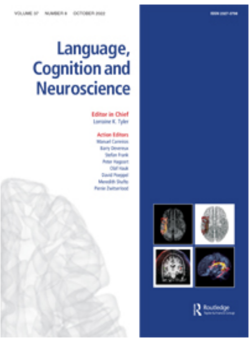

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Effects of healthy aging and left hemisphere stroke on statistical language learning

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ABSTRACT

Spoken sentences are continuous streams of sound, without reliable acoustic cues to word boundaries. We have previously proposed that language learners identify words via an implicit statistical learning mechanism that computes transitional probabilities between syllables. Neuroimaging studies in healthy young adults associate this learning with left inferior frontal gyrus, left arcuate fasciculus, and bilateral striatum. Here, we test the effects of healthy aging and left hemisphere (LH) injury on statistical learning. Following 10-minute exposure to an artificial language, participants rated familiarity of Words, Part-words (sequences spanning word boundaries), and Non-words (unfamiliar sequences). Young controls (N = 14) showed robust learning, rating Words > Part-words > Non-words. Older controls (N = 28) showed this pattern to a weaker degree. Stroke survivors (N = 24) as a group showed no learning. A lesion comparison examining individual differences revealed that "non-learners" are more likely to have anterior lesions. Together, these findings demonstrate that word segmentation is sensitive to healthy aging and LH injury.

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Word segmentation; statistical learning; language; aging; stroke

1. Introduction

1.1. General introduction

Statistical learning is a form of implicit learning by which learners extract patterns and regularities from their environment (Aslin et al., 1998; Aslin & Newport, 2012; Newport, 2016; Saffran, Aslin, et al., 1996). Reber (1967) suggested some time ago that the learning of language-like sequential patterns can occur implicitly, without full awareness. Saffran, Newport, et al. (1996) focused on word segmentation, the process by which learners identify words in an acoustically continuous speech stream, and suggested a precise computational mechanism by which this process might be occurring in infant and adult learners.

Early on, Harris (1955) laid the groundwork for such a mechanism by suggesting that, in the context of linguistic analysis, phoneme co-occurrences might help linguists identify words in an unfamiliar language. Hayes and Clark (1970) then showed that such co-occurrences could be used by adult listeners to segment an acoustic stream of nonlinguistic sounds. Saffran, Newport, et al. (1996) suggested that co-occurrence information might be used by human language learners via a *statistical learning* mechanism. In particular, the authors proposed that learners may compute transitional probabilities (TPs) between syllables – the probability from one syllable to the next in a corpus of speech – to perform word segmentation in a previously unknown language (Saffran, Newport, et al., 1996). Groups of syllables with *high* transitional probabilities would be potential words, while syllables with low transitional probabilities would be potential word boundaries. In a series of experiments with synthesised speech streams from an artificial language, they demonstrated that infant, child, and adult learners can indeed segment words from fluent speech via this mechanism (Aslin et al., 1998; Saffran et al., 1997, 1999; Saffran, Newport, et al., 1996).

Infants and adults have also been shown to use this same statistical computation to extract regularities in a variety of non-language stimuli, including non-linguistic auditory (Gebhart et al., 2009; Saffran et al., 1999) and visual (Fiser & Aslin, 2002) sequences. Learners can also employ other statistical computations to acquire aspects of language beyond word segmentation, from the discrimination of speech sound categories (Maye

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et al., 2002) to the acquisition of syntactic phrases (Thompson & Newport, 2007) and other types of grammatical rules (Gòmez & Gerken, 1999; Reeder et al., 2013). These findings suggest that statistical learning is a robust and powerful learning mechanism by which human learners can acquire many aspects of language structure from their linguistic input.

1.2. Changes in statistical learning ability during healthy aging

In general, implicit memory is thought to be spared relative to explicit memory during healthy aging (Hedden & Gabrieli, 2004). In many cases, older adults do show preserved implicit learning on non-linguistic serial reaction time (SRT) tasks (Nissen & Bullemer, 1987) when compared to direct learning measures of the same sequence (Howard & Howard, 1989, 1992; King et al., 2013; Weiermann & Meier, 2012). However, there is also significant evidence for *decreased* implicit learning ability in older adults compared to younger adults in several types of implicit/procedural tasks, including probabilistic sequence learning for higher order serial dependencies and non-rule-based categorisation tasks (Filoteo & Maddox, 2004; Howard & Howard, 1997). This decline may begin during middle age (Feeney et al., 2002). Researchers have found that older adults' performance on implicit learning tasks is predicted by their cognitive and working memory ability (Cherry & Stadler, 1995). Implicit learning is thus not entirely spared during healthy aging; rather, there are likely several processes under the umbrella of implicit learning, each of which may be differentially affected by aging (Howard & Howard, 2013).

In the literature on statistical learning, a specific form of implicit learning, emphasis is often given to the fact that the statistical learning mechanism is available from birth (Aslin, 2017; Bulf et al., 2011; Gervain et al., 2008; Teinonen et al., 2009). Given this, one may assume that the statistical learning mechanism is relatively invariant over age. Indeed, among the few studies that have investigated statistical language learning ability across the lifespan, many have found age-related decline only under difficult learning circumstances (see Rieckmann & Bäckman, 2009 for a discussion) or when the task also invokes *explicit* learning processes. For example, Muylle and colleagues (2021) recently demonstrated that older Dutch-speaking adults were able to show implicit learning of novel phonotactic constraints as successfully as younger adults but showed reduced sensitivity to certain aspects of learning supported by explicit memory processes (Muylle et al., 2021). In contrast, there is also evidence for age-related decline in certain aspects of statistical language learning regardless of task difficulty or the role of explicit memory, such as in statistical learning of word categories (e.g. *noun* or *verb*). In a study comparing young and older adults on the same task, older adults do succeed in showing significant learning of word categories, but their levels of learning are significantly lower than young adults (Schwab et al., 2016).

Here, we are specifically interested in word segmentation, which is an aspect of statistical language learning that has not been adequately examined in older adults. In one recent study, Palmer and colleagues (2018) compared young (18-25 years old), middle-aged (40-50 years old), and older adults (60-81 years old). They found that, while word segmentation ability was "remarkably resilient to aging", the older adults performed worse than young and middle-aged adults in most task paradigms and had more difficulty when the task was more demanding (Palmer et al., 2018, p. 1035).

