Speech rehabilitation in post-stroke aphasia using visual illustration of speech articulators. A case report study

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Abstract

Recent studies on the remediation of speech disorders suggest that providing visual information of speech articulators may contribute to improve speech production. In this study, we evaluate the effectiveness of an illustration-based rehabilitation method on speech recovery of a patient with non-fluent chronic aphasia. The *Ultraspeech-player* software allowed visualization by the patient of reference tongue and lips movements recorded using ultrasound and video imaging. This method can improve the patient's awareness of their own lingual and labial movements, which can increase the ability to coordinate and combine articulatory gestures. The effects of this method were assessed by analyzing performance during speech tasks, the phonological processes identified in the errors made during the phoneme repetition task and the acoustic parameters derived from the speech signal. We also evaluated cognitive performance before and after rehabilitation. The integrity of visuo-spatial ability, short-term and working memory and some executive functions supports the effectiveness of the rehabilitation method. Our results showed that *illustration-based rehabilitation technique* had a beneficial effect on the patient's speech production, especially for stop and fricative consonants which are targeted (high visibility of speech articulator configurations) by the software, but also on reading abilities. Acoustic parameters indicated an improvement in the distinction between consonant categories: voiced and voiceless stops or alveolar, post-alveolar and labiodental fricatives. However, the patient showed little improvement for vowels. These results confirmed the advantage of using *illustration-based rehabilitation technique* and the necessity of detailed subjective and objective intra-speaker evaluation in speech production to fully evaluate speech abilities.

Key-words: speech, aphasia, recovery, Ultraspeech, neuropsychology, speech signal

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Introduction

Aphasia is an acquired communication disorder that impairs language functions (expression or comprehension) following brain damage (Benson & Ardila, 1996; Damasio, 1998). Stroke is the most common cause of aphasia (21-38%, Cortese, Riganello, Arcuri, Pignataro, & Buglione, 2015; Engelter et al., 2006). The focus of the present study is on post-stroke non-fluent aphasia (expressive or Broca's aphasia) that is frequently associated with lesions located within the left inferior frontal gyrus (Ardila et al., 2016; Van Der Meulen et al., 2016). Broca's aphasia is characterized by non-fluent spontaneous speech, apraxia of speech, agrammatism, anomia, effortful speech production, limited vocabulary access and short sentence production, while language comprehension remains relatively intact (Baqué et al., 2015; Cortese et al., 2015; Feenaughty et al., 2017). These deficits often include symptoms such as articulation errors or dysfluencies that are also typical of dysarthria or apraxia of speech. These speech and language disturbances may be due to one or several impaired speech production processes, such as selection and planning of speech output, articulatory implementation of selected and planned speech segments, articulatory implementation of speech phonetic parameters and coordination of speech articulators (Kurowski, Hazen, & Blumstein, 2003; Nespoulous, Baqué, Rosas, Marczyk, & Estrada, 2013). Recent studies have shown that less fluent speech may be caused by the inability to create and use an efference copy (internal representation of the speech plan) for speech motor control (Feenaughty et al., 2017; Fridriksson et al., 2012, 2015). For patients with aphasia following stroke, speech and language therapy has been shown to be beneficial in terms of improving language comprehension and production (Brady et al., 2016). Speech and language therapy (SLT) is commonly adapted to fit the individual's ability to integrate auditory and visual speech information and allows the patient to compare his or her own productions (auditory feedback) with those of the speech therapist (auditory and visual feedback – lip reading). This type of SLT should be applied as early as possible, as it is most effective when started early. The most substantial language recovery tends to occur during the first few weeks after the stroke onset (Bhogal et al., 2003). However, according to Hamilton et al. (2011), some degree of spontaneous recovery occurs within 2-3 months after stroke, corresponding to the acute and subacute post-stroke phases. Thus, during the first months after stroke, it is impossible to disentangle between the contributions of rehabilitation and of spontaneous recovery to language improvement (Gerstenecker & Lazar, 2019). It is generally accepted that language recovery slows down significantly and often plateaus after 3 to 6 months, even if some patients experience continued periodic improvement throughout the rest of their lives (El Hachioui et al., 2013; Gerstenecker & Lazar, 2019). A recent study by Breitenstein et al., (2017) reported that in cases where patients receive fewer than 5 hours of SLT per week, the effect of the therapy decreases after a few months during the chronic stage (6 months post-stroke). In this context, more recent innovative approaches to SLT based on emerging assistive speech technologies (i.e., speech recognition software, virtual reality interfaces) could act as valuable supplements or promising alternatives to conventional SLT techniques. Given that aphasia often results in articulation disorders a rehabilitation program aiming at improving language production by training articulation is relevant.

Speech production is based on both motor aspects (articulatory gestures that produce speech sounds) and perceptual aspects (visual and somatosensory representations of these gestures and

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auditory representations of corresponding sounds) (Sato & Grabski, 2014). The dynamics of this perception-action interaction suggest that speech communication skills might be improved using speech and language rehabilitation strategies that center on the observation and the execution of motor gestures. Indeed, a number of studies have shown how important visible articulatory features (e.g. lips, jaw, tongue tip, teeth) are to speech production and perception (Benoît & Le Goff, 1998; Erber, 1975; Garnier et al., 2018; Mcgurk & Macdonald, 1976; Sumby & Pollack, 1954). Moreover, representations of non-visible articulators, such as the tongue or velum, could also play a role. Montgomery, (1981) showed that children display awareness of articulation processes as early as 8 years of age. In this study, children were able to match phoneme sounds with pictures of sagittal sections of the mouth displaying typical configurations of the lips, teeth and tongue. In this line, it has been suggested that tongue reading abilities, similar to lip reading, can be used in SLT for speech perception and production rehabilitation or for pronunciation training (Badin et al., 2007, 2010). Two distinct methods of speech and language rehabilitation have developed on this principle of visual guidance: visual illustration and visual biofeedback (Blyth et al., 2016; Cleland et al., 2015; Fabre et al., 2016; Gibbon et al., 2001; Preston et al., 2013; Roxburgh et al., 2015). The present study focuses exclusively on the visual illustration method, which allows for the visualization of speech articulator movements via pre-recorded images. Among visual illustration methods, audiovisual articulatory synthesis, that involves virtual talking heads, offers potential speech and language rehabilitation outcomes. This technology uses life-like representations to visualize the different active articulators (tongue, jaw, lips, velum) in motion during speech production (Badin, Elisei, et al., 2008; Badin, Tarabalka, et al., 2008; Fagel & Madany, 2008; Massaro & Light, 2004). Several studies have reported integrating animated 3D talking-head interfaces into SLT for aphasic patients (for a review see Chen et al., 2016). Another example of technology that builds on the method of using visual illustration is the *Ultraspeech-player* software (Hueber, 2013). This software allows to visualize movements of actual speech articulators (tongue and lips) recorded on a reference speaker during production of vowels or consonants (isolated or combined). Sagittal movements of the tongue are recorded using ultrasound and front views of lip movements are captured through video imaging. When using this software, the patients deal with three types of information: auditory (recorded sounds produced by the reference speaker and auditory feedback of their own speech production), visual (images of both visible and non-visible speech articulators – front views of the lips and sagittal views of the tongue, respectively) and somatosensory (feeling one's own articulators in motion). Fabre et al., (2016) showed that using the *Ultraspeech-player* improved articulatory awareness and performance of children with phonological disorders (substitution of /tʁ/ by /kʁ/).

Our primary interest in conducting this study was to investigate changes in the quality of speech production (mainly at the phoneme level) following a visual illustration-based rehabilitation therapy (based on the *Ultraspeech-player* software). The quality of phonemic production can be assessed with respect to articulatory (e.g. tongue position) and acoustic features (voice onset time, spectral moments or formants). Voiceless and voiced stop consonants in French (/p, t, k/ vs /b, d, g/) are distinguished by the voice onset time (VOT) which is the time between the voicing onset and the instant of the burst (the release of a stop consonant). In French, VOT is negative for voiced stops and null or positive for voiceless stops. French fricative consonants

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(/f, v, s, z, ʃ, ʒ/) are characterized by their spectral moments (center of gravity, standard deviation, skewness and kurtosis) that describe the spectral properties of the frication noise observed when these consonants are produced (Li et al., 2009; Nissen & Fox, 2005). Spectral moments can distinguish between labiodental (/f, v/), alveolar (/s, z/) and post-alveolar (/ʃ, ʒ/) fricative places of articulation. Fricatives can further be described by their VOT, which can distinguish between voiced (/v, z, ʒ/) and voiceless (/f, s, ʃ/) fricatives (see e.g. Abramson & Whalen, 2017). Oral vowels can be characterized by the first and second formant frequencies (F1 and F2). A graphical representation of F1 as a function of F2 is typically used to assess vowel formant space (Meunier, 2007). Nespoulous et al., (2013) studied voicing control disorders with respect to consonants in non-fluent aphasic patients. They showed that patients were more likely to make devoicing errors on voiced target consonants than voicing errors on voiceless target consonants. Several studies on patients with aphasia have shown that deficits occur in VOT production (suggesting a disorder in temporal coordination of laryngeal and supralaryngeal gestures) and also in the production of voiced fricatives (Baum et al., 1990; Freeman et al., 1978; K. M. Kurowski et al., 2007). Acher et al., (2016) reported that following rehabilitation therapy, a patient with chronic non-fluent aphasia exhibited improved vowel formant production as well as improved voicing for several consonants.

