Published in final edited form as:
Aphasiology. 2015 ; 29(6): 724–743. doi:10.1080/02687038.2014.982500.

Speech segmentation in aphasia

Claudia Peñaloza[a], **Annalisa Benetello**[b,c], **Leena Tuomiranta**[d], **Ida-Maria Heikius**[d], **Sonja Järvinen**[d], **Maria Carmen Majos**[e], **Pedro Cardona**[f], **Montserrat Juncadella**[f], **Matti Laine**[d,†], **Nadine Martin**[b,†], and **Antoni Rodríguez-Fornells**[a,g,h,*,†]

[a]Cognition and Brain Plasticity Group, Bellvitge Biomedical Research Institute – IDIBELL, Barcelona, Spain [b]Department of Communication Sciences and Disorders, Eleanor M. Saffran Center for Cognitive Neuroscience, Temple University, Philadelphia, PA, USA [c]Department of Psychology, University of Milano-Bicocca, Milan, Italy [d]Department of Psychology and Logopedics, Abo Akademi University, Turku, Finland [e]Hospital Universitari de Bellvitge (HUB), Rehabilitation Section, Campus Bellvitge, University of Barcelona, Barcelona, Spain [f]Hospital Universitari de Bellvitge (HUB), Neurology Section, Campus Bellvitge, University of Barcelona, Barcelona, Spain [g]Department of Basic Psychology, Campus Bellvitge, University of Barcelona, Barcelona, Spain [h]Institució Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain

Abstract

Background—Speech segmentation is one of the initial and mandatory phases of language learning. Although some people with aphasia have shown a preserved ability to learn novel words, their speech segmentation abilities have not been explored.

Aims—We examined the ability of individuals with chronic aphasia to segment words from running speech via statistical learning. We also explored the relationships between speech segmentation and aphasia severity, and short-term memory capacity. We further examined the role of lesion location in speech segmentation and short-term memory performance.

Methods & Procedures—The experimental task was first validated with a group of young adults ($n = 120$). Participants with chronic aphasia ($n = 14$) were exposed to an artificial language and were evaluated in their ability to segment words using a speech segmentation test. Their performance was contrasted against chance level and compared to that of a group of elderly matched controls ($n = 14$) using group and case-by-case analyses.

[*]Corresponding author. antoni.rodriguez@icrea.cat.
[†]Shared senior authorship listed in alphabetic order.

Outcomes & Results—As a group, participants with aphasia were significantly above chance level in their ability to segment words from the novel language and did not significantly differ from the group of elderly controls. Speech segmentation ability in the aphasic participants was not associated with aphasia severity although it significantly correlated with word pointing span, a measure of verbal short-term memory. Case-by-case analyses identified four individuals with aphasia who performed above chance level on the speech segmentation task, all with predominantly posterior lesions and mild fluent aphasia. Their short-term memory capacity was also better preserved than in the rest of the group.

Conclusions—Our findings indicate that speech segmentation via statistical learning can remain functional in people with chronic aphasia and suggest that this initial language learning mechanism is associated with the functionality of the verbal short-term memory system and the integrity of the left inferior frontal region.

Keywords

speech segmentation; statistical learning; language learning; aphasia

Introduction

Recent years have witnessed a growing research interest in the potential of people with aphasia for new language learning. Studies in this field have evidenced that (i) people with aphasia demonstrate some ability to learn new words and their corresponding novel meaning after training (Gupta, Martin, Abbs, Schwartz, & Lipinski, 2006) and (ii) the maintenance of part or all of the acquired vocabulary can last for days (Kelly & Armstrong, 2009) or even months (Tuomiranta et al., 2014; Tuomiranta, Rautakoski, Rinne, Martin, & Laine, 2012). Moreover, these studies show that novel word learning ability can vary largely between aphasic individuals (Tuomiranta et al., 2011) and can be severely limited in some cases (Gupta et al., 2006). To the best of our knowledge, no previous studies have further investigated the initial stages of language learning such as the segmentation of words from continuous speech in people with aphasia. The present study aims to fill this gap by examining chronic aphasic individuals' ability to isolate and segment new words from an unknown language.

In language acquisition, the discovery of words in spoken language is one of the first prerequisites for mapping words onto meanings (Evans, Saffran, & Robe-Torres, 2009). Segmenting words from fluent speech is a considerable challenge to language learners as speech does not provide clear acoustic markers for word boundaries. An important feature of continuous speech that can aid in the extraction of words is the statistical properties of sound sequences. A number of studies have demonstrated that healthy infants, children and adults can extract words from fluent speech by computing the transitional probabilities (TPs) between adjacent syllables from a speech stream (for a review, see Gómez & Gerken, 2000; Saffran, 2003). This process of extracting patterns from input using distributional regularities is known as statistical learning. Importantly, it has been demonstrated that the isolation of word candidates from the speech signal via statistical learning facilitates word learning through the generation of new representations (word-like units). These prelexical units can be further mapped onto meanings, as shown in tasks involving novel object–word pairings (Cunillera, Laine, Càmara, & Rodríguez-Fornells, 2010; Evans et al., 2009; Mirman, Magnuson, Estes, & Dixon, 2008).

The neural substrates of speech segmentation abilities have been investigated in healthy adults by functional magnetic resonance imaging (fMRI). These studies have revealed an increased activation in the posterior superior temporal gyrus (pSTG) and the superior ventral premotor cortex (svPMC) in association with the segmentation of words from an artificial language (Cunillera et al., 2009; McNealy, Mazziotta, & Dapretto, 2006). In addition, an increased activation in the pars opercularis and pars triangularis regions has been reported (Karuza et al., 2013). These studies suggest the involvement of a left lateralised network in the mature brain, which engages fronto-temporal regions of the dorsal pathway in the process of speech segmentation (Rodríguez-Fornells, Cunillera, Mestres-Missé, & de Diego-Balaguer, 2009). Furthermore, it has been demonstrated that white matter microstructure of the left arcuate fasciculus predicts the capacity of healthy participants to segment new words (López-Barroso et al., 2013).

More recently, the study of speech segmentation has contributed to a more fine-grained description of the language processing abilities of people with developmental disorders. For instance, it has been suggested that impaired speech segmentation may underlie delayed lexical development and language deficits in children with specific language impairment, as speech segmentation ability predicts lexical knowledge in typically developing children (Evans et al., 2009). Speech segmentation tasks have also revealed deficits in the identification of sounds embedded in speech in adults with developmental dyslexia (Kujala et al., 2006). Interestingly, it has been shown that children with highly functional autism and no language deficits are able to segment words from running speech (Mayo & Eigsti, 2012). In aphasia, this research may elucidate important initial language learning mechanisms and their neural underpinnings in a damaged adult brain. The functionality of such learning mechanisms may also have implications for treatment of aphasia and prognosis for recovery.

One important aspect to consider in the study of speech segmentation ability in people with aphasia is the role of verbal short-term memory (STM) in this type of word learning. It has been suggested that the availability of working memory resources can constrain the efficiency of statistical learning (Krogh, Vlach, & Johnson, 2013; Ludden & Gupta, 2000). Moreover, the sensory-motor network that has been associated with speech segmentation (Rodríguez-Fornells et al., 2009) has also been proposed as the neural circuit for verbal STM (Hickok, 2009), and there is evidence supporting the role of the articulatory rehearsal aspect of phonological STM in speech segmentation (López-Barroso et al., 2013). Yet, people with aphasia have a limited capacity to maintain the activation of phonological and semantic representations of words in the short-term (Martin & Ayala, 2004; Martin & Gupta, 2004; Martin, Kohen, & Kalinyak-Fliszar, 2010). Thus, an important additional question that arises is whether the ability of people with aphasia to segment words from the speech signal is associated with their verbal STM capacity.