Most other studies of word segmentation in older adults have been done in the context of lesion studies, where the older adults serve as a control group for comparison with stroke survivors. Peñaloza et al. (2015, 2017) used older controls as a comparison for their stroke survivor population in two studies of people with left hemisphere stroke (see Section 1.3). While both studies showed that older controls and younger controls performed above chance on a word segmentation task, a pairwise comparison in the second study showed a significant difference in the performance of these two age groups, suggesting the possibility of age-related decline (Peñaloza et al., 2017). In Shaqiri et al. (2018), older controls were again used as a comparison group for stroke survivors with left- and right-hemisphere brain injury, in a series of experiments that included repeated exposure to a single language as well as exposure to two languages (with and without a break). Word segmentation ability was assessed via two-alternative forced choice (2AFC) tasks and older controls' performance was above chance across all experiments, although the authors note evidence of an "attenuated capacity limit" (p. 6) in older controls compared to younger controls when learning two languages (Shaqiri et al., 2018). Taken together, these studies show that there can be differences in statistical language learning ability across the lifespan; however, findings differ across studies and the specific impact of healthy aging on word segmentation ability has not been adequately examined.

1.3. Neural correlates of statistical learning in language

A small number of studies have investigated the neural correlates of word segmentation, either in healthy young adults or in brain injury populations. The majority of studies on word segmentation in healthy young adults have focused on activation related to exposure to the speech stream, but without confirmation that learning has occurred. These studies have found activation of bilateral superior temporal cortex as well as the left inferior and middle frontal gyri in association with exposure to statistically regular speech streams (Cunillera et al., 2009; McNealy et al., 2006).

An fMRI study by Karuza et al. (2013) was the first experiment in which researchers examined the neural correlates of statistical learning for word segmentation in healthy adults while also directly demonstrating behavioural learning and controlling for auditory processing. Like earlier studies, they found bilateral superior temporal gyrus (STG) activation during simple exposure (Cunillera et al., 2009; McNealy et al., 2006), but a contrast of forward vs. backward speech showed left lateralisation during the forward stream (Karuza et al., 2013). They identified a key role for left inferior frontal gyrus (LIFG) and the bilateral striatum (caudate and putamen) specifically in learning by demonstrating that better learning during the word segmentation task was associated with increased activation in LIFG. They suggested a cortico-striatal circuit underlying task performance (Karuza et al., 2013). A similar behavioural paradigm was used in Spanish speakers to examine the role of white matter connectivity in word segmentation (López-Barroso et al., 2013). In this study, the structural integrity of the left arcuate fasciculus (AF) and the functional connectivity of brain regions connected by the AF were found to be related to word learning ability. The authors concluded that direct connections between Broca's and Wernicke's areas (i.e. the long segment of the left AF) underlie the ability to learn words in a speech stream (López-Barroso et al., 2013).

The above studies in healthy adults suggest that the network used for statistical learning includes not only left-lateralised (Karuza et al., 2013; López-Barroso et al., 2013) but also bilateral structures (Cunillera et al., 2009; Karuza et al., 2013; McNealy et al., 2006). Studying this ability in left hemisphere stroke survivors may help to determine whether word segmentation critically relies on structures in the left hemisphere. To date, however, only three published studies have examined word segmentation after left hemisphere stroke. Peñaloza et al. (2015) performed a word segmentation study and found that groups of young adults, older adults, and adults with aphasia all performed above chance on a 2AFC task. They suggested that - despite structural damage to language areas - statistical learning remained intact in stroke survivors with post-stroke aphasia. However, examination of the individual scores shows that only four of 14 participants with aphasia performed above chance; each of these individuals had a stroke in the posterior left hemisphere, involving temporal and parietal (but not frontal) regions (Peñaloza et al., 2015). These findings are consistent with the functional activation studies previously described, since above-chance performance was demonstrated only by stroke survivors with no damage to frontal regions previously implicated in this ability. In a later study of cross-situational word learning in individuals with aphasia, three of 16 Spanish speakers with aphasia demonstrated above-chance word segmentation performance in a similar paradigm (Peñaloza et al., 2017). Direct comparisons between participant groups showed that the aphasia group performed worse than healthy older controls, who in turn performed worse than healthy young adults (Peñaloza et al., 2017). In both studies, the 2AFC task compared familiar "words" to "non-words," sequences that never occurred in the exposure language, so successful performance may reflect relatively simple sequence learning (Peñaloza et al., 2015, 2017).

The most recent study on word segmentation ability after stroke was performed in stroke survivors with either left- or right-sided stroke, compared with healthy older controls and healthy young adults (Shaqiri et al., 2018). In this study, participants were exposed to two different artificial languages and learning was assessed through a 2AFC post-test; importantly, in this study the choices were either "words" or "part-words," with the latter representing sequences that did occur in the listening stream but that spanned word boundaries. The results indicated that the two control groups performed well (with no statistical difference between young vs. older adults) and that all stroke survivor groups performed worse than the controls (Shaqiri et al., 2018). A separate experiment tested whether repeated exposure to a single language would improve stroke survivor performance, but both left- and right-hemisphere stroke survivors again performed worse than the older controls. A final analysis in the study used voxel-based lesion-symptom mapping (VLSM) in a subset of stroke survivors ($N = 17$), using a hemisphere-flipping procedure for combining left- and right-hemisphere stroke survivors into a single analysis. Although no brain regions survived a statistical threshold, the authors note that the area with the "most extreme *z* statistic" (p. 9) is the anterior portion of BA 22 (Shaqiri et al., 2018). Given the small sample size and unconventional approach to combining stroke survivors with lesions in opposite hemispheres, this particular result should be interpreted with caution.

Beyond these limited lesion studies of word segmentation, lesion studies examining a broader set of implicit statistical learning tasks in the verbal domain may also be informative, as these tasks share some key properties with word segmentation tasks (e.g. Perruchet & Pacton, 2006). The studies most closely related to word segmentation use an adaptation of an SRT task called a "serial search task" (SST), where a statistical regularity occurs within an auditory sequence (rather than a motoric sequence as in most SRT tasks) (Goschke et al., 2001; Nissen & Bullemer, 1987). However, results from this SST literature are similarly mixed. Goschke et al. (2001) showed that five individuals with Broca's aphasia following left hemisphere stroke demonstrated impaired learning for phoneme sequences but spared spatio-motor sequence learning. In contrast, Schuchard and Thompson (2014) demonstrated that 10 individuals with agrammatic aphasia following left hemisphere stroke performed as well as age-matched controls in implicit learning of an SST using concrete words rather than phonemes. These mixed results thus provide inconclusive evidence regarding the ability of left hemisphere stroke survivors to perform verbal implicit learning tasks.