Our primary focus here was to evaluate the effect of a visual illustration therapy on speech recovery in a patient with non-fluent chronic aphasia. The effects of the therapy were assessed by comparing the patient's scores on speech tasks performed both before and after the SLT. As Nespoulous et al., (2013) reported in their work, comparing intra-speaker variations in speech production is essential for evaluating both deficits and speech and language rehabilitation methods. Speech performance can be simply assessed using accuracy scores (% correct responses), but such broad measures do not provide a thorough description of the patients' attempts at producing the target sounds. To better describe speech production patterns, errors themselves can be informative, as they can reveal specific acoustic or articulatory trends. For instance, a sound may be substituted for another acoustically or articulatorily close sound. Therefore, it is interesting to assess the distance between phoneme targets and their actual realizations, by examining confusion matrices. Moreover, an entire class of sounds may be substituted for another class of sounds in a systematic way, such as velars replaced with alveolars. Such a substitution reflects a fronting process and informs on the patients' deficit in the control of the antero-posterior position of the tongue. Consequently, characterizing errors in terms of underlying phonological processes can provide a better description of patients' articulation abilities. Phonological processes that are typically examined in articulation and phonological disorder assessment include velar and nasal assimilations, substitution (fronting, stopping, gliding) and devoicing (Bauman-Waengler, 2012). We therefore assessed the presence of such processes in the errors made by our patient. However, even though, these measures are obtained from transcriptions made by trained phoneticians, they remain subjective assessment. It is interesting to complement these subjective findings with more objective acoustic measurements. Acoustic measurements made on the correctly produced sounds can further characterize the patient's performance. The speech scores examined here are the following: (i) overall speech performance (% of correct responses) during tasks involving phoneme repetition, word repetition, reading, phonemic discrimination; (ii) consonant and

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vowel confusion matrices associated with phoneme repetition; (iii) phonological processes at play in the errors identified during phoneme repetition; and (iv) acoustic parameters derived from the analyses of the audio speech signal recorded during phoneme repetition. The *Ultraspeech-player* software used during the rehabilitation permits the patient to train on all phonemes, however some are specifically targeted by the software because of the higher visibility of tongue and lips configuration (in contrast to *non-targeted* phonemes which have less informative tongue and lip configurations). We suggest that integrating this technology into SLT could improve speech abilities and could result in (a) improved speech performance, with specific increase in phoneme awareness during the phoneme repetition task; (b) a decrease in the percentage of errors associated with typical phonological processes; and (c) a closer alignment of acoustic parameters (formant frequencies, spectral moments and VOT) with the standard values, specifically on the phonemes targeted by the training.

Materials and methods

Patient MG

Demographic and clinical features of the patient are presented in Figure 1 and Table 1. This 41-year-old male patient was included in our study in the chronic phase, at 6 months after the stroke (chronic phase). Clinically, the patient showed Broca's aphasia associated with right hemiparesis, induced by a left hemispheric lesion with damage of the inferior frontal gyrus, insula, primary motor and premotor cortices and partially the superior temporal gyrus (see Figure 1). The lesion was induced by an ischemic stroke caused by the obstruction of the left middle cerebral artery, superficial territory. Right after the stroke, in the acute phase, the patient showed symptoms of a global aphasia (fluent and non-fluent aphasia) but at the moment of examination in the chronic phase, he showed only a non-fluent aphasia. The selection criteria for recruitment of this patient included: (i) the absence of upper limb apraxia (Apraxia Screen of Tulia, AST; Vanbellingen et al., 2011) to ensure the patient's ability to use the computer mouse; (ii) the absence of spatial neglect (bells test and line bisection; GEREN, 2002) to ensure that the patient could visualize all information on the computer screen; (iii) the absence of any comprehension disorder (written and oral comprehension; Boston Diagnostic Aphasia Examination, BDAE; Mazaux & Orgogozo, 1981) to ensure that the patient could understand the explanations about the rehabilitation software; (iv) the absence of bucco-facial apraxia (Montreal-Toulouse protocol, MT86; Nespoulous, Lecours, & Lafond, 1986); and (v) patient familiarity with digital tools (test developed by the neuropsychologist from the Hospital). The language and neuropsychological assessments of the patient validated all these inclusion criteria (see Supplementary Material Table A-B). However, the patient showed a slight bucco-facial apraxia but not prejudicial when using the rehabilitation method. As mentioned in Supplementary Material Table A, the patient's lexical and syntactic oral comprehension was generally preserved, however some errors were made with words belonging to same semantic categories (e.g. body part identification). Written comprehension of words and sentences were preserved; however, the comprehension of written text was more difficult and appeared to depend on length and complexity. Most importantly, the patient exhibited noticeable difficulty with oral expression, produced many perseverations and appeared to suffer from severe arthritis that hindered motor functioning. Written expression was preserved; it became the patient's favorite mode of communication. However, he struggled to write long and infrequent words

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and he presented written dyssyntaxia. The patient successfully performed word repetition for monosyllabic words without complex consonant groups but struggled with longer more complex words and resorted to phonetic pronunciation trial and error without reaching the target word. Oral word reading was impossible (the patient was unable to access articulatory representations from written forms).

Table 1. Demographic and clinical information of the patient.

GENDER, AGE	M, 41 years
HANDEDNESS	Right (Edinburgh test = 0,7)
WORK SITUATION	Painter-craftsman
ISCHEMIC LESION	Left sylvian artery, superficial territory
STROKE ONSET (AGE)	2017-10-13 (40 years)
LANGUAGE DEFICITS	**Initial:** Global aphasia **Symptoms:** stereotypies, preserved written language, preserved comprehension, mute. Non-verbal communication (mimes, gestures, facial mimicry), write isolated words without syntax. **Actual:** Broca's aphasia **Symptoms:** preserved oral and written comprehension (except long text), arthritic disorders, many perseverations, significant deficit of overt reading (except simple syllables with trial and error), and preserved written expression (with the left hand).
ASSOCIATED NEUROLOGICAL DEFICIT	Right hemiparesis

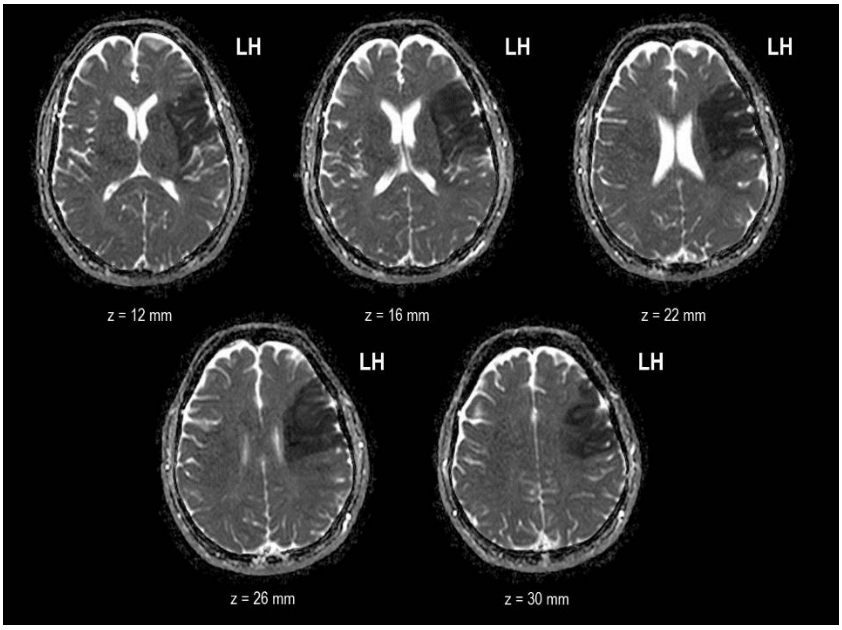

Figure 1. Anatomical MR (T1) axial slices illustrating the lesion observed in the patient, with damage of the left hemisphere (LH) in the inferior frontal gyrus, insula, partially the superior temporal gyrus, motor and premotor cortices, induced by an ischemic stroke in the superficial territory of the left middle cerebral (sylvian) artery.

Rehabilitation procedure

Rehabilitation consisted of 11 sessions using the *Ultraspeech-player* software (Hueber, 2013). Each session lasted 30 minutes and was administered 3 times per week over a four-week period.