The main purpose of the present multicentre study was to explore the ability of people with chronic aphasia to segment words from running speech via statistical learning. We first aimed to determine whether individuals with chronic aphasia were able to segment words from continuous speech above chance level. A second aim was to compare the speech segmentation ability of the aphasic participants and that of a group of healthy elderly individuals matched for age, gender, and years of education. We addressed these questions using group analyses to describe general patterns of group performance and proceeded with case-by-case analyses to examine the performance variability of aphasic individuals that can reveal important information on the cognitive-linguistic and neural correlates of speech segmentation ability. If some aphasic individuals demonstrate a preserved ability to parse words from running speech via statistical learning, the examination of the cognitive and neural features that support this ability would be crucial to advance our knowledge on the functionality of this initial stage of language learning in chronic aphasia. Thus, we also sought to explore the relationship between the speech segmentation ability of the aphasic participants and their aphasia severity and STM performance. In addition, we aimed to examine how people with aphasia differ in their speech segmentation ability and their STM capacity according to their lesion location (anterior-posterior). We discuss our findings with regard to the integrity of the left dorsal speech processing pathway that has been related to speech segmentation.

Methods

Participants

The study included altogether 148 participants (88 female) recruited and tested in three laboratories: Barcelona (Spain) (n = 82), Philadelphia (USA) (n = 8), and Turku (Finland) (n = 58). The total sample was composed of three groups. The first group consisted of 120 healthy young adults (hereafter, “young adults”). The second and third groups included 14 individuals with stroke-induced chronic aphasia and 14 healthy controls (hereafter, “elderly controls”), respectively. The aphasia and elderly control groups were roughly matched for gender, age, and education. The demographic characteristics of the three groups are summarised in Table 1. All young adult participants had normal vision and hearing, and visual and auditory deficits were ruled out after screening in both the aphasic participants and the elderly controls. None of the participants reported a background of neurological disorders (other than stroke for the aphasia group), mental illnesses, or learning impairments.

The young adult group was included to validate the speech segmentation task employed in this study and to ensure that the standard achievable level of speech segmentation was comparable across languages. The Spanish speakers were undergraduate psychology students at the University of Barcelona. The English speakers were involved in different student exchange programs in Barcelona. The Finnish and Swedish speakers were undergraduate students at the University of Turku and the Abo Akademi University in Turku, Finland, except for two young students who were tested in Barcelona.

The demographic and clinical information of the participants with aphasia are provided in Table 2 (see also Figure 1 for a sample of structural imaging results for seven representative cases). The inclusion criteria for participants in the aphasia group were as follows: (i) age between 25 and 77 years, (ii) first and single stroke confirmed by CT or MRI scan, (iii) persistent stroke-induced aphasia at least 1 year from stroke onset as determined by formal speech and language assessment (described later), (iv) preserved ability to understand and follow instructions to complete the experimental task (assessed online through performance on the training task preceding the speech segmentation task).

The participants with aphasia enrolled in the study on average 53.8 months (*SD* = 48.3) after stroke onset. The Spanish speakers in the aphasia group had been admitted to the stroke unit of the Hospital Universitari de Bellvitge, Spain. The English speakers with aphasia were recruited from the subject pool of the Aphasia Rehabilitation Research Laboratory at Temple University. The Finnish speakers with aphasia were contacted through an aphasia association and the Swedish speakers through the university speech therapy clinic. The procedures were conducted in accordance with the Declaration of Helsinki, and all participants signed written informed consent forms approved by the relevant ethical committees at each participating institution.

Language and STM assessment

The Boston Diagnostic Aphasia Examination (BDAE, Goodglass, Kaplan, & Barresi, 2005; Laine, Niemi, Koivuselkä-Sallinen, & Koivusalo, 1986; Laine, Niemi, Koivuselkä-Sallinen, & Tuomainen, 1997) was used to diagnose chronic aphasia and to assess aphasia severity, comprehension, and repetition skills in the Spanish, Swedish, and Finnish speakers with aphasia. More specifically, verbal comprehension ability was assessed with the word comprehension, commands, and complex ideational material subtests of the BDAE and the Token test (De Renzi & Faglioni, 1978). Repetition ability was evaluated with the word repetition and the sentence repetition subtests of the BDAE. The Western Aphasia Battery Revised (WAB-R, Kertesz, 2006) was used to diagnose the clinical profile and severity of aphasia and to evaluate the verbal comprehension and repetition abilities in the English speakers with aphasia. In addition, the aphasia severity ratings of the BDAE (Goodglass, Kaplan, & Barresi, 2001) were obtained for these participants in order to examine the relationship of aphasia severity and speech segmentation ability with homogeneous measurements for all the aphasic participants.

The assessment of verbal comprehension in the participants with aphasia was done to rule out the presence of severe comprehension impairments, while the assessment of repetition ability was important because this language domain shares common neural mechanisms with speech segmentation ability. The dorsal speech pathway associated with speech segmentation (Rodríguez-Fornells et al., 2009) is also related to repetition ability that relies on the auditory and motor speech systems to efficiently map auditory input into articulatory output (Hickok & Poeppel, 2004; Moritz-Gasser & Duffau, 2013). Tables 3 and 4 summarise the speech and language profiles of the participants with aphasia.

Additionally, four STM subtests of the Temple Assessment of Language and Short-term memory in Aphasia (TALSA; Martin et al., 2010) available in English, Spanish and Finnish (Tuomiranta, Laine, & Martin, 2009) were administered to 11 aphasic participants. The Swedish speakers with aphasia were not evaluated with these subtests as the TALSA battery has not yet been validated in this language. The subtests included the word pointing span, the digit pointing span, the word repetition span, and the digit repetition span. The word pointing span subtest consists of 10 strings of words in each of seven-string length conditions (one word, two words, etc.), and it requires the participant to hear each sequence of words and point to the items in sequence on a visual array of nine possible items. In this test, the sequences of words are generated from a finite set of nine words, and the visual array randomly changes on each trial. The digit pointing span is similar but the items presented are single digits ranging from 1 to 9. The word and digit repetition span subtests have an analogous structure to the pointing span subtests, with the exception that no visual referents are provided, and verbal output is required after the auditory presentation of single words or digits. The words are matched in syllable length with the digit names. The span size is calculated for each one of the four subtests (for items recalled in serial order only) using Shelton, Martin, and Yaffee (1992) formula: string length at which at least 50% of the strings are recalled + (0.50 × proportion of strings recalled in the next string length). Further descriptions about these measures are available in Martin and Ayala (2004). The results of the participants with aphasia on the TALSA spans are provided in Table 5.

Speech segmentation task

Exposure phase—The speech segmentation task reported in the present study involved the exposure to a small artificial language followed by a speech segmentation test. A schematic representation of the task is provided in Figure 2. The artificial language was created with the same structure as that used by Saffran, Aslin, and Newport (1996). The speech stream was composed of four trisyllabic nonsense words (hereafter, “words”) created in accordance with the phonotactic rules of the native language of the participants: Spanish, English, Finnish, and Swedish (four different artificial languages in total). Each word was repeated 84 times in the language (336 words in total). Words were combined in a pseudorandomised order to form a text stream with the constraint that the immediate repetition of the same item could not occur in the language. Text streams were transformed into acoustic speech streams with MBROLA, a speech synthesiser based on the concatenation of diphones (Dutoit, Pagel, Pierret, Bataille, & van der Vreken, 1996) using a monotone male voice. The duration of the streams was adjusted to a millisecond precision using the Adobe audition software (Adobe Systems Incorporated, CA, USA). All phonemes had the same duration (150 ms) and pitch (200 Hz; equal pitch rise and fall, with maximum pitch at 50% of the phoneme). The speech stream was modified at the beginning by gradually increasing the audio signal from silence during the first 1350 ms (fade-in effect) and at the end by gradually reducing it to silence during the last 1350 ms (fade-out effect) in order to avoid the detection of the initial or ending syllables. The resulting speech stream had a total duration of 5.2 min (200 syllables/66.7 words per min) and provided no acoustic or prosodic cues, stress differences, or pauses signalling word boundaries. The only cues to detect word boundaries were the TPs between syllables (TP was 1.0 between syllables forming a word and 0.33 between syllables spanning word boundaries). A sample of the artificial language for the Spanish-speaking participants is presented in Figure 2. The artificial stream was divided into two parts equated in the duration, the number of times each word was presented, and the fading effects. This was necessary because a pilot study indicated that participants with aphasia became fatigued or distracted with a longer exposure.

Testing phase—The speech segmentation test consisted in a 2-alternative forced-choice test (2AFC test), and it required the discrimination of words of the novel language from nonwords. Nonwords were test foils created using syllables of the language that were never concatenated in the speech stream (see Appendix). The test included 16 test pairs formed by the exhaustive combination of the four words and the four nonwords. After the presentation of each test pair, the participant was to decide by pressing a response button whether the first or the second item of the pair was a word of the new language. The next pair was not presented until a response was provided. The items of each pair were separated by a 400-ms pause. The presentation of the tokens was counterbalanced, and test pairs were pseudo-randomised for each participant.