To summarise, work with healthy adults suggests a statistical language learning network that activates bilateral STG, bilateral striatum, and left-lateralised regions of the frontal cortex (e.g. LIFG) (Cunillera et al., 2009; Karuza et al., 2013; López-Barroso et al., 2013; McNealy et al., 2006). Based on these patterns of activation, some researchers have hypothesised that a cortico-striatal circuit underlies performance on statistical learning tasks (Karuza et al., 2013). This suggests that statistical language learning ability should be affected when these regions are not functioning well, either due to the brain's natural aging process or by lesions. Research on statistical and implicit learning across the lifespan suggests that these forms of learning may be preserved into older adulthood, but this preservation likely depends on cognitive ability (Cherry & Stadler, 1995; Howard & Howard, 2013; Palmer et al., 2018). Rieckmann and Bäckman (2009) have suggested that age-related decline in striatal regions (Bäckman et al., 2006; Raz et al., 2003) may lead to a reorganisation of the regions that implicit learning recruits, allowing older adults to preserve their performance on these tasks by relying more heavily on frontal regions to compensate. Similarly, Howard and Howard (2013) have argued that older adults shift from using the basal ganglia to using cortical regions for successful completion of SRT tasks. Taken together, these findings suggest that age-related decline in statistical language learning should be visible for more demanding tasks (e.g. comparing words to part-words), and older adults with damage to frontal regions (e.g. stroke survivors with left hemisphere lesions) should show even greater deficits. However, the limited lesion work on this topic has yet to establish a strong causal relationship between damage to specific brain areas and behavioural impairments in learning. In the present work, we aim to fill this gap by testing word segmentation ability in a group of healthy older adults compared with older adults who have suffered a left hemisphere stroke, using a comparative lesion analysis approach to examine brain-behaviour relationships.

1.4. The current study

Here we examine word segmentation in young adults, older adults, and left hemisphere stroke survivors. As our behavioural measure of statistical language learning, we use the Saffran, Aslin, et al. (1996) word segmentation paradigm, adapted slightly for use with stroke survivor populations (Saffran, Aslin, et al., 1996). We selected this paradigm because learning of these materials has been robust and replicable across a variety of populations and conditions (Aslin & Newport, 2012; Saffran, 2003). We examine differences in learning across the three participant groups, then compare the lesion locations of two subgroups within our stroke survivor population: "learners," who perform the task successfully, and "non-learners," who do not, in order to explore specific brain regions where damage may be related to behavioural impairment.

Based on prior research on statistical learning and implicit sequence learning in healthy older adults, our hypothesis is that statistical learning in the context of word segmentation will be reduced in this population relative to younger adults. Further, we predict that word segmentation ability will be impaired in left hemisphere stroke survivors, particularly those with lesions of LIFG and striatal regions, and possibly those with lesions to left STG or AF.

2. Materials and methods

2.1. Participants

Informed consent for all participants was obtained under a protocol approved by the Georgetown University Institutional Review Board. Three groups of participants were recruited: healthy young adults (N = 14), healthy older adults (N = 31), and older adults in the chronic phase of recovery from left hemisphere stroke (N = 39). Some individuals did not meet the inclusion criteria listed below and were excluded from our analyses.

Note that these inclusion criteria were selected prior to the collection of data.

- Native English speakers, defined as being immersed in English by the age of five years old (one stroke survivor excluded)
- Monitoring task: during the listening phase of the experiment, participants were required to press a button in response to 20 beeps embedded in the auditory stream (one older adult control participant excluded due to 148 false presses, well beyond 3 standard deviations from the mean number of button presses in this group)
- Post-test rating scale: participants were excluded if they failed to understand the task. We quantified this as having assigned the same rating to ≥ 90% of post-test items (one older adult control participant and 11 stroke survivors excluded)

For the stroke group, there were two additional inclusion criteria:

- Occurrence of a left hemisphere stroke at least six months prior to participation
- Absence of symptomatic stroke outside of the left hemisphere (three stroke survivors excluded)

For the older adult control group, there was one additional inclusion criterion:

- Scoring 26 or higher on the Montreal Cognitive Assessment (MoCA) (one older adult control participant excluded)

The final cohort of participants for the study included three groups: healthy young adults (N = 14), healthy older adults (N = 28), and older adults in the chronic phase of recovery from left hemisphere stroke (N = 24) (see Table 1 for detailed demographic information). For the stroke survivor group, the average time since stroke onset was 57.2 months (SD = 56.6, range = 6.3-256). All participants in this group had received a diagnosis of aphasia following their stroke. The average Aphasia Quotient (AQ) score from the Western Aphasia Battery-Revised (WAB-R) (Kertesz, 2006) at the time of participation in this study was 76.0 (SD = 18.3, range = 41.8-99.8) on a scale from 0 (most impaired) to 100 (normal language function). Three participants scored above the WAB-R AQ cut-off score of 93.8 indicating normal language performance; however, all participants including these three reported ongoing language impairments at the time of participation in this study. The participant group included a range of subtypes, as defined by the WAB-R criteria: 6 Broca's aphasia, 4 conduction aphasia, 11 anomic aphasia, and 3 not classified (AQ above 93.8) (see Table A1 for details of individual stroke survivors).

Table 1. Demographic information for study participants.

Participant group	N	Age Mean (SD)	Gender M:F	Education Mean (SD)
Young controls	14	19.1 (1.4)	6:8	12.6 (1.0)
Older controls	28	57.8 (13.8)	13:15	16.5 (2.9)
Stroke survivors	24	59.9 (10.9)	17:7	16.8 (3.2)

Older adults and stroke survivors underwent pure-tone audiometry hearing screenings. Each ear was tested separately at 500, 1000, 2000, and 4000 Hz to identify the perception threshold. These results were then averaged across the 8 values to produce an overall measure of hearing acuity, which was used as a covariate in the behavioural analysis (see Section 3.1), to allow examination of potential impact of hearing acuity on performance.

2.2. The artificial language

The artificial language used in this study (a modified stream from Saffran, Aslin, et al., 1996) was constructed from 12 syllables combined to form four 3-syllable words. Each syllable appears in only one word, always in the same position. The four words were sequenced in a continuous stream produced by a speech synthesiser unaware of the word boundaries; the stream therefore contained no acoustic cues to word boundaries. Each word was followed by one of the other three words with equal frequency. Transitional probabilities (TPs) between syllables within words were therefore 1.0; TPs between syllables across a word boundary were 0.33 (Figure 1). The speech stream was synthesised using the female voice Victoria in MacinTalk© with a flat monotone setting. All syllables were coarticulated so that the stream contained no pauses or prosodic cues to indicate word boundaries. The stream from MacinTalk© was further edited using Sound Edit 16 version 2

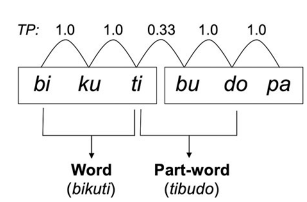

Figure 1. Transitional probabilities (TPs) in the artificial language. TPs between syllables within words are 1.0 and TPs between syllables across word boundaries are 0.33. A part-word (presented in test) is a sequence of 3 syllables that crosses a word boundary.

in order to ensure that all syllable durations, both within and across words, were approximately the same.