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During the same time period, the patient received conventional SLT (3 times/week). The first session was dedicated to presenting the software to the patient and explaining how it worked. The patient was seated in front of the computer screen and the experimenter manipulated the *Ultraspeech-player* software to play the sounds associated with different consonants and vowels and to simultaneously show videos of corresponding tongue or lip movements. The *Ultraspeech-player* software includes several sets of sounds and video recordings, made on several of reference speakers (speech therapists, phoneticians). In this rehabilitation program, the recordings from a female trained phonetician were used. The speaker's midsagittal tongue movements had been recorded using ultrasound imaging (60fps, 640x480pixels) and the lip movements had been captured using a video camera (60fps, 640x480pixels), with frontal view. Both sensors were maintained fixed relatively to the speaker's head using a customized version of the helmet manufactured by Articulate Instruments (www.articulateinstruments.com). Importantly, the software also allows the user to slow-down both the articulatory gesture and its corresponding acoustic realization (allowing a more intuitive visualization). The *Ultraspeech-player* software is illustrated in Supplementary Material Figure A. After the initial introductory session, the SLT based on sensory-motor integration (SMI) started and continued during eleven sessions. During each of these sessions, the patient observed and listened to the target item which he was then asked to repeat back (about five times) and then moved on to the next item, with the agreement of the experimenter. During each session, the patient performed two exercises: the first based on phonemes trained in the previous session (three or four items) and the second contained new phonemes for which he had never trained before (three or four new items). Each session was personalized according to the patient's progress and difficulties encountered during previous sessions. The trained phonemes were: French consonants and semi-consonants /w, j, p, t, k, b, d, g, f, s, ʃ, v, z, ʒ, m, n, l, ʁ/ and vowels /a, œ, ø, e, ɛ, o, ɔ, y, u, i, ɛ̃, ɑ̃, ɔ̃/, isolated or combined (vowel-consonant-vowel, VCV).

All phonemes mentioned above were integrated into the software for the rehabilitation procedure, but they were classified into distinct categories as targeted phonemes and non-targeted phonemes. Indeed, the *Ultraspeech-player* software is particularly suited to train phonemes with visibly specific sagittal configurations of the tongue or frontal views of the lips. Specifically, stop consonants /p, t, k, b, d, g/, fricative consonants /f, v, s, z, ʃ, ʒ/, and the liquid consonant /l/ were selected as target phonemes. Phonemes for which the tongue and lip configurations were less informative, were considered as non-target phonemes. These include: (i) the oral vowels /i, y, u, a, Œ, O, E/ (with archiphoneme: /Œ/ = /œ, ø/, /O/ = /ɔ, o/ and /E/ = /e, ɛ/) and glides /j, w/, which can be difficult to discriminate because the difference in the oral aperture or lip configuration may be visually unnoticeable; (ii) the uvular fricative /ʁ/, whose place of articulation is difficult to extract because the uvula is not visible ; (iii) the nasal vowels and consonants /ɛ̃, ɑ̃, ɔ̃, m, n/, for which information on velum lowering is not provided.

Neuropsychological assessment

The patient underwent a neuropsychological evaluation carried out by a neuropsychologist, before and after rehabilitation (Table 2). The assessment included different tests in order to evaluate: cognitive performance (Cognitive Assessment Scale for Stroke Patients, CASP; Barnay et al., 2012); executive functions (visuo-spatial span, Ruff figural fluency test, Trail

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Making Test; Godefroy & GREFEX, 2008; Ruff, Light, & Evans, 1987; Wechsler, 2012); visual episodic memory (*Batterie d'Efficience Mnésique de Signoret*, BEM84; Signoret, 1991); mental rotation abilities (Albaret & Aubert, 1996; Vandenberg & Kuse, 1978); and mood (Hospital Anxiety and Depression Scale, HAD; Zigmond & Snaith, 1983).

Table 2. Scores obtained by the patient during the neuropsychological assessment performed before and after rehabilitation (* low score; ** pathological score). This neuropsychological assessment evaluated: cognitive performance (Cognitive Assessment for Stroke Patients, CASP); executive functions (visuo-spatial span; Ruff Figural Fluency Test, RFFT; and Trail making test, TMT); visual episodic memory ("*Batterie d'efficience mnésique*", BEM84); mental rotation abilities; and mood (Hospital Anxiety and Depression scale, HAD).

	TASKS	**BEFORE REHABILITATION**	**AFTER REHABILITATION**
COGNITIVE ASSESSMENT FOR STROKE PATIENTS (CASP)	Naming	0.5/3	1/3
	Comprehension	3/3	3/3
	Reproducing a copy of a cube	3/4	3/4
	Graphic series	2/2	2/2
	Inhibition/Flexibility (total) Conflicting orders Go / NoGo	4/4 2/2 2/2	4/4 2/2 2/2
	Bisection of a horizontal line	2/2	2/2
	Image recall	6/6	6/6
	Praxis (total) Meaningless gestures - imitation Symbolic gestures - pantomime Recognition	6/6 2/2 2/2 2/2	6/6 2/2 2/2 2/2
	Calendar	6/6	6/6
	Global score (CASP)	32.5/36	33/36
EXECUTIVE FUNCTIONS ASSESSMENT	Visuo-spatial span		
	Span forward	6	6
	Span backward	6	6
	Figural fluency (RFFT)		
	Number of unique designs generated	26	24
	Percentage of perseverations (cut-off: 15%)	15.4*	16.6**
	Trail Making Test (TMT)		
	Part A: time (seconds) (cut-off : 67)	33 s	29 s
	Part A: error (cut-off: 2)	0	1
	Part B: time (seconds) (cut-off: 151)	161 s**	117 s
	Part B: error (cut-off: 3)	1	1
	Part B-A: time (seconds) (cut-off: 120)	128 s**	88 s
	Part B-A: error (cut-off: 1)	1 *	0
VISUAL EPISODIC MEMORY (BEM 84)	Immediate recall	10/12 (-0.3σ)	8.5/12 (-1.45σ)*
	Delayed recall	7.5/12 (-1.97σ)**	8/12 (-1.6σ)*
MENTAL ROTATION ABILITIES	Score	22 (standard value)	22 (standard value)
	Time (total)	3min 35	8min 06
MOOD ASSESSMENT (HAD SCALE)	Anxiety score (cut-off ≤ 7)	5	15**
	Depression score (cut-off ≤7)	0	13**

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Speech assessment

In order to evaluate speech performance, before and after rehabilitation, the patient performed: a phoneme repetition task (PR) with isolated vowels (V = /a, œ, ø, e, ɛ, o, ɔ, y, u, i, ɛ̃, ɑ̃, ɔ̃/), semi-consonants in vowel context (/ja, wa, ɥi/) and consonants in /a/ context with the consonants placed in initial (/Ca/) or medial (/aCa/) positions (C = /p, t, k, b, d, g, f, s, ʃ, v, z, ʒ, m, n, ɲ, l, ʁ/); a simple word repetition task (WR); a reading task; a phonemic discrimination task. The PR (for isolated vowels and consonants in /Ca/ condition) and WR are derived from the "*Batterie d'Evaluation Clinique de la Dysarthrie"* (BECD; Auzou & Rolland-Monnoury, 2006) and the phonemic discrimination task is derived from the "*Batterie Analytique du langage écrit"* (BALE; Jacquier-Roux, Lequette, Pouget, Valdois, & Zorman, 2010). During the PR and WR the speech therapist produced the phonemes or words and the patient was asked to repeat them. The reading task was developed by the speech therapists in Grenoble hospital. During the reading task, the patient was asked to read aloud a series of syllables presented one above the other on a piece of paper. During the phonemic discrimination task, the speech therapist produced a pair of syllables and the patient was asked to indicate whether they were identical or not by using his finger to point to the words "Same" or "Not Same" written on a piece of paper. PR and reading tasks were performed three times, while WR and phonemic discrimination were performed once. All tasks were recorded via a microphone. Supplementary Material Table C showed items used in each task.

Data processing

Acoustic data

The acoustic signal obtained from the recording of PR and WR tasks, before and after rehabilitation, was recorded at 44.1 kHz. Each recording was labeled and phonetically transcribed by a trained phonetician using Phon (Hedlund & Rose, 2018; Rose et al., 2006; Rose & MacWhinney, 2014) and acoustic analyses were performed using the Praat (Boersma & Weenink, 2010) software (see Appendix A for more details). All data from PR were re-transcribed by a second phonetically-trained native speaker of French, with 82% agreement, which is more than standard values observed in patient audio data transcription.

In addition to the phonetic transcription, an acoustic analysis was carried out on the sounds judged as correctly produced, in order to assess their degree of accuracy more objectively. Typical acoustic parameters were extracted for phonemes judged as correct or emergent during the PR: the first two formants F1 and F2 for the 10 oral vowels /i, e, ɛ, a, y, ø, œ, u, o, ɔ/; the first two spectral moments (Center of Gravity, CG and Standard Deviation, SD) for the 6 fricative consonants /f, v, s, z, ʃ, ʒ/ in /Ca/ and /aCa/ conditions; and the voice onset time (VOT) for the 6 stop consonants /p, t, k, b, d, g/ in /Ca/ and /aCa/ conditions.

Speech performance

As concern the PR and WR tasks, the percent phonemes correct (PPC) and the PPC in words were extracted, respectively, using Phon scripts. For the reading and phonetic discrimination tasks, the average percentage of syllables correctly read and the percentage of correctly discriminated syllable pairs were extracted. In order to evaluate the accuracy during each task

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we calculated global evolution indices (EI) based on scores determined for each item, allowing us to compare performance levels before and after rehabilitation. The score was +1 if the item was incorrect before but correct after rehabilitation, -1 if the item was correct before but incorrect after rehabilitation, 0 if the item was correct before and after rehabilitation or incorrect before and after rehabilitation.

