results with only two auditory comprehension tasks: noncanonical sentences and sequential commands. Seven clusters were identified by VSLM analysis of auditory comprehension of noncanonical sentences during the chronic phases, yielding seven clusters (see Supplementary Material 1 for a detailed description of each cluster). The largest cluster yielded 38851 voxels with the peak z-score (z = -3.9) centered within the left supramarginal gyrus (MNI coordinates = -54 -53 27) and extending to the left insula, rolandic operculum, and STG. As shown in the upper part of Figure 3, impairments in comprehension of noncanonical sentences were also associated with damage in the MTG. Similar results were obtained for comprehension of sequential commands. The largest cluster yielded 34842 voxels with a peak z-score (z = -5.9) centered within the left MTG (MNI coordinates = -28 5 24), which extended to the left insula, rolandic operculum, and STG. As shown in the lower part of Figure 3, impairments in sequential commands were also associated with damage to the left frontal inferior operculum and *pars triangularis.*

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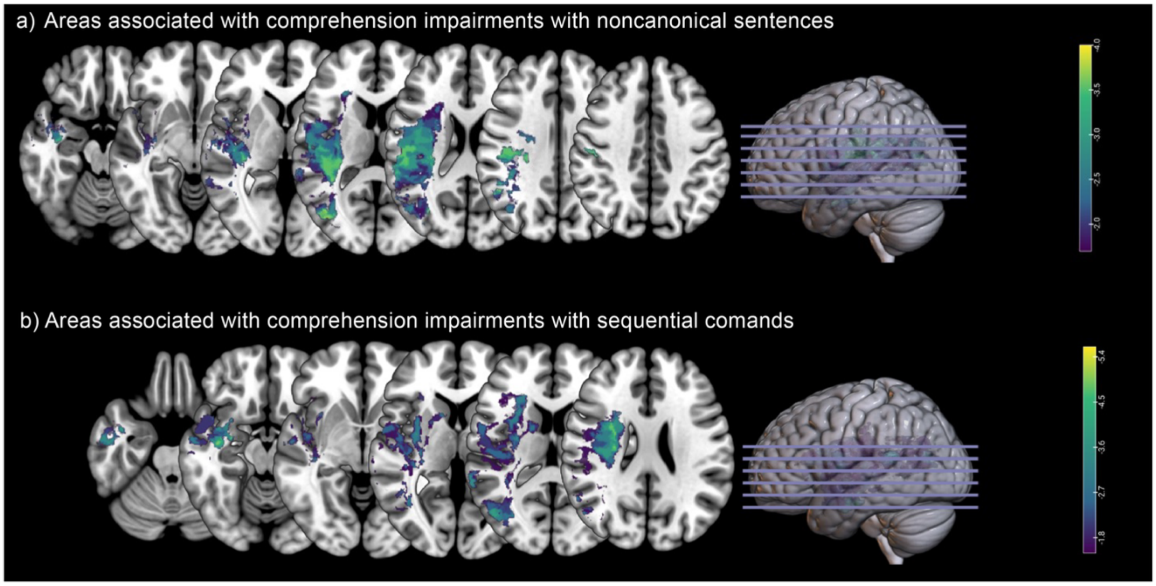
Figure 3. LSM maps showing neural correlates of (a) noncanonical sentences and (b) sequential commands of the Token test. Color bars reflect *t*-values.



Discussion

The present study aimed to explore, for the first time, the longitudinal changes in auditory comprehension in PWA speaking Laurentian French by analyzing the performance of five auditory comprehension measures. As predicted, the present results showed overall positive changes for all five auditory comprehension variables. The improvements were significant only between the acute and chronic phases. Compared to the performance of persons without brain injury, the performance of PWA with canonical sentences and sequential commands was more persistent over time. Regarding the effect of severity, people with more severe initial aphasia achieved performances similar to those with milder initial aphasia on all five comprehension measures in the chronic phase. Our LSM results demonstrated that deficits in the most difficult auditory comprehension tasks were linked to lesions in the MTG and the supramarginal gyrus. As expected, impairments in comprehension of noncanonical sentences and sequential commands were also linked to lesions in the insula.

As hypothesized, significant improvements were observed across all auditory comprehension tasks between acute and chronic phases. However, somewhat unexpectedly, no significant changes were observed between the acute and subacute phases, which is consistent with our previous study that investigated the longitudinal trajectory of narrative discourse using an identical timeline (Brisebois et al., 2021). Large-scale research on early post-stroke aphasia recovery (Pedersen et al., 1995) has shown that the most substantial recovery typically occurs within the first few weeks after stroke, although the number of weeks varies based on initial severity. The heterogeneity of our sample likely contributes to the lack of significant differences in the early recovery phase. Additionally, our study followed the timeline established by Saur et al. (2006), with the first two assessments conducted approximately one week apart. To capture a more granular view of recovery trajectories, our future studies will include additional time points, particularly in the hyperacute phase (within 24 h post-stroke) and at the beginning of the late subacute phase. This refined timeline will allow for a more comprehensive understanding of the early recovery patterns in post-stroke aphasia.