Participants listened to the exposure stream for 10 minutes while performing a concurrent monitoring task, using PsychoPy presentation software (Peirce, 2009). The monitoring task required a button press in response to beeps that were embedded every 20-40 seconds within the stream. While this monitoring task was not included in the original experiments using this language (Saffran, Aslin, et al., 1996), it was included here for all groups in order to ensure sustained attention to the stream in the older adult and stroke survivor populations. While some studies have found concurrent monitoring tasks to hinder statistical learning (Franco et al., 2015; Lopez-Barroso et al., 2011; Palmer & Mattys, 2016; Toro et al., 2005), these studies are specifically designed to divert attention from the stream (e.g. short exposure, multiple simultaneous streams, 2-back tasks). Here instead we focused on increasing attention to the stream itself by instructing participants there would be a recognition test later and requiring them to respond to beeps only once or twice per minute of exposure. The instructions for the listening and monitoring tasks were as follows:

> Now, I'd like you to listen closely to a long stream of speech. It's not English and might sound a little like a foreign language. It will last about 10 minutes. As you listen, parts of it might become familiar. When you are done listening, I will ask you questions about how much you recognize from what you just heard. Here is an example of what you'll hear (*a sample clip is played*). That is what you will hear and you will need to listen very closely. While you are listening, you will also hear beeps from time to time. Every time you hear a beep, I want you to press the space bar. Let's practice together. *[Sample clips are played to provide practice; once the participant demonstrates proficiency, the experiment begins.]*

All participant groups were exposed to the same sample and practice streams to minimise differences in exposure to the artificial language. After the 10-minute exposure speech stream, participants completed a 30-item post-test. Given the exposure stream, there were three types of trisyllabic sequences assessed during the post-test: *Words*, the 3-syllable sequences that form the high-TP sequences in the stream (*tudaro, bikuti, pigola, budopa); Part-words*, 3-syllable sequences that occur in the stream but span a word boundary (*tibudo, golatu, daropi, pabiku*); and *Non-words*, 3-syllables sequences that never occur in the corpus (*kudabi, tigobu*). Each of these 10 sequences appeared 3 times on the post-test[1]. On each test trial, participants heard a *Word*, *Part-word*, or *Non-word* and answered the question "How familiar does this sound?" on a visually presented rating scale from 1-5 (1 = not at all familiar, 5 = very familiar). There was no time limit for response. If participants implicitly learned the statistical regularities in the language, *Words* should be rated significantly higher than *Part-words*, and both of these familiar sequences should be rated higher than unfamiliar *Non-words*. Previous studies utilising these or similar stimuli used either a 2AFC task or a rating scale to measure word learning (Karuza et al., 2013; Saffran, Aslin, et al., 1996; Saffran, Newport, et al., 1996). Here we chose a rating scale so that participants would only have to hold one sequence in mind to make a decision, thereby reducing working memory demands.

2.3. Structural imaging: scanning and image preparation for lesion analyses

Stroke survivors underwent structural MRI using a 3 T Siemens Magnetom Trio scanner at the Center for Functional and Molecular Imaging at Georgetown University. A T_1-weighted structural scan (MPRAGE) was performed using the following parameters: 1900ms TR, 2.56 ms TA, FOV 250 × 250, 9° flip angle and 160 contiguous sagittal slices (voxel size = 1 mm^3). To prepare these structural images for analysis, lesions were manually traced by trained lab members in MRIcron (http://www.mccauslandcenter.sc.edu/mricro/mricron). Author P.E.T., a board-certified neurologist, verified and finalised all lesion segmentation using ITK-SNAP (www.itksnap.org)(Yushkevich et al., 2006). The anatomical scans on which each participant's lesion was traced were then warped to Montreal Neurological Institute (MNI) space using the Unified Segmentation routine implemented in SPM12. Lesion tracings were used as cost-function masks. The resulting warps were then applied to each participant's native space lesion mask to bring them to MNI space.

2.4. Statistical analysis

Behavioural data were analyzed in R (R Core Team, 2020) via Google Colab, a cloud-based Jupyter notebook (Kluyver et al., 2016). Figures and general data wrangling were accomplished with the *tidyverse* package (Wickham et al., 2019). To determine the effect of age and left-hemisphere stroke on statistical learning ability, we calculated two learning scores for each participant. First, we took each participant's mean rating for *Words*, *Part-words*, and *Non-words* on the post-test. From these, we then calculated two difference scores (learning scores): *Words* minus *Part-words*, a robust measure of statistical learning, and *Words* minus *Non-words*, a less stringent measure of statistical learning. To analyze these data, we built a mixed-effects regression model predicting learning score by test type (*Words – Non-words*, *Words – Part-words*), participant group (Young control, Older control, Stroke survivor) and their interaction. In the model, we included test type and participant group as simple-coded fixed effects and participant as a random intercept (*lmerTest* package: Kuznetsova, Brockhoff, & Christensen (2017)).

Imaging analyses in stroke survivors (N = 24) were performed using a whole-brain analysis. First, we compared total lesion volume to statistical learning via a Spearman's rank-order correlation. Because the sample size did not provide adequate power for formal lesion-symptom mapping analyses, we then examined the relationship between lesion location and learning using a lesion overlap comparison. We divided our stroke survivors into two groups: Learners (N = 11), defined as those who rated *Words* greater than *Non-words*, and Nonlearners (N = 13), defined as those who did not. A lesion overlay map for **Nonlearners - Learners** was created using SPM12 (http://www.fil.ion.ucl.ac.uk/spm) running under Matlab R2015a. This map shows the difference in proportion of Nonlearners vs. Learners who had a lesion at each voxel in the brain. Areas with high values can be interpreted as those areas in which brain injury impairs the ability to perform the statistical learning word segmentation task.

3. Results

3.1. Behavioural results

Performance on the monitoring task (20 button presses) was examined across the three groups to rule out effects of attention on statistical learning. Multiple subjects in all groups had at least one false press, but there was no significant difference in the number of button presses between young controls (mean = 20.07, SD = 0.47) and older controls (mean = 20.12, SD = 0.88); $t(37) = -0.19$, $p = 0.85$. There was also no significant difference between older controls and stroke survivors (mean = 20.58, SD = 1.52); $t(47) = -1.31$, $p = 0.20$.

To assess learning in the word segmentation task, we analyzed participant learning scores by test type (*Words – Non-words*, *Words – Part-words*) and participant group (Young controls, Older controls, and Stroke survivors). The average learning scores for each participant group across the two tests of statistical learning are shown in Figure 2 and Table 2 (individual stroke survivor performance is presented in the appendix; Table A1).