Complementary analyses of the errors observed during the PR was performed. First, in order to assess the distance between phoneme targets and their actual realizations, an R script was used to create confusion matrices that represent target phonemes as a function of phonemes actually produced, both before and after rehabilitation. We performed three confusion matrices: one for vowels with archiphonemes (/Œ/ = /œ, ø/, /O/ = /ɔ, o/, /E/ = /e, ɛ/), one for consonants and semi-consonants in /Ca/ condition and one for consonants in /aCa/ condition. These archiphonemes were used because the underlying open-mid and close-mid vowels are often confused, even by typical speakers (Durand et al., 2014). Secondly, the Phon software allowed us to extract several typical phonological processes in the errors observed during the PR, especially for the consonants identified as incorrect in /Ca/ and /aCa/ conditions, before and after rehabilitation. The Phon software compares “target phonemes” with “actual phonemes”, and uses phonological rules adapted to French to extract the percentages of occurrence of a set of phonological processes identified in the errors. We extracted seven processes: devoicing (producing an voiceless consonant instead of a voiced consonant, e.g. /p/ instead of /b/); voicing (producing a voiced consonant instead of a voiceless consonant, e.g. /d/ instead of /t/); velar fronting (producing a alveolar consonant /t/ or /d/ instead of a velar /k/ or /g/, respectively); fricative stopping (producing a stop instead of a fricative or continuous consonant, e.g. /p/ instead of /f/); coronal backing (producing a posterior consonant instead of a coronal, e.g. /k/ instead of /t/); lateralization (producing a lateral consonant instead of the target consonant, e.g. /l/ instead of /n/); nasalization (producing an oral consonant instead of a nasal consonant, e.g. /b/ instead of /m/).

Statistical analyses of data

Statistical analyses were carried out to determine if there was a significant difference between before and after rehabilitation in the speech assessment tasks. Logistic regression was used to evaluate the association between accuracy during speech assessment tasks and rehabilitation. Thus, we performed five logistic regressions for: (i) the PR task of consonants in /Ca/ condition; (ii) the PR task of consonants in /aCa/ condition; (iii) the PR task of vowels; (iv) the WR task; (v) the reading task. These statistical analyses were carried out using R software. To perform each logistic regression we defined two variables: (i) a binary dependent variable, which is accuracy (correct or incorrect response to the task); (ii) a binary independent variable, which is the time (before or after rehabilitation).

Results

Neuropsychological results

The neuropsychological assessment (Table 2) indicated that the patient exhibited a picture naming deficit but comprehension, visuo-constructive abilities, mental flexibility (CASP), temporo-spatial orientation and recognition ability, before and after rehabilitation, appeared

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unaffected. The patient showed correct performance in working memory and visuospatial short-term memory tasks, before and after rehabilitation. He did exhibit a deficit in cognitive flexibility during figural fluency before and after rehabilitation, and only before rehabilitation during TMT (Part B). The patient also showed impaired visual episodic memory reflected in a pathological score before rehabilitation but a low (non-pathological) score after rehabilitation. Finally, the patient presented preserved mental rotation abilities with increased processing duration and mood aggravation after rehabilitation.

Speech performance

Accuracy

Table 3 shows the patient's performance levels during the speech assessment. The recorded values show a significant improvement in the production of consonants in /Ca/ (from 57.30% before to 80.30% after rehabilitation; z = 2.95, p < .01) and /aCa/ (from 32.65% before to 65.67% after; z = 4.09, p < .001) conditions, with an EI of +8 and +12, respectively. However, there was no significant improvement for vowels between before and after rehabilitation (34.48% before and 39.68% after rehabilitation), with an EI of +1. During the WR, the PPC contained in words increased significantly after rehabilitation (from 43.04% to 56.27%; z = 3.06, p < .01), with an EI of +13. Regarding the reading task, a significant improvement was observed with an increase in the percentage of correctly read syllables (from 39.22% to 66.67%; z = 2.74, p < .01), with an EI of +11. Finally, the patient's performance was 100% in the phonemic discrimination task, before and after rehabilitation (EI = 0).

Table 3. Accuracy (%) of each tasks performed during the speech assessment, before and after rehabilitation, judged by the transcriptor as correct: the percent phonemes correct (PPC) during the phoneme repetition task for each condition (isolated vowels /a, œ, ø, e, ɛ, o, ɔ, y, u, i, ɛ̃, ɑ̃, ɔ̃/, semi-consonants /j, w, ɥ/ and consonants in /Ca/ and /aCa/ conditions with C = /p, t, k, b, d, g, f, s, ʃ, v, z, ʒ, m, n, ɲ, l, ʁ/); the PPC in words during word repetition; the average percentage of syllables correctly read; and the percentage of correctly discriminated syllable pairs. We also calculated global evolution indices (EI) for each task and we performed logistic regressions for each task to assess whether the evolution of the patient's performance was significant (*p < .01 and **p < .001).

		BEFORE REHABILITATION	AFTER REHABILITATION	EI	z value	p-value
PHONEME REPETITION	**/Ca/**	57.30%	80.30%	+8	2.95	**0.00316***
	/aCa/	32.65%	65.67%	+12	4.09	**$4.31*10^{-5}$****
	/V/	34.48%	39.68%	+1	0.59	0.55462
SIMPLE WORD REPETITION		43.04%	56.27%	+13	3.06	**0.00218***
READING		39.22%	66.67%	+11	2.74	**0.00614***
PHONEMIC DISCRIMINATION		100.00%	100.00%	0	-	-

Confusion matrices

Figure 2 shows the confusion matrices for vowels, semi-consonants and/or consonants in /Ca/ and /aCa/ conditions. The confusion degree (CD) is a value between 0 and 1. A CD value equals to 1 indicates no confusion, i.e. the actually produced phoneme is the target phoneme (the phoneme production was 100% correct). A CD value equals to 0 means that the correct phoneme was never produced like the corresponding target.

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We observed that the vowels /a, i, u/ were mastered by the patient after the SLT (Figure 2A-B). Post-therapy, the production of /E/ improved from 38% to 67% correct, with a substitution by [a] (CD = 0.25) and [i] (CD = 0.08). However, the production of /y, Œ/ was impaired after rehabilitation with substitution of /y/ by [i] (correct place of articulation but incorrect lip rounding) and substitution of /Œ/ by [O, y] (correct lip rounding but incorrect place of articulation) and [a, E] (incorrect manner and place of articulation). Concerning nasal vowels, the patient substituted /ɔ̃/ by [O] (CD = 1.00), /ɑ̃/ by [a] (CD = 0.50, with 25% of success of /ɑ̃/). The percentage of correct production of /ɛ̃/ increased (from 0% to 67%, with 33% of substitution by [a]). The nasal vowel substitution shows that while the patient was able to control the place of articulation, nasalization was never fully mastered.

For consonants in /Ca/ condition (Figure 2C-D), the results show confusion among stops /t, d, k, g/ and fricatives /f, s, z/, before rehabilitation. Post-rehabilitation, the patient perfectly produced the phonemes /t, d, k, s/. The production of /g/ improved (from 0 to 67% correct) with a substitution by [d], suggesting that voicing was correct but place of articulation was incorrect (anteriorization of the tongue). The patient also improved his production of /z, m/ but manner and place of articulation were still imperfectly controlled. The phoneme /n/ was perfectly mastered following the therapy. However, after rehabilitation, the percentage of correct production of /f/ decreased (from 100% to 75%) with a substitution by [s], suggesting correct manner of articulation, but the place of articulation was still imperfectly controlled. Finally, the semi-consonants (/j, w, ɥ/) were perfectly mastered before rehabilitation but the patient substituted /ɥ/ by /j, y/ (CD = 0.25) after rehabilitation, suggesting that the dynamics of articulators was imperfectly controlled.

Before rehabilitation, the patient exhibited difficulty producing consonants in /aCa/ condition (Figure 2 E-F) and made numerous perseveration by substituting /p, b, t/ by [k], /d, k, g/ by [t], or /z, ʒ, m, n, ɲ/ by [v]. After rehabilitation, the patient perfectly mastered the phonemes /p, b, k, ʃ, z, m, ɲ/ and he improved in his production of /t, d, g, v, ʒ, n/ while the manner and/or place of articulation as well as the voicing were imperfectly controlled for these consonants. After rehabilitation, the patient perfectly mastered the phoneme /ɲ/, which was not produced in /Ca/ condition. Finally, before and after rehabilitation, in /Ca/ and /aCa/ conditions, the patient substituted /ʁ/ by [χ] (correct place of articulation but incorrect voicing).

Phonological processes

The phonological processes that were observed in the errors (incorrectly produced phonemes) during the PR of consonants are shown in Table 4. The percentage of devoicing errors decreased between before and after rehabilitation (from 24.8% to 13.5%), suggesting better coordination between laryngeal and supra-laryngeal movements. The percentage of velar fronting decreased between before and after rehabilitation (from 50.0 to 11.1%), suggesting better control of the tongue in the anterior position. The percentage of nasalization errors decreased after rehabilitation (from 58.0% to 18.2%), suggesting better coordination between speech articulators. Finally, there was no change in the percentage of voicing errors (from 1.9% to 2.3%), fricative stopping (from 1.6 to 2.0%), coronal backing (from 4.0 to 4.1%) and lateralization errors (from 1.5 to 0.3%), between before and after rehabilitation.