Procedure

The speech segmentation task was preceded by a brief training task included to ensure the familiarisation and the correct understanding of the 2AFC test. In this task, the participants were presented with a set of six real words of their native language four times and were to perform a short 2AFC test on those words. The words were three bisyllabic and three trisyllabic tokens of different CV structure. These tokens varied in length in order to avoid carry-over effects from the training task that may bias word segmentation during exposure to the speech stream. The test included six old–new word pairs. The target words and the foils were matched by length in phonemes, frequency, and imageability. In the test, the participants were to decide whether the first or the second item of the pair was presented in the exposure phase. Participants were then administered the speech segmentation task: they were exposed to the artificial speech stream and were instructed to carefully listen to the novel language as later they would need to respond to a few questions about the language. After hearing the first part of the speech stream, the examiner reinforced the previous instructions by indicating that the language was new and that one needed to carefully listen to the language in order to learn some of it. After this brief pause, participants were presented with the second part of the artificial language. At the end of the exposure phase the 2AFC test was administered. All the stimuli were presented using E-prime 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA, USA).

Statistical analysis

Statistical analyses were computed using SPSS 17.0. First, we evaluated the comparability of speech segmentation performance across languages using a one-way between-groups analysis of variance (ANOVA) to compare the performance of the young adults according to their linguistic background in the 2AFC test. Because there were no significant differences in performance across languages (as reported later), the data from all young adults were collapsed into a single group for further analyses. Two analyses were conducted to determine whether participants with aphasia could successfully segment words from the novel language. At the group level, their mean per cent of correct responses in the 2AFC test was contrasted against chance using a one-sample *t*-test with chance level defined as 50% correct performance. For comparison, this group analysis was also conducted for the total group of young adults and for the elderly controls. At the case level, the individual performances of participants with aphasia in the 2AFC test were contrasted against chance using the exact binomial test (one-tailed) to determine which particular aphasic participants were able to segment words from the novel language. The speech segmentation performance of the participants with aphasia was compared to that of the elderly controls using an independent sample *t*-test. Pearson correlations were used to examine the associations between the speech segmentation performance of the participants with aphasia in the 2AFC test and the aphasia severity ratings as measured by the BDAE, as well as the STM capacity as measured by the TALSA subtests. Finally, the Mann–Whitney test was used to compare the aphasic participants according to their lesion location in left cortical regions, namely *predominantly anterior lesions* involving frontal regions versus *predominantly posterior lesions* involving temporal and/or parietal regions with spared frontal cortex. The dependent variables were speech segmentation ability (n = 12) and STM capacity (n = 10). Participants RS and BB were excluded from these two analyses due to pure subcortical lesions and right hemisphere lesions, respectively. Participants AE and BL were also excluded from the comparison on STM capacity due to unavailable data on this measure. Statistical significance is reported at the .05 level (two-tailed), and the effect size is provided.

Results

Speech segmentation performance in healthy young adults

We first compared the mean performance of the young adults on the 2AFC test according to their native language: Spanish (n = 44; M = 73.11%; SD = 14.4%), English (n = 24; M = 79.17%, SD = 19.65%), Finnish (n = 27 M = 72.92%, SD = 16.54%), and Swedish (n = 25; M = 82%, SD = 14.36%) (see Figure 3). The one-way between-groups ANOVA yielded no significant differences between the performances of the four groups on the speech segmentation test [$F(3,118) = 2.267$, $p = .084$; $\eta^2 = .05$]. These results support the validity of the comparisons of performance on the speech segmentation task across languages as presented later. The mean per cent of correct responses for the whole group of young adults on the 2AFC test was 76.16% (SD = 16.31%). One-sample *t*-tests indicated that their performance on the segmentation test was significantly above chance level [$t(119) = 17.49$, $p < .001$, $d = 1.60$]. Thus, the ability of parsing words of the speech stream by detecting the TPs between syllables was clearly evidenced in our large sample of young healthy speakers in the current speech segmentation task.

Speech segmentation in healthy elderly adults and participants with aphasia

The speech segmentation performance of the participants with aphasia and the elderly controls is presented in Figure 3. The mean per cent of correct responses in the 2AFC test was 59.82% (SD = 15.25%) for the aphasic participants and 72.32% (SD = 18.78%) for the elderly controls. One-sample *t*-tests evidenced that the aphasia group [$t(13) = 2.41$, $p = .032$, $d = .64$] and the elderly control group [$t(13) = 4.45$, $p = .001$, $d = 1.18$] performed significantly above chance in the 2AFC test. We further examined the individual performances of the aphasic participants in the 2AFC test against chance level using the binomial test. These analyses indicated that 4 out of 14 aphasic participants performed above chance level. Participants AF and QH produced 13/16 correct responses (binomial test, one-tailed, $p = .01$), and participants CM and JS achieved 12/16 correct responses (binomial test, one-tailed, $p = .04$). Independent samples *t*-test revealed that the difference between the mean per cent of correct responses of the participants with aphasia (M = 59.82%, SD =

15.25%) and the elderly controls (*M* = 72.32%, *SD* = 18.78%) was non-significant [$t(26) = -1.93$, $p = .064$].

Speech segmentation, aphasia severity, and STM

Pearson correlations indicated that the performance of the participants with aphasia in the speech segmentation test was not significantly associated with aphasia severity ($r = .398$, $p = .16$). There was a significant correlation between the scores of the aphasic participants ($n = 11$) in the 2AFC test and their performance on the word pointing span test ($r = .655$, $p = .029$) (see Figure 4). The correlations between the aphasic participants' performance on the 2AFC test and the word repetition span test ($r = .375$, $p = .25$), the digit pointing span test ($r = .525$, $p = .09$), and the digit repetition span ($r = .453$, $p = .16$) pointed in the same direction but did not reach statistical significance at the .05 level.

Lesion location and speech segmentation

The Mann–Whitney test revealed that the aphasic participants with predominantly posterior lesions (Md = 75%, $n = 7$) showed a significantly better speech segmentation performance than participants with predominantly anterior lesions (Md = 43.75%, $n = 5$) in the 2AFC test ($U = 5.5$, $z = -1.97$, $p = .048$, $r = .57$).

Lesion location and STM

The Mann–Whitney test evidenced that the aphasic participants with predominantly posterior lesions (Md = 3.15, $n = 6$) had a significantly better verbal STM capacity than participants with predominantly anterior lesions (Md = 2.2, $n = 4$) as measured by the Word pointing span subtest ($U = .0$, $z = -2.57$, $p = .010$, $r = .81$). The aphasic participants with predominantly posterior lesions (Md = 4.5, $n = 6$) were also significantly better than participants with predominantly anterior lesions (Md = 3, $n = 4$) in the digit pointing span test ($U = 2$, $z = -2.14$, $p = .038$, $r = .68$). The differences between these two groups of aphasic participants in the word and the digit repetition span subtests were statistically nonsignificant ($p > .05$ in both the cases).

Discussion

The present study explored the functionality of speech segmentation in individuals with chronic aphasia. Our group-level findings provide an overall view of the preserved ability of at least part of chronic aphasic individuals to segment words from a novel language, the first elementary step in language learning. Moreover, our case-by-case analyses propose relevant albeit preliminary findings regarding the individual patterns of speech segmentation performance in individuals with chronic aphasia. We will discuss such findings in relation to both the neural underpinnings of speech segmentation and the cognitive abilities needed to perform speech segmentation tasks. As noted in the Introduction section, the dorsal speech pathway (Hickok & Poeppel, 2004) has been put forth as the neuroanatomic substrate of speech segmentation (López-Barroso et al., 2013; Rodríguez-Fornells et al., 2009). This pathway projects from the left posterior temporal regions involving the parieto-temporal boundary and extends to frontal regions (Hickok & Poeppel, 2004; Saur et al., 2008). This dorsal stream has been suggested to support auditory-motor integration from very early stages of language acquisition (Friederici, 2011; Hickok & Poeppel, 2007; Scott & Wise, 2004). Indeed, the speech segmentation process in the neurologically intact brain has been proposed to involve the mapping of sensory representation of the novel words in temporal regions onto articulatory-based representations in the premotor areas, allowing for the recently segmented words to remain active through phonological rehearsal (Rodríguez-Fornells et al., 2009).