As shown in Figure 2, there is a significant main effect of test type on learning score ($\chi^2(1) = 19.16$, $p < 0.001$), indicating that learning is reduced overall for the more difficult *Words – Part-words* comparison ($\beta = -0.58$, SE = 0.11, $t(63) = -5.27$, $p < 0.001$) (see Table A2 for all model coefficients). There is also a significant main effect of participant group ($\chi^2(2) = 28.60$, $p < 0.001$), with both older adult controls and stroke survivors showing reduced learning overall compared to young adult controls (*older:* $\beta = -0.54$, SE = 0.20, $t(63) = -2.76$, $p = 0.008$; *stroke*: $\beta = -1.15$, SE = 0.20, $t(63) = -5.71$, $p < 0.001$). To determine specifically whether stroke survivor learning differed from older adult controls, we re-leveled our model with older adults as the reference level and found that stroke survivor learning was indeed significantly reduced compared to older adult controls ($\beta = -0.61$, SE = 0.17, $t(63) = -3.66$, Bonferroni corrected $p = 0.001$). Importantly, a significant interaction between test type and participant group suggests that the effect of test type depends on participant group ($\chi^2(2) = 8.42$, $p = 0.01$). Indeed, as can be seen in Figure 2, the effect of test type for stroke survivors, but not older adult controls, differs significantly from young adult controls (*older:* $\beta = 0.42$, SE = 0.28, $t(63) = 1.48$, $p = 0.14$; *stroke*: $\beta = 0.83$, SE = 0.29, $t(63) = 2.883$, $p = 0.005$).

As a group, stroke survivors show no learning on both test types, with many individuals failing to learn (learning score $<=$ 0) even on the less stringent test of statistical learning (*Words – Non-words*). However, the individual data points also suggests that many of the stroke survivors *are* learning, despite left hemisphere injury. To assess statistical learning in these individuals, we re-ran our learning score analysis including only *learners*, defined as those with a positive learning score on the less stringent *Words - Non-words* comparison. Of all participants in our sample, 0 young controls, 6 older controls, and 13 stroke survivors failed to learn by this definition. In the revised analysis, we observed the same main effects as in our initial learning score analysis: learning was reduced for the more robust *Words – Part-words* distinction ($\chi^2(1) = 37.00$, $p < 0.001$, $\beta = -0.83$, SE = 0.12), and learning was reduced for both older adult controls and stroke survivors compared to young adult controls ($\chi^2(2) = 9.59$, $p = 0.008$, $\beta_{older} = -0.41$, $SE_{older} = 0.20$, $\beta_{stroke} = -0.72$, $SE_{stroke} = 0.23$). However, releveling the model to compare older controls directly to stroke survivors showed that stroke survivor learning is no longer significantly different from older adults in the learners-only model ($\beta = -0.31$, SE = 0.21, $t(44) = -1.46$, Bonferroni corrected $p = 0.30$). Further, the interaction term is no longer significant ($\chi^2(2) = 2.03$, $p = 0.36$). This reflects what we can see in the learners panel of Figure 3: for learners, the effect of test type does not depend on participant group, with all three groups showing better learning for *Words – Non-words* compared to *Words – Part-words*.

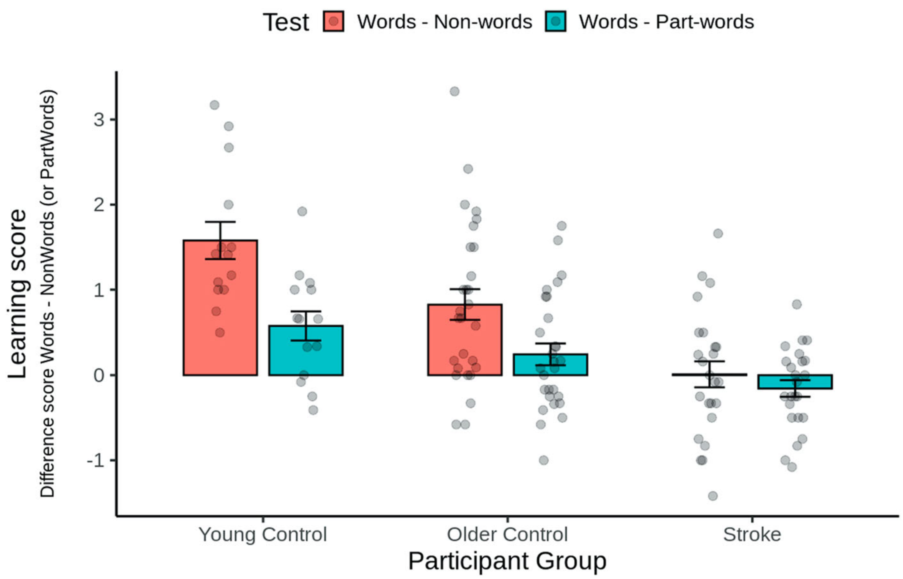

Figure 2. Learning scores by test type and participant group. Dots are individual participant learning scores and error bars are standard error.

Because our older adult and stroke participants demonstrated a range of hearing acuity, we re-ran the original learning score analysis with hearing as a fixed effect. Additionally, because our stroke participant group was not balanced for sex (Table 1), we included sex as an additional fixed effect. Neither hearing acuity nor sex were significant predictors of learning score (*hearing*: $\chi^2(1) = 0.61$, $p = 0.44$, *sex*: $\chi^2(1) = 0.46$, $p = 0.50$).

Finally, we examined the relationship of overall aphasia severity to statistical learning in the stroke survivor group. Statistical learning was defined by our two difference scores (learning scores): *Words* minus *Part-words*, a robust measure of learning, and *Words* minus *Non-words*, a less stringent measure of learning. WAB-R AQ did not correlate with either *Words – Part-words* ($r(22) = 0.03$, $p = 0.89$) or *Words – Non-words* ($r(22) = 0.28$, $p = 0.19$), showing that aphasia severity did not relate to statistical learning ability across the group.

Our results suggest that, while both young and older adult controls could distinguish between *Words* and *Non-words* and (to a lesser extent) *Words* and *Part-words*, participants with left hemisphere injury were unable to make either distinction. However, several individual stroke survivors ($N = 11$) did successfully distinguish between *Words* and *Non-words*, demonstrating learning that was not significantly different from the older adult control group. This suggests that some individuals had relatively intact statistical learning ability, despite a left hemisphere injury. We will return to this point in our lesion analysis in the next section.

Table 2. Mean and SD of learning score for Words – Non-words and Words – Part-words across participant groups.