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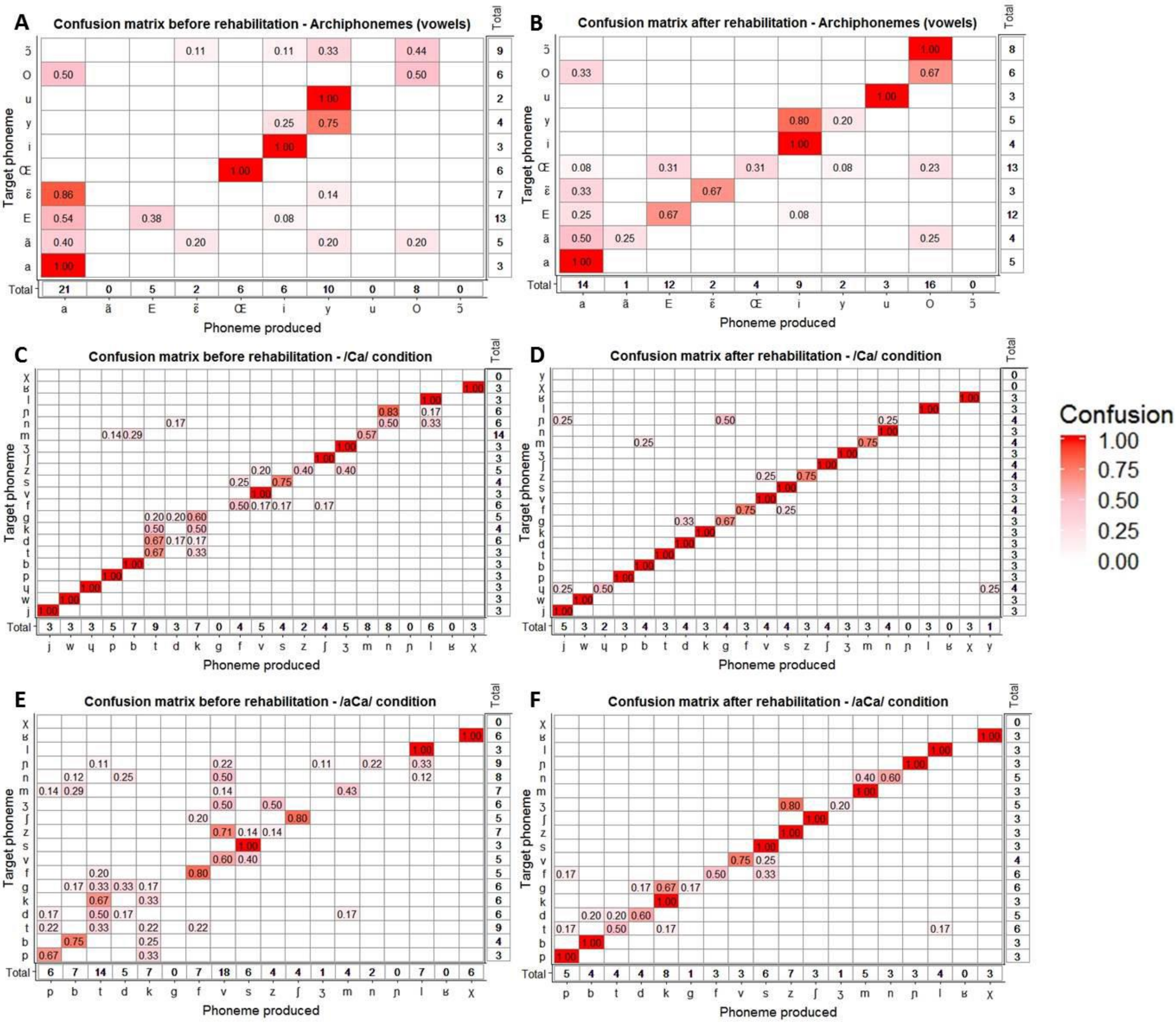

Figure 2. Confusion matrices showing target phonemes as a function of phonemes produced, as well as the number of target phonemes requested (in row) and the number of actual produced phonemes (in column). The confusion matrices show: (A-B) isolated vowels with archiphonemes (V = /a, y, u, I, Œ, E, O, ɛ̃, ɑ̃, ɔ̃/); (C-D) consonants and semi-consonants in /Ca/ condition (C = /j, w, ɥ, p, t, k, b, d, g, f, s, ʃ, v, z, ʒ, m, n, ɲ, l, ʁ/); (E-F) consonants in /aCa/ condition (C = /p, t, k, b, d, g, f, s, ʃ, v, z, ʒ, m, n, ɲ, l, ʁ/). The confusion degree (CD) is a value between 0 (the correct phoneme was never produced like the corresponding target) and 1 (no confusion; the actually produced phoneme is the target phoneme; phoneme production was 100% correct).

Table 4. Percentage of typical phonological processes in the errors observed during the phoneme repetition task of consonants in /Ca/ and /aCa/ conditions, before and after rehabilitation. We identified 7 processes: devoicing, voicing, velar fronting, fricative stopping, coronal backing, lateralization and nasalization.

	BEFORE REHABILITATION	AFTER REHABILITATION
DEVOICING	24.8%	13.5%
VOICING	1.9%	2.3%
VELAR FRONTING	50.0%	11.1%
FRICATIVE STOPPING	1.6%	2.0%
CORONAL BACKING	4.0%	4.1%
LATERALIZATION	1.5%	0.3%
NASALIZATION	58.0%	18.2%

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Acoustic results

Formant spaces (F1/F2) and intra-vowel distances obtained before and after rehabilitation, for the vowels judged as correctly produced, are presented in Figure 3 (see also Appendix A for more details on intra-vowel distance). The intra-vowel distance decreases for /i, o, œ/ while it increases for /a, e/ (Figure 3C). The vowel /ø/ was correctly produced only before but not after rehabilitation, while /ɔ, u/ were produced only after rehabilitation. The vowel /y/ was produced 3 times before rehabilitation but only one time after and the vowel /ɛ/ was produced neither before nor after rehabilitation (Figure 3A, B). The values of spectral moments (CG and SD) obtained for the voiceless fricatives are presented in Figure 4. The CG values (Figure 4 A-B) did not show the expected order (alveolar > labiodental > post-alveolar), before and after rehabilitation. However, the CG value was higher for the alveolar fricative /s/ than for the post-alveolar one /ʃ/, suggesting that the patient was able to make a distinction between the alveolar consonant /s/ and the post-alveolar /ʃ/. Whereas the SD values (Figure 4 C-D) presented the expected order (labiodental > alveolar > post-alveolar) before and after rehabilitation, suggesting that the patient successfully distinguished the labiodental /f/ from the alveolar and post-alveolar /s, ʃ/. For stops, mean VOT values are shown in Table 5. The VOT values obtained for the speech therapist (from Haldin et al., 2018) show the typical distinction between voiced (negative value) and voiceless (positive value) stop consonants. For voiceless stops produced by the patient, mean VOT values were positive and close to the normal value (compared with reference data from a speech therapist), before and after rehabilitation, whereas for voiced stops, mean VOT values were more negative than normal values, before and after rehabilitation, but values increased after rehabilitation (gradually became less negative).

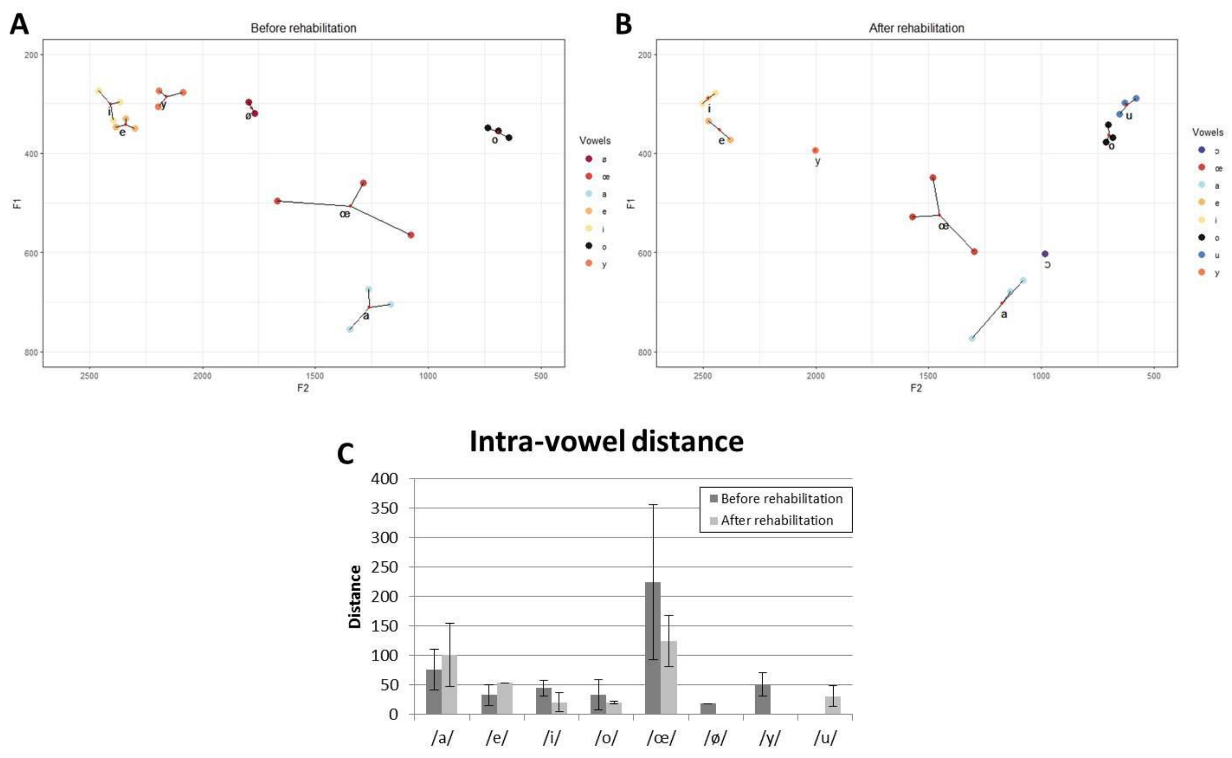

Figure 3. Vowel F1/F2 formant space for the patient before (A) and after (B) rehabilitation. The centroid (barycenter) of each vowel was identified (red dot) and intra-vowel distance (C) was calculated (distance between each vowel and its centroid).