In our study, we found that the participants with chronic aphasia with different stroke-induced lesions involving the aforementioned critical regions for speech segmentation were nevertheless able to successfully segment words from a novel language. As a group, the aphasic participants were able to discriminate the recently segmented words from nonwords, and their performance did not significantly differ from the elderly controls. Furthermore, speech segmentation ability was not associated with aphasia severity. These findings indicate that even in the face of an acquired lesion and persistent aphasia, an adult brain can compute the distributional properties of a novel speech input to discover word boundaries, and extract word-like units on the basis of this information. It has been suggested that people with aphasia may utilise different cerebral mechanisms that not only depend on re-accessing damaged neural pathways but may also be related to establishing new neural connections for new learning processes (Kelly & Armstrong, 2009). Thus, it is possible that preserved word segmentation via statistical learning is also related to aspects of neural reorganisation in the brain following stroke-induced aphasia.

Importantly, the marginal difference between the aphasia and the elderly control groups clearly suggested that some aphasic participants did not show spared speech segmentation ability. The binomial tests further confirmed that only four participants with chronic aphasia were significantly above chance level in their speech segmentation performance. It is likely that individual variability in this respect is modulated by lesion location and extent, preserved cognitive abilities, and brain compensatory capability. While the present data do not allow for a more detailed analysis of lesion-deficit correlations, some important preliminary findings are worth noting. The four aphasic participants with above chance speech segmentation performance (AF, QH, CM, and JS) were all diagnosed with mild fluent aphasia, and they all had predominantly posterior lesions involving parietal (AF and CM) or temporal regions (QH and JS) while their frontal regions remained spared. They also outperformed the participants with predominantly anterior damage. Three aphasic participants with lesions in predominantly posterior regions (BL, EP, and FS) were at chance level in the 2AFC test, which might be associated with the presence of haemorrhagic lesions involving more extensive cortical areas (BL and EP) or reduced verbal STM as measured by the word pointing span subtest (EP and FS). Moreover, participant FS had a classical conduction aphasia and evidence of damage to the arcuate fasciculus, a critical component of the dorsal speech pathway relevant to word segmentation ability (López-Barroso et al., 2013). Conversely, the participants with more predominant anterior lesions involving the opercular and insular regions (with or without damage to the basal ganglia) achieved lower scores on the speech segmentation test, the majority of them (AM, AE, and KM) showing the most impaired, chance-level performance of the whole aphasia group. Albeit structural lesion data enabling quantitative analyses of the lesions were not available for our aphasia group, these results suggest that the integrity of the left frontal cortex is critical for supporting an effective segmentation of words from fluent speech. This is in line with the evidence from fMRI studies showing that the ventral premotor and inferior frontal regions are recruited in speech segmentation tasks in neurologically intact adults (Cunillera et al., 2009; Karuza et al., 2013).

The inferior frontal cortex has been attributed a role in sequential processing and learning (Christiansen, Louise Kelly, Shillcock, & Greenfield, 2010; Gelfand & Bookheimer, 2003) of both linguistic and non-linguistic structures (Goschke, Friederici, Kotz, & van Kampen, 2001). Considering word segmentation as a linguistic type of sequential learning as it requires the computations of the statistical properties of adjacent syllables in a linguistic sequence, our results are in convergence with those reported by Goschke et al. (2001) who demonstrated that people with Broca's aphasia were unable to learn phoneme sequences. These lines of evidence thus support the idea that linguistic sequential learning may be compromised in aphasic individuals with damage to frontal regions. Although beyond the scope of our study, it is worth noting that the study conducted by Goschke and colleagues also demonstrated that people with Broca's aphasia (anterior lesions) and people with Wernicke's aphasia (posterior lesions) were able to learn visuo-motor sequences as measured by a serial reaction time task, thus suggesting a dissociation between the linguistic and non-linguistic aspects of sequential learning in aphasia (but see Christiansen et al., 2010 for contradictory evidence). Further studies are required to disentangle the domain-general versus domain-specific role of sequential learning in aphasic individuals.

We also found that the successful segmentation of words from a novel language in the aphasia group was significantly associated with their performance on the word pointing span subtest, a measure of verbal STM. The corresponding correlations with the other STM tests were lower but pointed in the same direction. One reason for the present prominence of the word pointing span test can be that out of the four STM tasks used here, it is the one most strongly related to lexical processing abilities in aphasia (Martin & Ayala, 2004). Lexical processing may play a role even in the early stages of establishing protowords in the lexicon. At a more general level, evidence from neurologically intact individuals indicates that word learning depends on the integrity of verbal STM processes (Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006; Gathercole, Hitch, Service, & Martin, 1997; Gupta & Tisdale, 2009; Papagno, Valentine, & Baddeley, 1991). This includes the phonological loop, a STM component that plays a crucial role in the maintenance of memory traces in the temporary phonological store by an articulatory rehearsal process (Baddeley, 2003a, 2003b). Recently, it has been demonstrated that speech segmentation in healthy young adults can become significantly impaired when subvocal rehearsal is impeded (López-Barroso et al., 2011), which suggests that this ability also benefits from this rehearsal mechanism (Cunillera et al., 2009). Thus, our findings suggest that speech segmentation in aphasia depends on the individual's preserved/impaired STM abilities, as well as the integrity of the left inferior frontal regions linked to the phonological loop (i.e., Brodmann areas B44, B6 and B40; Baddeley, 2003a). Damage to these regions may disrupt the immediate retention of potential word candidates after exposure to the to-be-segmented speech signal by impeding the active subvocal rehearsal. This would make it difficult to retain the phonological representations of the word candidates after learning.

The examination of the effects of linguistic background on speech segmentation was beyond the scope of our study, but some findings are worth considering. Our comparative analysis of the speech segmentation ability of 120 young adults across the four languages reported (Spanish, English, Finnish, and Swedish) revealed no significant between-group differences. These results suggest that the detection of word boundaries in running speech can be reliably achieved through statistical learning by computing the TPs between adjacent syllables and that this ability is not critically sensitive to language-specific knowledge. Languages differ, for example, in terms of phonotactic constraints, lexical stress, vowel harmony, phonetic cues, and prosodic contours (Jusczyk, Houston, & Newsome, 1999; Saffran, Newport, & Aslin, 1996), and the exploitation of such features in speech segmentation can vary between individuals with varying linguistic backgrounds (Tyler & Cutler, 2009). However, the artificial languages used in the present study were neutral regarding these language-dependent cues as TPs were the only reliable cue for learners to segment words. Our results support the idea that the statistical regularities across adjacent speech units in phonetic input are a robust, universal, language-general cue to detect word boundaries (Ngon et al., 2013). Our findings also indicate that this observation not only is valid for healthy adult learners but also extends to people with aphasia. In our study, the aphasic participants who were able to segment words and did not significantly differ from the group of elderly controls had different linguistic backgrounds. Thus, the linguistic group did not appear to affect speech segmentation through statistical learning in aphasia. Studying the effects of bilingualism on speech segmentation in people with chronic aphasia was beyond the scope of our study, and the information regarding bilingualism in our participants was not sufficiently detailed to properly address this question. Future studies are needed to determine the extent to which the premorbid ability to speak multiple languages can influence the functionality of speech segmentation in aphasia.

Conclusion

The present study provides preliminary evidence that the ability to segment words from speech via statistical learning can remain functional in people with chronic aphasia in spite of damage to brain regions essential for language processing. Our findings suggest that effective speech segmentation ability is associated with verbal STM capacity and the integrity of the left inferior frontal region. Further research is necessary to elucidate the cognitive and neural substrates that support the ability to segment words in people with aphasia. In future studies, a detailed analysis of the integrity of the different parts of the dorsal speech pathway in individuals with aphasia can provide important insights about the neural substrates that sustain speech segmentation.

Acknowledgments

The authors would like to thank Dr. Daniel Mirman for his valuable comments on the design of the present study. We are grateful to all the participants and particularly to the participants with aphasia for their time and commitment to this research. We thank Mary Guerrero for her assistance in the data collection in Philadelphia.