	Mean learning score (SD)	
Participant group	Words – Non-words	Words – Part-words
Young controls	1.58 (0.82)	0.58 (0.64)
Older controls	0.83 (0.94)	0.24 (0.68)
Stroke survivors	0.01 (0.75)	-0.16 (0.48)

3.2. Lesion results

Overall, our behavioural results show a significant negative impact of left-hemisphere injury on word segmentation ability. To test the hypothesised role of LIFG and the striatum in statistical learning of word segmentation, we performed a lesion analysis comparing the lesion locations of stroke survivors who learned (Learners, $N = 11$) with those who did not (Nonlearners, $N = 13$). As noted above, we defined learning as a positive learning score for the *Words - Non-words* comparison on the behavioural post-test. Within the stroke survivor group, there was no correlation between overall lesion size and this *Words – Non-words* difference score ($r(22) = -0.02$, $p = 0.93$). In Figure 4, lesion overlay maps for Learners (in **4A**) and Nonlearners (in **4B**) demonstrate that the area of greatest overlap in Nonlearners is more anterior than the area of greatest overlap in Learners, suggesting the importance of frontal regions in successful learning. Because the sample size was not sufficient for formal lesion-symptom mapping statistical methods, we used a simple subtraction technique to identify specific voxels that were lesioned in more Nonlearners than Learners. Figure 4C shows the relevant

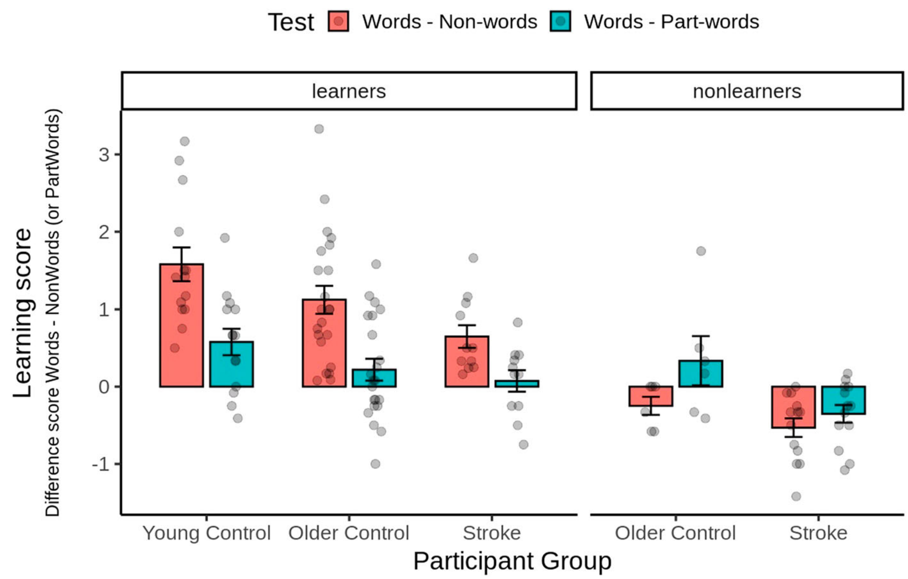

Figure 3. Learning score by test type and participant group, separated by Learners and Nonlearners. Dots are individual participant learning scores and error bars are standard error.

brain regions where the presence of a lesion is associated with a failure to distinguish *Words* from *Non-words*. These regions include LIFG pars opercularis, ventral premotor cortex, insula, and the white matter adjacent to the striatum (caudate and putamen). The peak voxels resulting from this comparison are three areas where none of the 13 Learners had damage, but a large proportion of Nonlearners did have damage: white matter adjacent to the putamen (peak difference 53.8%; 7 of 13 Nonlearners had lesions), white matter adjacent to the caudate (peak difference 46.2%; 6 of 13 Nonlearners had lesions), and ventral precentral gyrus (peak difference 46.2%; 6 of 13 Nonlearners had lesions). These peaks are visible in the coronal slices of Figure 4C.

4. Discussion

4.1. Overall findings

Our results replicate prior evidence that healthy adults can successfully perform statistical language learning: both young control participants and healthy older adult controls showed positive learning scores for *Words – Non-words* and (to a lesser extent) *Words – Part-words*. We did find a significant interaction between test type and participant group, but this interaction reflected a significant difference in stroke survivors, in which learning scores were low on both tests of statistical learning. Indeed, this interaction disappeared when we restricted our analyses to include only stroke survivors who learned to distinguish *Words* from *Non-words*. The finding that older adults were able to perform some statistical learning converges with prior evidence for spared statistical learning of word categories (Schwab et al., 2016) and for spared implicit learning of sequences in aging (Howard & Howard, 1989, 1992; Peñaloza et al., 2015). The main effect of participant group, revealing that older learners exhibit reduced learning overall when compared to younger learners, also accords with a number of earlier findings (Feeney et al., 2002; Filoteo & Maddox, 2004; Howard & Howard, 1997; Palmer et al., 2018; Peñaloza et al., 2017; Schwab et al., 2016).

In contrast, many left hemisphere stroke survivors were unable to distinguish *Words* from *Part-words* or *Words* from *Non-words* during the rating test. At first glance, this appears inconsistent with prior studies examining word segmentation in this population (Peñaloza et al., 2015, 2017). However, many stroke survivors did successfully learn the *Words* vs. *Non-words* comparison — the comparison used in prior work — and further difference emerges from our use of a more stringent behavioural contrast: *Words – Part-words*. As pointed out by Saffran, Newport, et al. (1996), comparing *Words* to *Non-words* requires learners to calculate only serial-order information, since non-words are constructed from the same syllables as the exposure but in a different order. In the present study, our task required calculation of both serial-order and higher-level statistical probabilities in order to differentiate the three test item types, which included two types of familiar trisyllabic sequences *(Words* and *Part-words).* Part-words were composed of three syllable sequences

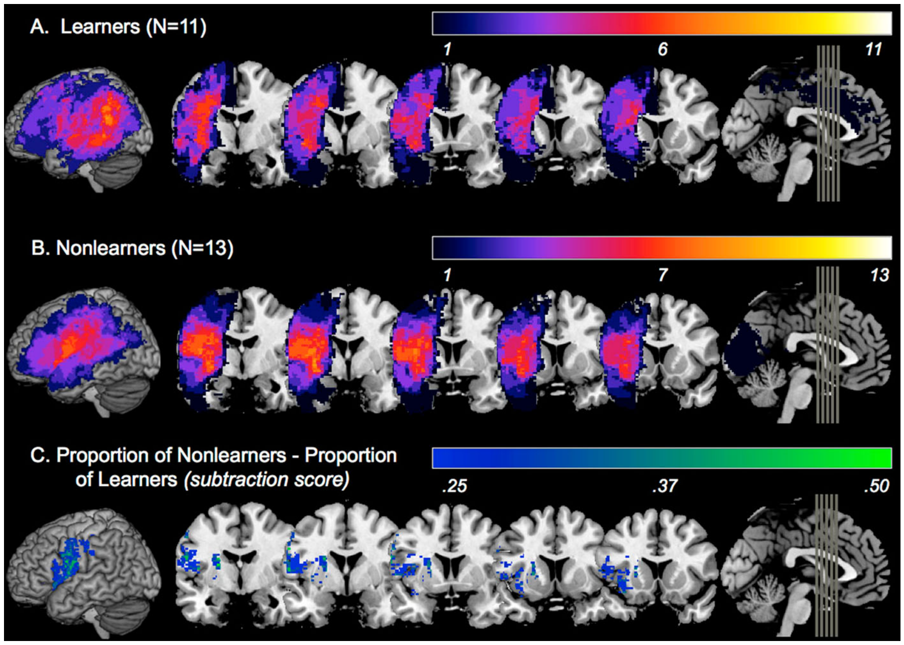

Figure 4. Lesion overlap maps showing the location of brain damage for (A) Learners (N = 11) and (B) Non-learners (N = 13), with colour scale indicating the number of patients in each subgroup with a lesion at each voxel. C. Results of the Nonlearners-Learners comparison, with colour scale indicating the difference between the two groups in the proportion of patients with lesions at each voxel. An arbitrary threshold of 0.25 was selected to show regions where at least 25% more Nonlearners had damage at a given voxel compared to Learners.