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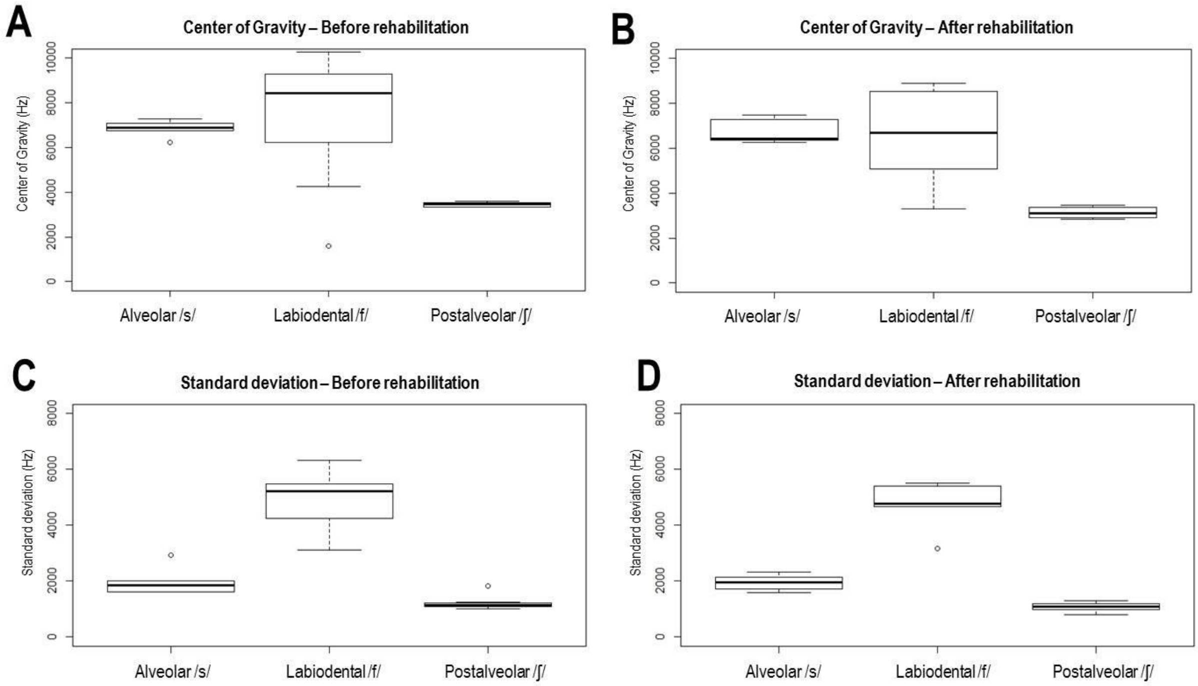

Figure 4. Boxplots of the two spectral parameters: Center of Gravity (CG) and Standard Deviation (SD), obtained before and after rehabilitation, for voiceless fricative consonants /f, s, ʃ/ in /Ca/ and /aCa/ conditions.

Table 5. Mean values of voice onset time (VOT, in ms) obtained for the patient and the speech therapist (from Haldin et al., 2018) for voiced (/b, d, g/) and voiceless (/p, t, k/) stop consonants produced during the phoneme repetition task in /Ca/ and /aCa/ conditions.

	VOT (in ms)	
	Voiced stops	**Voiceless stops**
BEFORE REHABILITATION	- 314.042 (± 124.057)	28.772 (± 20.727)
AFTER REHABILITATION	-264.480 (± 69.458)	31.639 (± 23.477)
SPEECH THERAPIST	-112.574 (± 46.698)	26.902 (± 10.382)

Discussion

In the present study, we evaluated the effectiveness of using visual illustration of tongue movements (pre-recorded using ultrasound imaging on a reference speaker and displayed in an intuitive manner via the *Ultraspeech-player* software) as a speech and language rehabilitation tool and assessed speech recovery in a 41-year-old male patient with non-fluent chronic aphasia (associated with right hemiparesis). The lesion was located within the left hemisphere, inducing damage of the inferior frontal gyrus, insula, primary motor and premotor cortices and partially the superior temporal gyrus. This lesion has been induced by an ischemic stroke caused by the obstruction of the left middle cerebral artery (superficial territory). Our evaluation was based on a thorough analysis of the patient's speech performance (percentage of correct responses during specific tasks, calculation of an evolution index, confusion matrices, and phonological processes identified in the errors) and acoustic parameters measured during a phoneme repetition task (PR). We also evaluated cognitive abilities of the patient (neuropsychological assessment).

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The patient showed oral expression disorders manifested through numerous perseverations and severe arthritis that hindered motor programming. The patient did not shows signs of disorders of cognitive abilities evaluated during the CASP (Barnay et al., 2012), except for the naming task (Table 2). The naming disorders we observed may have been attributed to the patient's severe arthritis that made it difficult for him to produce the words containing more than two syllables, which were presented during the CASP naming task (e.g., "*papillon"*, butterfly or "*pantalon"*, pants). Murray & Coppens (2017) showed that language disorders (expression or comprehension) have a negative impact on the performance of cognitive abilities that are language-mediated. The patient showed mental flexibility disorders during figural fluency (with many perseverations) before and after rehabilitation, and only before the therapy for the TMT (Part B). Aphasic patients with left hemispheric stroke often show language production disorders but also motor deficits (e.g. hemiparesis) which are additional factors that contribute to difficulties of patients during cognitive assessment. Tasks requiring motor activity, such as TMT or figural fluency, depend on motor speed and motor abilities, which represent additional obstacles for these patients and hinder their performance (Bonini et al., 2015; Lee & Pyun, 2014). The patient also showed visual episodic memory disorders with a lack of consolidation, before rehabilitation. Bonini et al., (2015) showed that post-stroke patients with aphasia presented poorer performance than non-aphasic patients during visual memory task. This result, also observed in our study, combined with correct performance in picture recognition task suggests that non-verbal encoding was preserved but that there was a deficit in the ability to retrieve visual information which may be stored using verbal encoding. Non-verbal ability disorders were difficult to interpret and may be due to: the involvement of verbal skills in nonverbal tests; the dysfunction of brain because of the lesion; or the involvement of language as additional resource to realize nonverbal task (Ardila & Rubio-Bruno, 2018; Fonseca et al., 2017). Finally, the patient did not exhibit any mental rotation disorders, but processing duration increased after rehabilitation, which could be linked to the decline in mood related to his personal life situation at the time of the assessment. As mentioned in previous studies, it is necessary to maintain the integrity of some cognitive abilities (verbal and visuo-spatial short-term memory, working memory, executive function) because of their impact on aphasia severity, language function and its recovery (Dignam et al., 2017; Fonseca et al., 2017; Seniów et al., 2009). Indeed, deficits in memory, executive functions, speed processing have been shown to be associated with an increase of aphasia severity (Fonseca et al., 2018). In addition, maintaining visuo-spatial processing abilities is necessary since the *Ultraspeech-player* software requires the patient to visualize typical articulatory gestures (lip and tongue movements) performed during speech production, in order to correct his own articulatory movements. Thus, the results of the neuropsychological assessment (integrity of some cognitive abilities) are in favour of the use of this rehabilitation method.