The most significant improvements were found with canonical sentences compared to noncanonical sentences, which is consistent with the findings of Sheppard et al. (2022). Nevertheless, the results demonstrated that PWA exhibited persistent difficulties with canonical sentences compared to people without brain damage, which is consistent with the findings of Sheppard et al. (2022). While many of their patients showed improvement between the acute and chronic phases, nearly half (8 out of 15) of their PWA still exhibited impaired performance with canonical sentences at the chronic stage, similar to our findings. In other words, although canonical sentences showed the largest improvements between the acute and the chronic phase, the performance did not reach a ‘normal’ performance. Despite the greater improvement observed for canonical structures, performance did not reach a fully recovered level. Thus, the canonical sentences from the MT-86 (Nespoulous et al., 1992) comprehension task may be more sensitive to persistent impairments in Laurentian-French speakers. These differences may be partially attributed to linguistic and methodological factors, including differences in sentence structure across English and French and the choice of assessment protocols. The ceiling effect observed with the canonical sentences in people without brain damage seems to help detecting mild persistent comprehension impairments.

For noncanonical sentences, although improvements were more modest between the acute and chronic phases, a larger proportion of PWA performed within the normal range in the chronic phase. Our findings diverge from those of Sheppard et al. (2022), as a smaller proportion of PWA in our sample exhibited persistent deficits in noncanonical sentence comprehension at the chronic phase. In particular, the MT-86 battery appears to assess a broader range of noncanonical sentences compared to the test used by Sheppard et al. While SOAP (Love & Oster, 2002) primarily distinguishes between canonical and noncanonical structures, it focuses on passive sentences (e.g., *The boy is kissed by the girl*) and object clefts (e.g., *It is the boy that the girl kisses*), both of which require thematic role reassignment but do not fully capture the diversity of complex sentence structures. In contrast, MT-86 includes a wider variety of noncanonical structures that further increase processing demands, such as object-relative clauses (e.g., *L’homme qui* *porte un chapeau embrasse la femme* / *The man who wears a hat kisses the woman*) and subject cleft sentences (e.g., *C'est le chien qui suit le garçon* / *It is the dog that follows the boy*). The inclusion of a wider range of syntactic structures in MT-86 allows for a more refined evaluation of sentence processing difficulties, particularly in populations with aphasia or other language impairments. However, the higher variability in noncanonical sentence comprehension observed in individuals without brain damage may have contributed to our inability to detect persistent impairments in PWA. Greater individual differences in performance within people without brain damage broadened the range of typical scores, making it more difficult to identify subtle deficits in the aphasia group. These results underscore the importance of studying auditory comprehension recovery in languages beyond English, as linguistic differences and diagnostic sensitivity may influence observed recovery trajectories. Without accounting for these methodological discrepancies, there is a risk of overgeneralizing findings across languages. Future research should prioritize cross-linguistic comparisons to develop more accurate, language-inclusive models of aphasia recovery.

Regarding the effect of severity, patients with severe aphasia in the acute phase showed the greatest recovery between the acute and chronic phases, which is consistent with previous findings (Mazzoni et al., 1992; Pickersgill & Lincoln, 1983). These greater improvements in the group of persons with moderate-to-severe aphasia led to similar performances between the two groups in the chronic phase on the five comprehension measures. As suggested by Mazzonni et al. (1992), individuals with milder aphasia recover faster and reach a ceiling effect in the earlier phase of recovery. Moreover, Pickergill and Lincoln (1983) suggested that the recovery of comprehension occurs before the recovery of expression, which could explain the greater recovery of comprehension over expression in the severe aphasia group.