that occurred during exposure (i.e. serial order would not distinguish them from words) but that differed in the precise statistical probabilities of their syllable sequences in the exposure corpus. The only prior study to examine *Words* vs. *Part-words* in stroke survivors (Shaqiri et al., 2018) also showed poorer performance in stroke survivors compared to controls. Computation of these sequence statistics is a complex cognitive process that appears to be more sensitive to left hemisphere lesions than simple sequence learning alone. In fact, 11 out of 24 stroke participants rated *Words* higher than *Non-words*, and for that reason we used this less stringent measure of learning for our comparative lesion analysis. Future replication of our findings (and/or the findings of a design like Peñaloza et al., 2015, 2017) would help to clarify the extent of impairment that a left hemisphere lesion can cause in statistical language learning.

4.2. Statistical language learning ability during healthy aging

Our findings revealed reduced word segmentation ability in healthy older adults, suggesting age-related decline in statistical language learning. As mentioned previously, there is converging evidence in the word segmentation (Palmer et al., 2018; Peñaloza et al., 2017; Shaqiri et al., 2018) and sequence learning literature (Hedden & Gabrieli, 2004; Howard & Howard, 1989, 1992; King et al., 2013; Nissen & Bullemer, 1987; Weiermann & Meier, 2012) that, while statistical learning ability is relatively spared with age, older adults do show reduced learning compared to younger adults in some contexts (Cherry & Stadler, 1995; Feeney et al., 2002; Filoteo & Maddox, 2004; Howard & Howard, 1997; Palmer et al., 2018; Rieckmann & Bäckman, 2009). If statistical learning is indeed impacted by healthy aging, what age-related changes in cognition underlie this decline? While our results rule out age-related changes in perceptual ability — hearing acuity did not predict performance on our rating test — they cannot distinguish between general age-related cognitive decline and selective impairments to sub-processes recruited by the statistical learning mechanism. Some researchers have speculated that older adults may rely more heavily on frontal or medial-temporal areas during implicit learning tasks like statistical learning to compensate for age-related decline in striatal areas (Rieckmann & Bäckman, 2009). Under this account, the newly recruited areas may struggle to perform implicit learning tasks as well as the striatal areas do, and the more taxing the task the more apparent this struggle becomes. An inverse relationship between task difficulty and implicit learning performance in older adults is supported by a number of prior studies (Rieckmann & Bäckman, 2009).

Other researchers have argued that a decline in statistical learning ability among older adults stems from changes in other cognitive processes/subprocesses that support learning and memory. A number of studies suggest a crucial interaction with declining *explicit* learning ability during healthy aging, wherein older adults are less able to rely on explicit memory processes to support performance during learning tasks that are ostensibly implicit in nature (Midford & Kirsner, 2005; Muylle et al., 2021; Verneau et al., 2014). Even more specifically, Palmer and colleagues (2018) found that performance on a working memory updating task best predicted word segmentation performance in older adults. They suggest that the subprocess of working memory updating may aid statistical learning ability by helping the learner "remove and replace erroneous syllable grouping from working memory leading to the more accurate representations required to distinguish words from other familiar-sounding sequences" (Palmer et al., 2018, p. 1043). Overall, our findings align with these prior studies showing that statistical language learning can be reduced in healthy older adults, but more research is needed to clarify the contexts in which learning is reduced as well as the precise cognitive mechanisms that underlie these age-related changes.

4.3. Statistical language learning ability after left-hemisphere stroke

As noted above, our stroke survivor participant group as a whole did not exhibit successful learning on the task. Some individual stroke survivors did exhibit learning on the task, however, so the group-level behavioural results may mask the impact of lesions in specific brain structures on word segmentation. There was no relationship between overall lesion size and statistical learning ability in our stroke survivor group, suggesting that the relationship between lesion and performance is driven by specific lesion location rather than the overall extent of damage. Our lesion analysis provides evidence that this learning may be particularly impacted by lesions to LIFG, ventral premotor cortex, insula, and the white matter adjacent to the striatum. Our sample size was not large enough to support the use of a more stringent statistical method for the lesion analysis, such as voxel-based or multivariate lesion-symptom mapping; a future study with a larger sample size utilising such an approach may help to confirm and narrow these findings to the most essential brain regions for statistical learning during word segmentation.

Although our results must be interpreted cautiously given the limited sample size, our findings in LIFG and ventral premotor cortex are largely consistent with prior correlational results from fMRI studies of the same learning in healthy adults (Cunillera et al., 2009; Karuza et al., 2013; McNealy et al., 2010). Our findings are also consistent with the first of three prior studies on statistical word segmentation learning in adults after stroke; the four participants (of 14) in that study who demonstrated learning all had lesions in temporal-parietal lesions, outside of the largely frontal regions implicated here (Peñaloza et al., 2015). The top stroke survivor performer in their follow-up study also had a non-frontal lesion (Peñaloza et al., 2017). In contrast, the most recently published lesion study suggests a possible role for anterior BA 22, although their VLSM analysis achieved no statistically significant results and was also not restricted to left-hemisphere stroke survivors (Shaqiri et al., 2018), leaving the results difficult to interpret.

The relationship tentatively observed between performance and lesions in the insula represents a novel finding that has not been reported in prior literature, and so warrants further examination. Additionally, although we did not have an adequate number of participants with damage to the striatum (caudate and putamen) to examine its role in this type of learning, our findings did indicate that the white matter adjacent to striatal structures may be relevant, which suggests that the striatum may serve as part of a network of brain structures that work together to support statistical language learning. Overall, the particular role of each of these regions cannot be identified in our experiment, but additional studies could be designed to differentiate the contributions of the various brain regions implicated here in the specific subcomponents of the task (e.g. listening to the stream, learning the statistics during exposure, and reporting that knowledge on an explicit task). Furthermore, the lack of significant effects in other structures previously implicated in word segmentation learning, such as the arcuate fasciculus (López-Barroso et al., 2013) or the striatum (Karuza et al., 2013), should not be over-interpreted until a larger lesion-symptom mapping study is performed. Finally, our lesion analysis was performed in a group of stroke survivors in the chronic phase of recovery, at least six months post-onset, so interpretation of these findings is limited to chronic stroke. The relationship between statistical learning and the brain regions identified here thus relates to the initial lesion as well as any possible effects of reorganisation after the injury.