The speech assessment showed that the patient's speech production abilities improved after rehabilitation and the patient's phonological awareness remained preserved both pre- and post-therapy (Table 3). Indeed, naming of written items and phoneme production abilities in words significantly improved after rehabilitation (positive EI). Improvement in reading performance suggests an enhancement in the grapheme-phoneme conversion ability. Results of the PR task showed no significant improvement for vowels: the patient's oral production of /E, u, O/ and

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nasal /ɛ̃, ɑ̃/ appeared to improve after the therapy, while his production of /Œ, y/ vowels declined (Figure 2). The intra-vowel distances decreased after the rehabilitation for /i, o, œ/ (suggesting a better reproducibility of these vowels across repetitions) but increased for /a, e/ (suggesting an increase in intra-vowel variability). For /i, e/, post-therapy, the patient produced one repetition less than pre-therapy, which may in part explain the variation of the intra-vowel distances measured pre- and post-therapy. It should be noted that some vowels are visually quite similar (in their lip or tongue configurations) in the *Ultraspeech player* software (/ø, œ/, /o, ɔ/ or /e, ɛ/). Thus, vowels do not constitute a privileged target for the software-based rehabilitation which could explain the absence of improvement, in contrast to consonants. Indeed, consonant production abilities, during PR, improved between before and after rehabilitation in both /Ca/ (EI = +8) and /aCa/ (EI = +12) conditions. The patient improved in the production of stops and fricatives (less perseveration in /aCa/ condition and less confusion in both /Ca/ and /aCa/ conditions). He also improved in the production of nasal consonants /m, n/ in /Ca/ and /aCa/ conditions, but also /ɲ/ in /aCa/ condition, after rehabilitation. However, under both conditions, the patient failed to produce the phoneme /ʁ/ which he substituted with /χ/ (devoicing). These results, in accordance with the analysis of phonological processes identified in the errors, suggest a better control of speech articulators (tongue, velum, larynx…) which is attested by a decrease in velar fronting, devoicing and nasalization errors after rehabilitation. Several previous works have reported that patients with Broca's aphasia present voicing and nasalization disorders characterized by impairments in the timing and coordination of articulators (between the release of supra-glottal closure and the onset of glottal excitation, for voiced stops; between the release of the closure in the oral cavity and the velum opening, for nasal consonants), as well as laryngeal control deficit for fricative consonants (Blumstein, 2016; K. Kurowski et al., 2003; K. M. Kurowski et al., 2007). Our results are also consistent with the findings of Nespoulous et al., (2013). They showed that patients produce devoicing errors more frequently than voicing errors, although voicing errors (voicing of a voiceless target consonant) do remain (see also Valdois & Nespoulous, 1998). The decrease in devoicing and nasalization errors observed here suggests a more adequate timing and coordination of articulators (laryngeal and supra-laryngeal for voicing; closure in the oral cavity and velum opening for nasalization). The articulatory improvements observed in our patient therefore suggest that this rehabilitation strategy is potentially adapted to intervention with Broca’s aphasia patients. Moreover, as mentioned by Valdois & Nespoulous (1998), patients with Broca's aphasia also show errors in place of articulation for voiceless consonants leading to substitutions such as /t/ instead of /k/ (velar fronting). Visualizing the target (correct) tongue movements may help the patient to correct his own production. The decrease in velar fronting errors suggests that our patient did gain greater control of his tongue position.

In addition, acoustic analyses on the stop consonants judged as correctly produced (Table 5) attest that the patient correctly produced voiceless stops, in terms of VOT, before and after rehabilitation. However, he improved his production of voiced stops with an increase of mean VOT value (approaching what is considered as a typical value, and closer to the values obtained for the speech therapist) but this value remained lower than normal, with an important amount of prevoicing. These results are consistent with those of some studies that have shown that patients maintain the difference in VOT between voiced and voiceless stops (Nespoulous et al.,

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2013; Ryalls et al., 1995). The longer prevoicing observed in our patient for voiced stops (relative to reference values in French), may be associated with an anticipatory strategy to prepare voicing long before consonantal occlusion, in order to facilitate voiced consonant production. These VOT measurements further attest that coordination between laryngeal and supralaryngeal gestures was improved after therapy, although not reaching typical values.

For fricative consonants, the CG values (Figure 4) objectively attests that following the therapy the patient was able to make a distinction between alveolar /s/ and post-alveolar /ʃ/ fricatives (CG values: alveolar > post-alveolar; Nissen & Fox, 2005) and between labiodental /f/ and alveolar and post-alveolar /s, ʃ/ fricatives (SD values: labiodental > alveolar > post-alveolar; Nissen & Fox, 2005). These acoustic measurements further attest that place of articulation was better controlled after therapy.

An important aspect and advantage of integrating a visual articulatory illustration software (such as *Ultraspeech-player)* into SLT is that it offers the patient both flexibility and autonomy. The patients can self-regulate the training, by selecting the phoneme to train on during the exercise and by moving to the next item at will, e.g. after about five repetitions. They can also slow down or speed up the articulatory gesture and its corresponding acoustic realization. Autonomy and self-adaptation is a potentially significant factor in terms of motivation and sustained engagement that are both clearly linked to progress and ultimately recovery (Kirmess & Maher, 2010). Given that the experimenter was present during the rehabilitation, she could help the patient if errors persisted during the trained phonemes repetition, which could have influenced rehabilitation and recovery. Nevertheless, in order to enhance the autonomy of the patient, the experimenter tried to interfere as little as possible. At the time of this study, our patient was relatively young, which may also be a contributing factor in successful speech recovery. Several studies have reported that age does play a role and that full speech recovery is more likely in younger patients (Ferro & Crespo, 1988; Holland et al., 1989; Ogrezeanu et al., 1994). Other authors posit that age is not a factor and dispute these results (for a review see Ellis & Urban, 2016). Moreover, adding *illustration-based rehabilitation technique* to conventional SLT increases the total duration of rehabilitation (intensive rehabilitation), which can also contribute to improving speech production abilities after rehabilitation. Taken together, our results show that visual illustration clearly facilitated improvement in terms of the patient's control of the position and coordination of his speech articulators (e.g., tongue, lips, velum, teeth etc.), notably for stop and fricative consonants pronunciation (phonemes targeted by this specific therapy). These results were observed not only in the percentage of phonemes judged as correct but also attested in terms of objective acoustic parameters. The patient improved in his production of target consonants in /Ca/ and /aCa/ conditions and exhibited greater control over his tongue position and voicing. It should be noted that the patient had no previous experience (lacked familiarity and training) with consonant repetition in /aCa/ condition before the therapy began. Visual illustration allowed this patient to focus specifically on practicing vowel or consonant pronunciation in isolated and combined conditions (vowel-consonant-vowel). The patient's improved performance in producing consonants in /aCa/ condition supports the argument that visual articulatory illustration is an effective approach for speech recovery, particularly for a few target phonemes. The patient simultaneously received the conventional therapy and the illustration-based rehabilitation program; thus, the results can be

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attributed to either of these methods. However, some results, such as the specific improvement on items which were never trained in the conventional therapy but which were included in the new method, are in favor of the latter. The fact that the patient showed little to no improvement in terms of vowel production did, however, indicate that he was still not fully able to control his speech articulators after this therapy.

Certain important limitations of this study should be noted: (i) this is a single case study and our results should be confirmed in further investigations involving multiple subjects; (ii) we used the same tasks before and after rehabilitation and the improved performance may be due to a task learning effect or a test-retest effect; (iii) at the time of this study wherein the patient received SLT using the *Ultraspeech-player*, he was simultaneously receiving conventional SLT, which could mean that certain results may be attributed to either the conventional therapy alone or a combination of the two. The specificity in the articulatory improvement observed, suggests that the *Ultraspeech-player*-based therapy was indeed effective, however. The *Ultraspeech-player* software is particularly suited to train phonemes that are clearly distinct in terms of sagittal configuration of the tongue or of frontal view of the lips. The sagittal lingual configurations associated with French vowels that only differ in terms of aperture, from close to mid-open (e.g. /i, e, ɛ/ or /u, o, ɔ/ or /ø, œ/), are not sufficiently visually distinct in ultrasound imaging. Therefore, the *Ultraspeech-player* software is not the best help for distinguishing between vowels on the aperture dimension. The fact that the patient's improvements are more important for consonants than vowels, suggest that his evolution was mainly due to the use of the *Ultraspeech-player* software, rather than to the simultaneous conventional SLT that he also benefited from.

In future studies we plan to add to our current speech evaluations, an assessment dedicated to modulations of brain activity during fMRI speech production tasks both before and after SLT, and a separate assessment dedicated to resting-state functional connectivity. We also plan to evaluate speech and language rehabilitation using a cross-over protocol, in which patients will perform illustration-based rehabilitation (in addition to conventional therapy) and then conventional SLT only and vice-versa. This will allow us to compare the two rehabilitation methods and to better describe which improvements are specifically due to the illustration-based rehabilitation.

Conclusion

This study shows the effect of visual articulatory illustration (provided by the *Ultraspeech-player* software), on speech recovery (improvement of speech production with better positioning of speech articulators) in a patient with post-stroke non-fluent aphasia in chronic stage. Our results need to be confirmed in a more controlled study with multiple subjects. However, this study shows: (i) the appropriateness of using a novel method based on visual illustration of speech articulators for speech and language rehabilitation, in semi-autonomy; and (ii) the necessity of using detailed subjective and objective intra-speaker evaluation in speech production in order to fully evaluate speech abilities and speech and language rehabilitation methods.

Acknowledgments

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Declaration of interest statement

The authors report no conflict of interest.