Funding

The study in Philadelphia was supported by the National Institutes of Health/National Institute on Deafness & Other Communication Disorders (NIHSS/NIDCD) under grant [grant number R01 DC01924-15] awarded to

Nadine Martin. The Finnish part of the study was supported by a grant from the Academy of Finland [grant number 135688] awarded to Matti Laine. In Spain, this study was supported by the Spanish Government under grant [grant number MICINN], [grant number PSI2011-29219] awarded to Antoni Rodríguez Fornells. Claudia Peñaloza has been supported by an IDIBELL predoctoral fellowship.

References

Baddeley A. Working memory and language: An overview. Journal of Communication Disorders. 2003a; 36:189–208. [PubMed: 12742667]

Baddeley A. Working memory: Looking back and looking forward. Nature Reviews Neuroscience. 2003b; 4:829–839. [PubMed: 14523382]

Baddeley A, Gathercole S, Papagno C. The phonological loop as a language learning device. Psychological Review. 1998; 105:158–173. [PubMed: 9450375]

Christiansen MH, Louise Kelly M, Shillcock RC, Greenfield K. Impaired artificial grammar learning in agrammatism. Cognition. 2010; 116:382–393. [PubMed: 20605017]

Cunillera T, Càmara E, Toro JM, Marco-Pallares J, Sebastián-Galles N, Ortiz H, Rodríguez-Fornells A. Time course and functional neuroanatomy of speech segmentation in adults. NeuroImage. 2009; 48:541–553. [PubMed: 19580874]

Cunillera T, Laine M, Cámara E, Rodríguez-Fornells A. Bridging the gap between speech segmentation and word-to-world mappings: Evidence from an audiovisual statistical learning task. Journal of Memory and Language. 2010; 63:295–305.

De Renzi E, Faglioni P. Normative data and screening power of a shortened version of the token test. Cortex. 1978; 14:41–49. [PubMed: 16295108]

Dutoit, T., Pagel, N., Pierret, F., Bataille, O., van der Vreken, O. The MBROLA project: Towards a set of high-quality speech synthesizers free of use for non-commercial purposes. Philadelphia, PA: CSLP, fourth international conference on spoken language; 1996 Oct 3–6.

Evans JL, Saffran JR, Robe-Torres K. Statistical learning in children with specific language impairment. Journal of Speech Language and Hearing Research. 2009; 52:321–335.

Friederici AD. The brain basis of language processing: From structure to function. Physiological Reviews. 2011; 91:1357–1392. [PubMed: 22013214]

Gathercole SE. Nonword repetition and word learning: The nature of the relationship. Applied Psycholinguistics. 2006; 27:513–543.

Gathercole SE, Hitch GJ, Service E, Martin AJ. Phonological short-term memory and new word learning in children. Developmental Psychology. 1997; 33:966–979. [PubMed: 9383619]

Gelfand JR, Bookheimer SY. Dissociating neural mechanisms of temporal sequencing and processing phonemes. Neuron. 2003; 38:831–842. [PubMed: 12797966]

Gómez RL, Gerken L. Infant artificial language learning and language acquisition. Trends in Cognitive Sciences. 2000; 4:178–186. [PubMed: 10782103]

Goodglass, H., Kaplan, E., Barresi, B. The assessment of aphasia and related disorders. 3rd. Baltimore, MD: Lippincott Williams & Wilkins; 2001.

Goodglass, H., Kaplan, E., Barresi, B. Evaluación de la afasia y los trastornos relacionados [The assessment of aphasia and related disorders, Spanish adaptation]. 3rd. Madrid: Panamericana; 2005.

Goschke T, Friederici AD, Kotz SA, van Kampen A. Procedural learning in Broca's aphasia: Dissociation between the implicit acquisition of spatio-motor and phoneme sequences. Journal of Cognitive Neuroscience. 2001; 13:370–388. [PubMed: 11371314]

Gupta P, Martin N, Abbs B, Schwartz M, Lipinski J. New word learning in aphasic patients: Dissociating phonological and semantic components. Brain and Language. 2006; 99:8–9.

Gupta P, Tisdale J. Word learning, phonological short-term memory, phonotactic probability and long-term memory: Towards an integrated framework. Philosophical Transactions of the Royal Society B: Biological Sciences. 2009; 364:3755–3771.

Hickok G. The functional neuroanatomy of language. Physics of Life Reviews. 2009; 6:121–143. [PubMed: 20161054]

Hickok G, Poeppel D. Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. Cognition. 2004; 92:67–99. [PubMed: 15037127]

Hickok G, Poeppel D. The cortical organization of speech processing. Nature Reviews Neuroscience. 2007; 8:393–402. [PubMed: 17431404]

Jusczyk PW, Houston DM, Newsome M. The beginnings of word segmentation in English-learning infants. Cognitive Psychology. 1999; 39:159–207. [PubMed: 10631011]

Karuza EA, Newport EL, Aslin RN, Starling SJ, Tivarus ME, Bavelier D. The neural correlates of statistical learning in a word segmentation task: An fMRI study. Brain and Language. 2013; 127:46–54. [PubMed: 23312790]

Kelly H, Armstrong L. New word learning in people with aphasia. Aphasiology. 2009; 23:1398–1417.

Kertesz, A. Western aphasia battery-revised. San Antonio, TX: Pearson; 2006.

Krogh L, Vlach HA, Johnson SP. Statistical learning across development: Flexible yet constrained. Frontiers in Psychology. 2013; 3:598. [PubMed: 23430452]

Kujala T, Halmetoja J, Näätänen R, Alku P, Lyytinen H, Sussman E. Speech- and sound-segmentation in dyslexia: Evidence for a multiple-level cortical impairment. European Journal of Neuroscience. 2006; 24:2420–2427. [PubMed: 17074059]

Laine, M., Niemi, J., Koivuselkä-Sallinen, P., Koivusalo, A. The experimental Swedish version of the Boston diagnostic aphasia examination. 2nd. 1986. Unpublished manuscript

Laine, M., Niemi, J., Koivuselkä-Sallinen, P., Tuomainen, J. Bostonin diagnostinen afasiatutkimus [The standardized Finnish version of the Boston diagnostic aphasia examination]. Helsinki: Psykologien Kustannus; 1997.

López-Barroso D, Catani M, Ripollés P, Dell'Acqua F, Rodríguez-Fornells A, de Diego-Balaguer R. Word learning is mediated by the left arcuate fasciculus. Proceedings of the National Academy of Sciences. 2013; 110:13168–13173.

López-Barroso D, de Diego-Balaguer R, Cunillera T, Camara E, Münte TF, Rodríguez-Fornells A. Language learning under working memory constraints correlates with microstructural differences in the ventral language pathway. Cerebral Cortex. 2011; 21:2742–2750. [PubMed: 21527790]

Ludden, D., Gupta, P. Zen in the art of language acquisition: Statistical learning and the less is more hypothesis. In: Gleitman, L., Joshi, A., editors. Proceedings of the twenty second annual conference of the Cognitive Science Society. Hillsdale, NJ: Lawrence Erlbaum; 2000.

Martin N, Ayala J. Measurements of auditory-verbal STM span in aphasia: Effects of item, task, and lexical impairment. Brain and Language. 2004; 89:464–483. [PubMed: 15120538]

Martin N, Gupta P. Exploring the relationship between word processing and verbal short-term memory: Evidence from associations and dissociations. Cognitive Neuropsychology. 2004; 21:213–228. [PubMed: 21038201]

Martin, N., Kohen, F., Kalinyak-Fliszar, M. A processing approach to the assessment of language and verbal short-term memory abilities in aphasia. Charleston, SC: Clinical aphasiology conference; 2010 May 23–27.

Mayo J, Eigsti I-M. Brief report: A comparison of statistical learning in school-aged children with high functioning autism and typically developing peers. Journal of Autism and Developmental Disorders. 2012; 42:2476–2485. [PubMed: 22382606]

McNealy K, Mazziotta JC, Dapretto M. Cracking the language code: Neural mechanisms underlying speech parsing. The Journal of Neuroscience. 2006; 26:7629–7639. [PubMed: 16855090]

Mirman D, Magnuson JS, Estes KG, Dixon JA. The link between statistical segmentation and word learning in adults. Cognition. 2008; 108:271–280. [PubMed: 18355803]

Moritz-Gasser S, Duffau H. The anatomo-functional connectivity of word repetition: Insights provided by awake brain tumor surgery. Frontiers in Human Neuroscience. 2013; 7:405. [PubMed: 23908617]

Ngon C, Martin A, Dupoux E, Cabrol D, Dutat M, Peperkamp S. (Non) words, (non) words, (non) words: Evidence for a protolexicon during the first year of life. Developmental Science. 2013; 16:24–34. [PubMed: 23278924]

Papagno C, Valentine T, Baddeley A. Phonological short-term memory and foreign-language vocabulary learning. Journal of Memory and Language. 1991; 30:331–347.