Regarding LSM results, impaired performance in comprehending noncanonical sentences was primarily associated with damage to the supramarginal gyrus, which extended to the insula and STG. The supramarginal gyrus is located in the somatosensory association cortex and thus plays a role in integrating sensory information with language processing. The supramarginal gyrus contributes to phonological processing (Hartwigsen et al., 2010) and sentence comprehension (Keller, 2001). More recently, this region has also been linked to verbal working memory (Deschamps et al., 2014; Sawczuk et al., 2024). Manipulation of verbal information to comprehend the meaning of noncanonical sentences requires the use of verbal working memory, which has been extensively reported (Tsaousides & Gordon, 2009). For instance, cognitive rehabilitation therapy (CRT), designed to enhance cognitive function following neuropsychological decline (Tsaousides & Gordon, 2009) could support working memory improvements alongside language therapy. This combined approach may enhance comprehension performance, especially in complex tasks, such as noncanonical sentence processing. However, the peak coordinates obtained in this study correspond to the posterior dorsal supramarginal gyrus, which is reported to be involved in the integration of lexical and sublexical information (Oberhuber et al., 2016). We were not able to directly address the role played by the supramarginal gyrus in auditory comprehension based on the present sample and stimuli, but the present results highlight the importance of investigating the interactions between language and other cognitive functions in PWA (Choinski et al., 2020). Among the studies conducted to date focusing on the interaction between cognitive functions and language, Leff et al. (2009) reported that performance in working memory and comprehension of spoken sentences were both predicted by the left STG in a group of 210 PWA. The present LSM results identified the MTG and STG as regions implicated in both noncanonical sentences and the Token Test, a finding that aligns with those of several previous studies. (e.g., Caplan et al., 2016; Dronkers et al., 2004; Kristinsson et al., 2020; Lwi et al., 2021; Matchin et al., 2023, 2024; Rogalsky et al., 2018; Thothathiri et al., 2012). Based on their findings, Leff et al. proposed that auditory short-term memory and sentence comprehension share the same neural substrate, because auditory short-term memory is likely involved in sentence comprehension. The present results provide novel data to support these claims since the STG was only associated with more complex stimuli. Future studies should include more cognitive measures to provide further evidence of interactions between language and other cognitive functions in PWA. These results could have important implications for the development of future auditory comprehension therapies.

A poorer performance in both the token test and noncanonical sentence comprehension was also associated with damage extending to the left insula. A poorer auditory understanding of the following commands has recently been linked to damage to the posterior insula in patients following a left-hemisphere stroke (Harrington et al., 2024). The posterior insula is involved in phonological processing tasks such as rhyming and short-term phonological verbal memory (Anderson et al., 2010; Bamiou et al., 2003). Given that sequential instructions and noncanonical sentences require additional effort to be understood, the left insula may support this process by integrating multimodal information (Bamiou et al., 2003). The left angular gyrus is one of the cortical areas adjacent to the traditional Wernicke's area, which supports more complex language tasks, such as retrieval of semantic information in phonological tasks. This emphasizes the interconnected nature of language processing in the brain, involving multiple areas beyond the traditional language regions. We hypothesized that only the two most complex and demanding comprehension measures are associated with the insula because they place higher cognitive demands or involve task-specific factors beyond basic auditory comprehension. Notably, the Token Test, the measure of sequential command comprehension used in the present study, has been associated with auditory–verbal span/auditory working memory and executive functions in individuals with right hemisphere stroke, further supporting the role of these cognitive mechanisms in language processing (Basagni et al., 2022). Similarly, phonological short-term memory plays a crucial role in comprehending complex sentences with high computational demands, such as coordinated structures and long-distance filler-gap dependencies, in a group of 15 individuals with fluent aphasia and 15 with agrammatic aphasia (Gilardone et al., 2023). This highlights the complexity of language processing in aphasia and underscores the need to consider cognitive-linguistic interactions when interpreting lesion-symptom relationships.

Nonetheless, our results should be interpreted with caution. First, the extent of our results is limited by the small number of patients who were able to maintain their participation throughout the year of data collection, which limits the generalization of the behavioral results and the statistical power of the LSM analysis. Second, our understanding of how therapy-related variables, such as timing, type, duration, and intensity, affected the outcomes between the subacute and chronic data collection points is limited in the present study, as in most longitudinal aphasia studies conducted to date. We were not able to collect detailed information about the timing, duration, intensity, and type(s) of therapy from all the rehabilitation institutes where our participants were transferred. All participants were covered by the public healthcare system in Quebec, which means that all patients had access to speech and language therapy. Based on the information gathered, speech and language therapy was customized to meet each individual's specific needs and therapeutic goals, often involving a wide variety of therapeutic approaches and, for many, a combination of different methods. Owing to the sample size, it would not have been possible to include these dimensions in the statistical analysis. Typically, patients with milder impairments receive fewer sessions, whereas those with more severe impairments undergo extended and intensive therapy. Notably, many longitudinal studies that do not specifically examine therapeutic effects do not account for the impact of treatment on longitudinal changes (e.g., Hillis et al., 2018; Stockbridge et al., 2019). Nonetheless, there remains a critical need for further research on how different aspects of therapy influence longitudinal changes in post-stroke aphasia. Third, given the logistical challenges of attending in-person assessments and the requirement for MRI in a larger study, we prioritized language measures over cognitive testing. Building on a growing body of evidence, our future studies will now incorporate non-language-based cognitive assessment measures, especially in nonfluent aphasia (Yan et al., 2022), to provide a more comprehensive profile of each PWA. Fourth, it is also important to consider the possibility that practice effects may have contributed to the observed increase in the scores over time. However, it is widely accepted that practice effects in language testing are minimal. Finally, Quebec is predominantly French-speaking, but its geographic location—surrounded by English-speaking provinces and the United States—creates a unique linguistic environment. As Canada is a bilingual country, exposure to English is an integral part of daily life for most Quebec residents. Consequently, we included participants with varying levels of English exposure to better reflect the linguistic realities of this population, ensuring the study's findings are representative of this distinct sociolinguistic context. In a city such as Montreal, where bilingualism is widespread, it is impossible to fully control the degree of proficiency in each language, as individuals' exposure and use vary across contexts and over time. To minimize the impact of this important variable, all participants spoke French on a daily basis prior to the onset of aphasia, ensuring sufficient pre-morbid proficiency in the language.