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Supplementary Material

Appendix A – Description of analysis of acoustic data

Five tiers were created in the Phon software (Hedlund & Rose, 2018; Rose & MacWhinney, 2014; Rose et al., 2006): the first tier contains the spelling of phoneme or word, the second contains target phoneme or word (in International Phonetic Alphabet, IPA), the third contains actual phoneme or word (in IPA), the fourth contains the sound accuracy (only for phoneme repetition task, PR) and the fifth contains comments from the transcriber. The level of accuracy was labeled as “correct”, “incorrect”, “emergent” (the target phoneme is preceded by a non-target phoneme, for example: for the target /z/ the patient produces the sound /s/ that gradually transforms into /z/) or “voicing error” (place and manner of articulation were correct but voicing was incorrect, for example the phoneme /p/ instead of /b/ or /b/ instead of /p/).

Praat scripts (Boersma & Weenink, 2010) allowed us to extract typical acoustic parameters for phonemes judged as correct or emergent during the PR: the first two formants F1 and F2 for the oral vowels; the first two spectral moments (Center of Gravity, CG and Standard Deviation, SD) for the fricative consonants; and the voice onset time (VOT) for the stop consonants. For vowels, formant values (F1 and F2) were obtained using a Praat script to detect the formants (between 0 and 5000 Hz) with a pitch of 0.01s, a Gaussian analysis window of 0.025s and a preemphasis of 50Hz. An R script (R Development Core Team, 2008) was used to plot formant spaces (F1 as a function of F2 for each repetition of each vowel). Intra-vowel distance was considered in order to capture acoustic stability of productions of the same vowel across repetitions, which is normally small. This measure refers to the distance within each vowel between its coordinate point in the (F2, F1) space and the corresponding centroid (barycenter). For each vowel, we computed the centroid point as the arithmetic mean of each coordinate (F2, F1). For fricative consonants, a Praat script allowed us to extract the spectral moments. These values were calculated by taking a 40ms Hamming window centered on the middle of the noise bandwidth generated by the consonant. Only the first two spectral moments (CG and SD) were considered here. The CG allows for the distinction between alveolar /s/ and post-alveolar /ʃ/; whereas the SD lets us distinguish between labiodental /f/ and alveolar and post-alveolar fricatives /s, ʃ/ (Li, Edwards, & Beckman, 2009). Conventionally, CG values should be in the following order: alveolar > labiodental > post-alveolar, while SD values should follow this order: labiodental > alveolar > post-alveolar (Nissen & Fox, 2005). An R script allowed us to represent these values as a boxplot. For stop consonants, VOT was determined by subtracting the instant of the burst (beginning of the consonant explosion) from the instant of voicing onset. We then calculated the average VOT values obtained, before and after rehabilitation, for voiced and voiceless stop consonants. The standard VOT values for the speech therapist were obtained in Haldin et al., (2018).

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Figure A. Illustration of the display provided by Ultraspeech-player software (Hueber, 2013; http://www.ultraspeech.com).

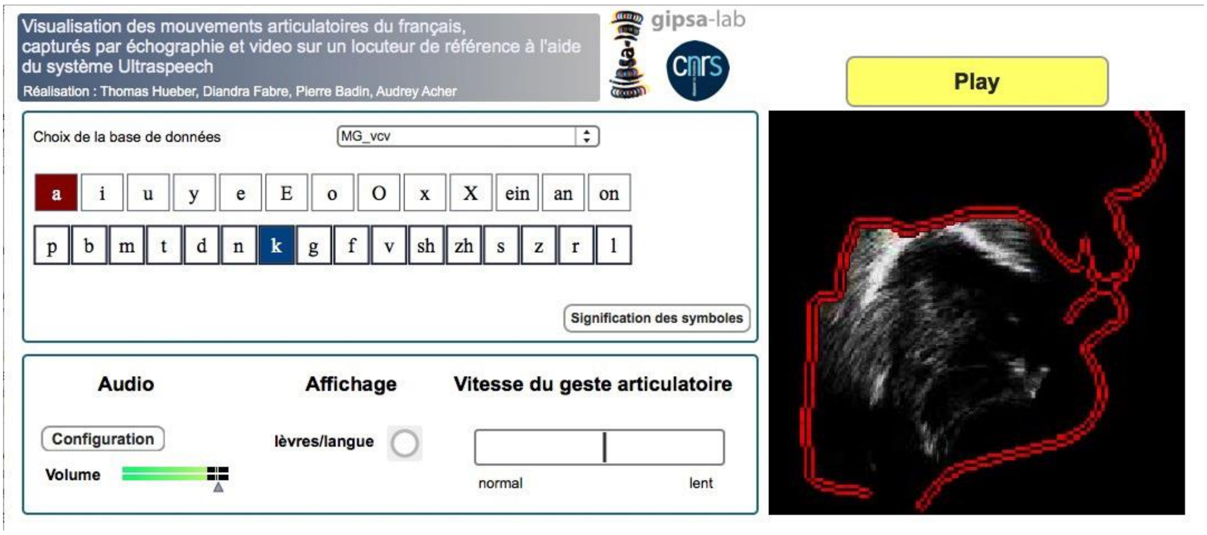

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Table A. Scores obtained by the patient during the assessment of language comprehension and production, performed before rehabilitation.

	Tasks	**Scores**
Oral comprehension BDAE	Word discrimination	71/72
	Body part identification	18/20
	Commands	15/15
	Complex ideational material	12/12
Written comprehension BDAE	Symbol and word discrimination	10/10
	Word recognition	8/8
	Word/picture matching	10/10
	Sentences-paragraphs comprehension	6/10
Oral expression BDAE	Automatized sequences	0/9
	Recitation	1/2
	Singing	0/2
	Responsive naming	1/10
Written expression (left hand) BDAE	Writing mechanics	3/3
	Serial writing	42/46
	Primer-level dictation	15/15
	Spelling to dictation	6/10
	Sentences to dictation	4/12
	Written naming	10/10
Transcoding BDAE	Word repetition	2/10
	Word reading	Impossible
Praxis MT86	Buccofacial praxis	5/6

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Table B. Scores obtained by the patient during the neuropsychological assessment performed before rehabilitation. This assessment validates the inclusion criteria: absence of upper limb apraxia (Apraxia Screen of Tulia, AST); absence of spatial neglect (bells test and line bisection); familiarity with digital tools.

	NEUROPSYCHOLOGICAL ASSESSMENT – INCLUSION CRITERIA					
UPPER LIMB APRAXIA (AST)	Imitation					
	Meaningless gestures	1/1				
	Intransitive (communicative) gestures	1/1				
	Transitive (tool-related) gestures	5/5				
	Pantomime					
	Intransitive (communicative) gestures	2/2				
	Transitive (tool-related) gestures	3/3				
	Global score	12/12				
SPATIAL NEGLECT	Bells test					
	Omissions (left)	0/15				
	Omissions (right)	0/15				
	Omissions (middle)	0/5				
	Omissions (total number)	0/35				
	Omissions (left minus right)	0				
	Omission column 1	1				
	Time (seconds)	112 sec				
	Bisection 20 cm					
	Deviation line 1	-2 mm				
	Deviation line 2	3 mm				
	Mean deviation	0.5 mm				
FAMILIARITY WITH DIGITAL TOOLS	Use of the computer tools	Never	Occasionally	Often	Most of the time	
	Use frequency	Several time/hour	Several time/day	Several time/week	Several time/month	
	Activity type	Internet-research	Internet-email	Online games	Social networks	Software (accounting, excel, word)

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Table C. Syllables, vowels and words used for the speech evaluation, with orthographic or phonetic notation.

TASKS		**NUMBER OF REPETITION**	**ITEMS**
PHONEME REPETITION	Vowels	3 times	a, œ, ø, e, ɛ, o, ɔ, y, u, i, ɛ̃, ɑ̃, ɔ̃
	Semi-consonants	3 times	ja, wa, ɥi
	Consonants /Ca/	3 times	pa, ta, ka, ba, da, ga, fa, sa, ʃa, va, za, ʒa, ma, na, ɲa, la, ʁa
	Consonants /aCa/	3 times	apa, ata, aka, aba, ada, aga, afa, asa, aʃa, ava, aza, aʒa, ama, ana, aɲa, ala, aʁa
SIMPLE WORD REPETITION		1 time	Râteau (*rake*), élu (*elected*), cheminée (*chimney*), combine (*combine*), gagnant (*winner*), douceur (*gentleness*), faute (*fault/mistake*), singe (*monkey*), neveu (*nephew*), aise (*easy*), appât (*bait*), gnon (*wallop*), paix (*peace*), moral (*moral*), gère (*manage*), tendon (*tendon*), azur (*azure*), Yves (*Yves*), veuf (*widower*), échasse (*stilt*), œuf (*egg*), ligne (*line*), nous (*us*), occupe (*occupy/assume*), zona (*zoster or hang around*), bague (*ring*), onde (*wave*), huche (*bin for bread*), égal (*equal*), outil (*tool*), léger (*light*), Europe (*Europe*), envie (*wish*), aube (*sunrise*), rein (*kidney*), sac (*bag*), infâme (*nefarious*)
READING		3 times	pa, ta, ka, ba, da, ga, fa, sa, ʃa, va, za, ʒa, ma, na, ɲa, la, ʁa
PHONEMIC DISCRIMINATION		1 time	pa/ba, si/ti, ma/ma, da/ta, za/za, ga/ca, fa/fa, ni/mi, da/da, vi/fi, ba/ba, ki/ki, sa/za, chi/ji

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