Rodríguez-Fornells A, Cunillera T, Mestres-Missé A, de Diego-Balaguer R. Neurophysiological mechanisms involved in language learning in adults. Philosophical Transactions of the Royal Society B: Biological Sciences. 2009; 364:3711–3735.

Saffran JR. Statistical language learning: Mechanisms and constraints. Current Directions in Psychological Science. 2003; 12:110–114.

Saffran JR, Aslin RN, Newport EL. Statistical learning by 8-month-old infants. Science. 1996; 274:1926–1928. [PubMed: 8943209]

Saffran JR, Newport EL, Aslin RN. Word segmentation: The role of distributional cues. Journal of Memory and Language. 1996; 35:606–621.

Saur D, Kreher BW, Schnell S, Kümmerer D, Kellmeyer P, Vry M-S, Weiller C. Ventral and dorsal pathways for language. Proceedings of the National Academy of Sciences. 2008; 105:18035–18040.

Scott SK, Wise RJS. The functional neuroanatomy of prelexical processing in speech perception. Cognition. 2004; 92:13–45. [PubMed: 15037125]

Shelton, J., Martin, R., Yaffee, L. Investigating a verbal short-term memory deficit and its consequences for language processing. In: Margolin, D., editor. Cognitive neuropsychology in clinical practice. New York, NY: Cambridge University Press; 1992.

Tuomiranta L, Càmara E, Froudist Walsh S, Ripollés P, Saunavaara J, Parkkola R, Laine M. Hidden word learning capacity through orthography in aphasia. Cortex. 2014; 50:174–191. [PubMed: 24262200]

Tuomiranta L, Grönholm-Nyman P, Kohen F, Rautakoski P, Laine M, Martin N. Learning and maintaining new vocabulary in persons with aphasia: Two controlled case studies. Aphasiology. 2011; 25:1030–1052.

Tuomiranta L, Laine M, Martin N. Adaptation of the temple assessment of language and short-term memory in aphasia (TALSA) into the Finnish language. 2009 Unpublished manuscript.

Tuomiranta L, Rautakoski P, Rinne JO, Martin N, Laine M. Long-term maintenance of novel vocabulary in persons with chronic aphasia. Aphasiology. 2012; 26:1053–1073.

Tyler MD, Cutler A. Cross-language differences in cue use for speech segmentation. The Journal of the Acoustical Society of America. 2009; 126:367–376. [PubMed: 19603893]

Appendix

Stimuli developed for the speech segmentation task according to the phonotactic rules of the native language of the participants.

Stimuli	Spanish	English	Finnish	Swedish
Words	ditume	fachivey	jitupo	kiretu
	mupeja	thozishey	koviti	molapi
	sunile	fuchotha	vovahi	tolifa
	docuga	shazovoo	talupu	pedana
Nonwords (2AFC test)	disuja	chithofu	jipohi	falana
	gamuni	zithashey	vivotu	todape
	doletu	favuzo	tikota	lipire
	mecupe	veichosha	puvalu	kimotu

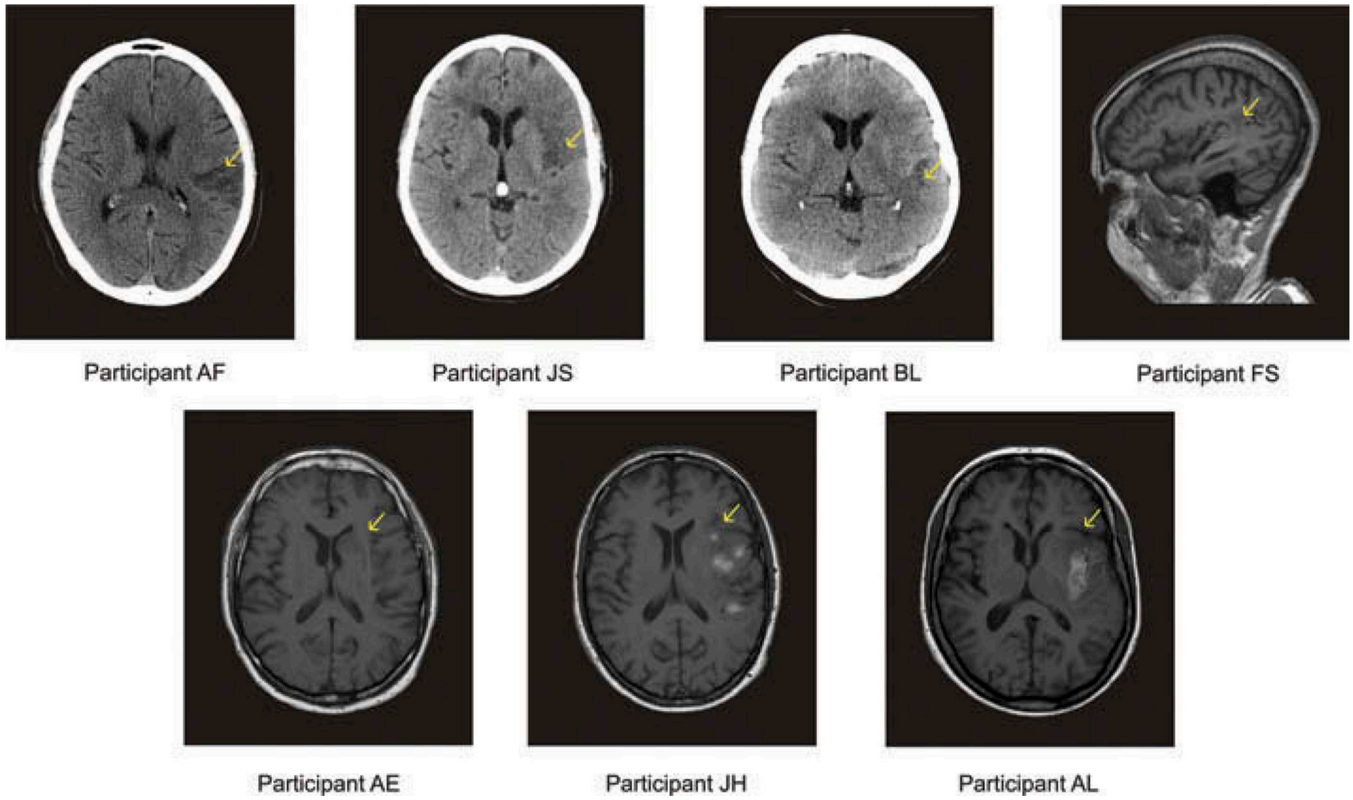

Figure 1.
Neuroimage scans of seven representative cases. Upper row: CT scans of participants with aphasia with parietal lesions (AF), temporal lesions (JS) and parieto-temporal lesions (BL). MRI T1-weighted scan of participant FS showing a lesion in the arcuate fasciculus. Participants AF and JS achieved the highest performance in the speech segmentation test, whereas participants BL and FS performed at chance level. Second row: MRI T1-weighted scans showing cortico-subcortical lesions in participant AE, and ischaemic lesions in fronto-temporal regions and the transformation to intracerebral haemorrhage in participants JH and AL. The aphasic participants with lesions involving the inferior frontal regions were unable to segment words from the novel language. [To view this figure in colour, please see the online version of this Journal.]