Despite these limitations, the present study provides valuable insight into the longitudinal changes in auditory comprehension among PWA speaking Laurentian French. Although previous research on auditory comprehension recovery after stroke has predominantly focused on English-speaking populations, this study broadens the scope by exploring recovery in a French dialect with unique phonological, syntactic, and lexical characteristics.

Conclusion

This study highlights the dynamic nature of language processing and recovery by examining changes in auditory comprehension and their associated neural correlates in individuals with acute post-stroke aphasia. Significant improvements in comprehension were observed between the acute and chronic phases, with early recovery trajectories influenced by the initial severity. Canonical sentences and directions showed the greatest improvement but did not reach performance levels comparable to those of individuals without brain damage in the chronic phase. These findings have important implications for both the assessment and intervention strategies for PWA. For instance, given that canonical sentences and sequential commands show the most persistent impairments over time, it may be possible to streamline assessment protocols in the acute phase by prioritizing these sentence structures. This could help reduce the cognitive and time burden of testing while still capturing the essential language deficits.

Moreover, the identified neural activation patterns highlight potential neuroplastic targets for therapy. Auditory comprehension of more complex tasks involves key language-related regions, including the supramarginal gyrus, middle temporal gyrus (MTG), superior temporal gyrus (STG), and insula in the left hemisphere, underscoring their critical role in sentence processing and recovery. These findings emphasize the need for further investigation of the interplay between language and broader cognitive functions in individuals with aphasia. A deeper understanding of these interactions could help identify the underlying cognitive mechanisms that contribute to language impairment, offering valuable insights into individualized treatment approaches. By refining assessment strategies and tailoring interventions to address both linguistic and cognitive deficits, clinicians may enhance treatment precision, accelerate recovery, and ultimately improve functional communication outcomes in individuals with aphasia.

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Data availability statement

The participants of this study did not provide written consent for their data to be shared publicly; therefore, so due to the sensitive nature of the research supporting data is not available.

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Supplementary Table 1. Areas with lesioned voxels were significantly associated with comprehension scores in the chronic phase. Detailed anatomical descriptions of the significant clusters were defined based on the regions of interest from Automated Anatomical Labeling (AAL).

			MNI 152 coordinates			
			Peak center MNI 152 coordinates			
Auditory comprehension task	**Area**	**Cluster size (*k*)**	**x**	**y**	**z**	***z* score**
Noncanonical sentences	Supramarginal gyrus left	38851	-54	-53	27	-3.9
	Insula left					
	Rolandic operculum					
	Superior temporal gyrus left					
	Middle temporal gyrus left	127	-67	-43	0	-3.4
	Middle temporal gyrus left	515	-60	-16	-22	-3.3
	Inferior temporal gyrus left					
	Postcentral gyrus left	44	-32	8	1	-2.6
	Middle temporal gyrus left	80	-61	4	15	-2.3
	Middle temporal gyrus left	79	-60	-32	-10	-2.2

	Middle temporal gyrus left	56	-69	-26	6	-2.2
Sequential commands (Token test)	Middle temporal gyrus left	34842	-28	5	24	-5.2
	Insula left					
	Rolandic operculum left					
	Superior temporal gyrus left					
	Superior temporal gyrus left	1068	-66	-45	17	-3.5
	Angular gyrus left	65	-54	-55	32	-3.0
	Putamen left	209	-17	12	0	-2.9
	Angular gyrus left	69	-13	12	4	-2.9
	Caudate left	87	-40	-47	32	-2.7
	Frontal inferior operculum left	94	-49	8	10	-2.5
	Frontal inferior *pars triangularis* left	52	-32	29	1	-2.1