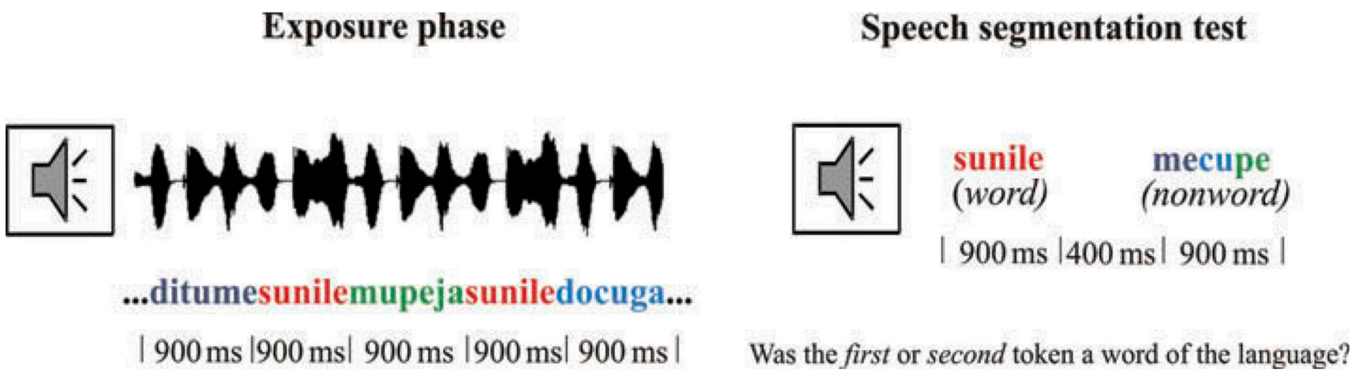

Figure 2.

Speech segmentation task. The figure depicts a sample of the Spanish-based artificial language created with four trisyllabic "words" (tokens are illustrated in different colours) followed by the speech segmentation test. [To view this figure in colour, please see the online version of this Journal.]

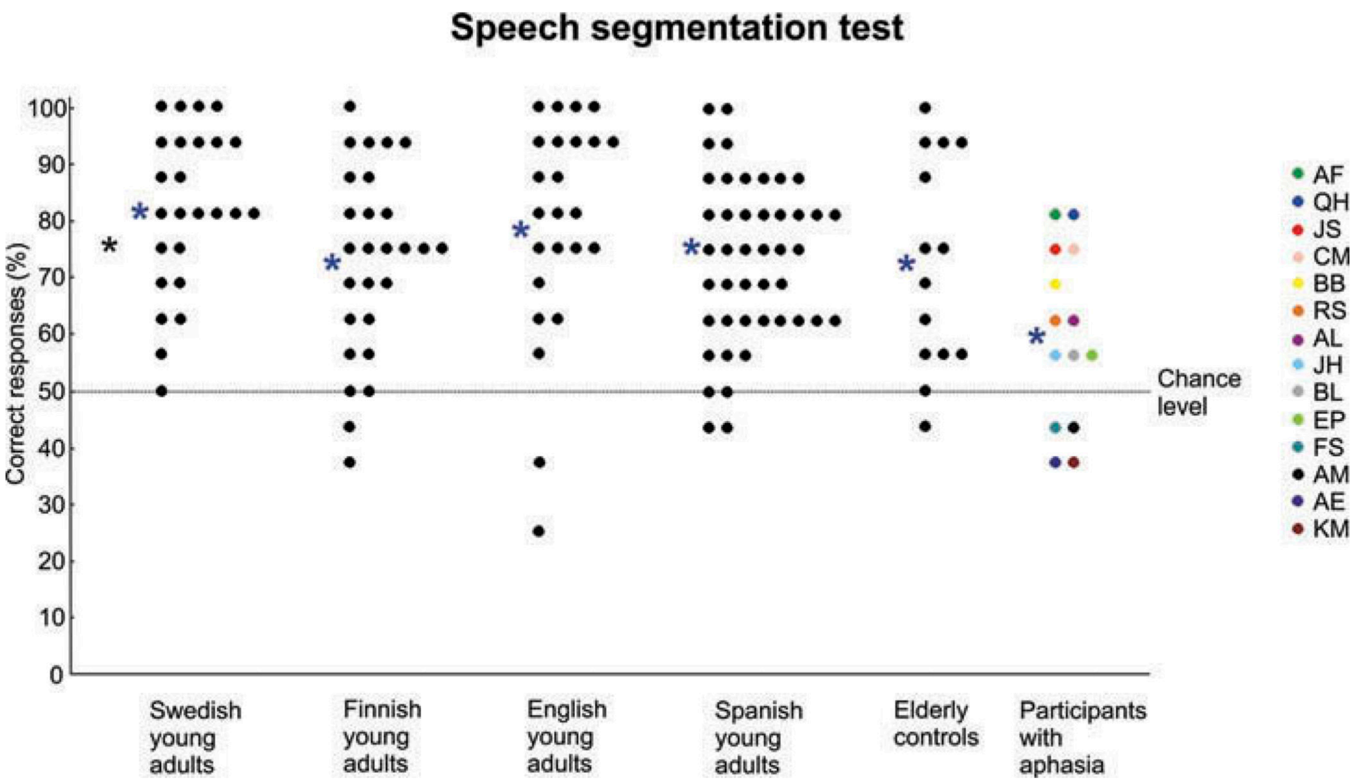

Figure 3.

Mean per cent of correctly segmented words per group in the speech segmentation test. Group means for the participants with aphasia, the elderly controls, and the young adults are depicted with an asterisk. Dots represent each individual's performance. The group mean (leftmost asterisk) of the complete group of young adults is shown for comparative purposes. Note that participants AF, QH, JS and CM who had lesions in posterior regions (parietal and/or temporal regions) and mild fluent aphasia reached the highest performance level in this test. [To view this figure in colour, please see the online version of this Journal.]

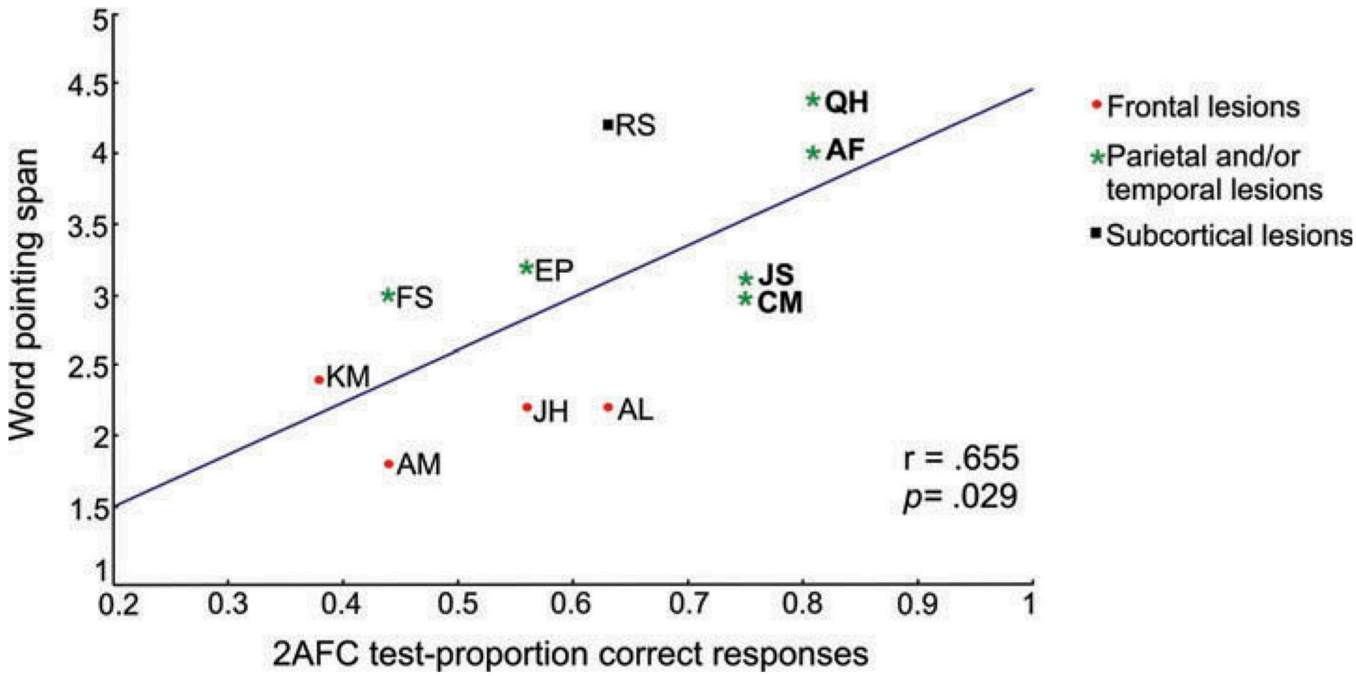

Figure 4.

Association between verbal STM and word segmentation ability in participants with aphasia. Pearson correlations between the performances of the participants with aphasia in the TALSA word pointing span and the speech segmentation test. Notice that QH, AF, JS, and CM (depicted in bold) with predominantly posterior lesions but spared frontal cortex performed above chance level in the speech segmentation test. [To view this figure in colour, please see the online version of this Journal.]

Table 1

Demographic information of the young adults, participants with aphasia and elderly matched controls.

	Young adults	Participants with aphasia	Elderly matched controls
Gender (% male)	31.7	78.6	78.6
Age	*M* = 23.8; *SD* = 5.76	*M* = 65.36; *SD* = 8.28	*M* = 66.57; *SD* = 6.42
Years of education	*M* = 14.96; *SD* = 1.4	*M* = 12.71; *SD* = 5.1	*M* = 15.36; *SD* = 4.4
Handedness (% right)	96.7	92.8[a]	100
Language background			
Spanish monolinguals (*n*)	–	3	3
Spanish early bilinguals: Catalan/Spanish (*n*)	44[b]	3	3
Swedish monolinguals (*n*)	20	1	1
Swedish bilinguals: Swedish/Finnish (*n*)	5	1	1
Finnish monolinguals (*n*)	10	2	2
Finnish bilinguals: Finnish/Swedish (*n*)	17	–	–
English monolinguals (*n*)	24[c]	4	4

Notes:

[a]Participant BB was left-handed and had suffered a right hemisphere stroke.

[b]Spanish speakers were predominantly early bilinguals (Catalan/Spanish) as they received formal education in both the languages.

[c]English speakers were predominantly monolinguals with some knowledge of Spanish.

Table 2

Demographic and clinical data of participants with chronic aphasia.

Case	Gender/ age (years)	Ed. (years)	Native language	Time from stroke (months)	Lesion location	Aetiology	Neurological examination (acute stage)	Aphasia type (chronic stage)
AE	M/66	11	Spanish	24	Insular and opercular frontal regions, caudate and lenticular nucleus, and postcentral parietal regions[b]	I	Right hemiparesis	Anomic/mild
JH	M/54	16	Catalan/Spanish[a]	19	Extensive MCA stroke/ intracerebral haemorrhage (frontal regions, caudate nucleus)[b]	I/H	Right hemiparesis	Broca/moderate
AF	M/69	8	Catalan/Spanish[a]	24	Left MCA stroke (parietal perisylvian regions)[c]	I	Right hemiparesis	Fluent aphasia/mild
AM	M/72	10	Spanish	17	Left MCA stroke (frontal regions, insula)[b]	I	Right hemiparesis/ homonymous hemianopsia	Broca/severe
RS	M/57	8	Catalan/Spanish[a]	15	Left MCA stroke (caudate nucleus, putamen and internal capsule)	I	Right hemiparesis	Anomic/mild
AL	F/75	Reading/writing	Spanish	19	Left MCA stroke/ intracerebral haemorrhage (insula, opercular frontal and temporal regions, BG)[b]	I/H	Right hemiparesis/ homonymous hemianopsia	Wernicke/moderate
CM	M/50	12	English	53	Left MCA stroke (parietal, bilateral subcortical lesions on the cerebrum, brainstem, cerebellum and putamen as well as white matter lesions)[c]	I	Visual difficulty in the right temporal field	Anomic/mild-moderate
FS	F/59	12	English	82	Left intracerebral haemorrhage within the temporal lobe[c]	H	Mild right hemiparesis	Conduction/ moderate
QH	M/61	18	English	55	Left posterior temporal intracranial haemorrhage/ left transverse sigmoid junction sinus thrombosis	I/H	Mild right hemiparesis/ decreased temporal and left nasal vision	Anomic/mild

Case	Gender/ age (years)	Ed. (years)	Native language	Time from stroke (months)	Lesion location	Aetiology	Neurological examination (acute stage)	Aphasia type (chronic stage)
					with venous infarct and haemorrhagic conversion (left hemicraniectomy)[c]			
KM	M/67	16	English	192	Left MCA-ACA stroke involving the left frontal, temporal, and parietal lobes and left BG[b]	I	Right hemiparesis	Transcortical motor/mild-moderate
BB	M/73	18	Swedish	96	Right MCA stroke	I	Left hemiparesis	Anomic/moderate
BL	F/63	16	Swedish/Finnish[a]	85	Aneurysm rupture in the PCA leading to subarachnoid haemorrhage. The haemorrhage lead to a vasospasm resulting in infarction in the left temporal and parietal lobes[c]	I/H	Right hemiparesis	Fluent aphasia/mild
JS	M/77	15	Finnish	36	Left MCA stroke (temporal regions)[c]	I	Right hemiparesis	Mixed/mild
EP	M/72	18	Finnish	36	Extensive left temporal intracranial haemorrhage[c]	H	Right hemiparesis/ homonymous hemianopsia	Anomic/moderate

Notes: Ed = education; M = male; F = female; MCA = middle cerebral artery; ACA = anterior cerebral artery; PCA = posterior cerebral artery; I = ischaemia; H = haemorrhage; BG = basal ganglia.

[a]Early bilinguals.

[b]Predominantly anterior lesions.

[c]Predominantly posterior lesions.

Table 3

Speech and language profile of the Spanish-, Finnish-, and Swedish-speaking participants with chronic aphasia.

	Participants with aphasia									
Language measure	**AE**	**JH**	**AF**	**AM**	**RS**	**AL**	**BB**	**BL**	**JS**	**EP**
BDAE										
Severity rating	5	3	5	1	5	3	3	2	4	3
Auditory comprehension										
Word comprehension	36/37	35/37	37/37	**24.5/37**	35/37	**33/37**	66.5/72	72/72	68/72	56.5/72
Commands	14/15	14/15	15/15	**12/15**	15/15	**12/15**	8/15	15/15	15/15	12/15
C. ideational material	11/12	**6/12**	10/12	10/12	10/12	**7/12**	6/12	10/12	11/12	10/12
Repetition										
Word repetition	10/10	**8/10**	10/10	**6/10**	**9/10**	**6/10**	8/10	9/10	9/10	10/10
Sentence repetition	8/10	**2/10**	9/10	**0/10**	9/10	**2/10**	2/8[a]	7/8[a]	7/8[a]	7/8[a]
							0/8[b]	5/8[b]	5/8[b]	6/8[b]
Other tests										
Token test	**25/36**	**14/36**	**28/36**	**12/36**	**31/36**	**20/36**	15/36	25/36	19.5/36	18.5/36

Notes: Scores below the 50th percentile are marked in bold (except for participants BB, BL, JS, and EP for whom normative data were unavailable).

C. ideational material = complex ideational material; NA = not administered.

[a]Repetition of high-probability sentences.

[b]Repetition of low-probability sentences.

Author Manuscript

Author Manuscript

Author Manuscript

Table 4

Speech and language profile of the English-speaking participants with chronic aphasia.

	Participants with aphasia			
Language measure	**CM**	**FS**	**QH**	**KM**
BDAE severity rating	4	4	5	3
WAB-R aphasia quotient	89.3	85.5	84.9	76
WAB-R auditory comprehension quotient	9.5	9.2	9.9	8.4
WAB-R repetition quotient	7.7	6.7	8.2	8.6

Table 5

Performance of the participants with aphasia in the TALSA word and digit span tests.

Span measure	AE	JH	AF	AM	RS	AL	CM	FS	QH	KM	BB	BL	JS	EP
Word pointing span	NA	2.2	4.0	1.8	4.2	2.2	3.0	3.0	4.4	2.4	NA	NA	3.1	3.2
Digit pointing span	NA	3.4	5.6	1.8	4.8	2.8	4.0	4.0	5.0	3.2	NA	NA	3.1	5.1
Word repetition span	NA	3.0	4.2	1.4	3.8	2.8	2.2	2.2	4.2	3.4	NA	NA	3.2	5.1
Digit repetition span	NA	3.2	5.2	2.0	4.8	2.6	3.2	3.2	5.6	3.8	NA	NA	4.0	6.1

Notes: The maximum span for all subtests is 7 (the number of string length conditions).

NA = not administered.