4.4. Alternative interpretations of the findings

An alternative explanation for reduced learning observed in both older adults and stroke survivors might be a lack of sustained attention during exposure. This concern is mitigated considerably by our inclusion of a simple monitoring task, which required participants to attend to the speech stream throughout the exposure period. It remains possible that the divided attention required for performance of the monitoring task concurrent with the speech stream exposure impacted learning in the older adults and stroke survivors more than young adults. However, prior studies in children and young adults have demonstrated that full attention to the speech stream is not required for learning (Saffran et al., 1997), so reduced attention is not likely sufficient to explain the loss of learning ability in older adults or stroke survivors. In fact, Turk-Browne and colleagues (2005) have argued that attending to the stimulus stream is all that is required for good statistical learning; monitoring another aspect of the stream (in this case, beeps) does not produce reduced learning of patterns in the attended stream. On the other hand, several studies have shown that statistical learning can be hindered, even for healthy young adults, when the learning task demands concurrent attention or taxing working memory loads (Franco et al., 2015; Lopez-Barroso et al., 2011; Palmer & Mattys, 2016; Toro et al., 2005). Importantly, these studies show hindering effects when the exposure is short (2-6 minutes), demands on concurrent attention are high (e.g. performing a 2-back task or attending to two simultaneous streams)[2], and participants are often instructed to passively listen (i.e. not informed there will be a recognition test afterward). Any such hindering effects are thus minimised in our experiment by increasing the exposure length to more than 10 minutes, explicitly informing participants that they will be tested on their recognition of the language, and designing our monitoring task to increase attention to the stream itself, not divert attention from it.

Another alternative interpretation is that the older adults and stroke survivors in our study did learn but were less able than young adults to demonstrate their learning on the rating task. This interpretation would be consistent with the early work of Howard and Howard, showing that implicit learning of simple sequences is spared, but ability to consciously demonstrate that learning is impaired (Howard & Howard, 1989, 1992). However, in light of prior evidence that older adults' performance is reduced for complex probabilistic sequences like the ones used in our study (Feeney et al., 2002; Howard & Howard, 1997) even when *implicit* measures of learning are used, we conclude that it is most likely that the learning itself was impaired. It is not obvious how one could indirectly measure implicit learning during exposure in an auditory statistical language learning task (as one does by examining reaction times in a motor sequence task), but doing so would help determine whether the learning itself, as opposed to the ability to demonstrate it, is in fact reduced in these populations. A related concern might be that participants in our study were relying somewhat on explicit learning processes for task performance, and that older adults thus showed weaker learning due to a decline in explicit learning and memory, rather than a decline in implicit learning ability. Future studies could help to clarify the relative contributions of these two learning systems to word segmentation tasks by incorporating self-report of strategies used during the task, by including additional tasks of implicit and explicit learning for comparison, or by directly comparing task performance in patient populations with damage to regions supporting implicit vs. explicit learning processes.

In the stroke group, there is an additional concern about the ability to demonstrate learning, in that stroke survivors may have failed to understand the rating task due to comprehension impairments or other stroke-related cognitive deficits. To minimise this risk, we excluded the 11 stroke survivors who clearly did not use the rating scale appropriately, i.e. those who provided the exact same rating on nearly all items presented in the post-test. Importantly, we have also previously shown that an overlapping participant group of older controls and stroke survivors were able to use a 5-point rating scale to judge the phonotactic regularity of a set of auditorily-presented pseudowords (Ghaleh et al., 2018). Moreover, lesions associated with impairment in phonotactic judgment were localised to the angular gyrus and posterior middle temporal gyrus and are thus completely disparate from the locations that appear to be most associated with loss of statistical learning here. This difference suggests that rating scale performance itself cannot explain the effects of lesions on learning observed in this experiment.

4.5. Clinical implications

The results in our group of stroke survivors have potential clinical implications. In general, our results suggest that the benefits of language rehabilitation after left-hemisphere stroke may depend on the type of learning needed for a given treatment approach, given that stroke survivors (as a whole) showed reduced statistical learning ability. There was no relationship between overall aphasia severity and statistical learning, so clinicians need to consider other patient-specific factors that do relate to statistical learning ability. Looking through the participant profiles of those characterised as Learners vs. Non-learners, there are no clear behavioural patterns in terms of traditional characteristics. Most Learners are stroke survivors with mild anomic aphasia or who scored above the WAB-R criterion for aphasia classification, but two Learners (XTK and PRO) exhibit moderate Broca's aphasia (AQ or 54.8 and 46.4). The Non-Learner group includes a diverse group of stroke survivors with a variety of aphasia subtypes and aphasia severity ranging from mild to moderate-severe, as well as one participant (SHB) whose WAB-R AQ was above 93.8. Therefore, broad features of the stroke survivor profiles (e.g. overall severity, subtype) do not appear to be predictive of statistical learning ability.

In contrast to the lack of apparent behavioural relationships between language abilities and statistical learning ability, it appears that specific lesion location may be a meaningful predictor of statistical learning ability after stroke. Our preliminary lesion analysis aligns with prior studies suggesting that the regions in the left frontal lobe may be particularly important for this type of learning. Therefore, stroke survivors with frontal lesions may differ from those with more posterior areas of damage in their ability to utilise statistical learning during rehabilitation. Treatments relying on implicit learning of language patterns may be less effective for individuals with frontal damage than those emphasising more explicit strategies, so clinicians may wish to consider learning ability in the context of treatment planning (Vallila-Rohter, 2017). No prior studies have directly examined the relationship between lesion location and response to implicit vs. explicit learning strategies in treatment. One prior study in a small group of individuals with agrammatic aphasia, which most often results from frontal lesions, showed that participants did not benefit from an implicit language treatment despite showing some preserved non-linguistic implicit learning ability (Schuchard et al., 2016). Overall, the relationship between learning ability and treatment outcomes is not yet well understood, and further research is needed to elucidate the nature of the learning impairments themselves[3] and, in turn, their potential impacts on clinical treatment.

5. Conclusions

In this study, we have replicated prior behavioural findings that young adults can perform robust statistically-based word segmentation learning during a relatively short exposure to a novel language. Older adults also showed robust sequence learning, but their word segmentation ability was reduced compared to young adults. These findings corroborate and expand upon similar prior findings regarding reduced statistical learning of word categories and probabilistic sequence learning in healthy aging. In contrast, the left hemisphere stroke survivors did not show robust statistical learning at the group level, and fewer than half of these participants showed successful sequence learning. Our lesion analysis tentatively suggests that impairments may relate to damage to specific left hemisphere areas including LIFG, as well as insula, precentral gyrus, and the white matter adjacent to the striatum. These findings have important implications regarding the ability of stroke survivors to learn new material, suggesting that rehabilitation approaches relying on implicit learning of sequences may not be effective for stroke survivors with damage to these particular areas, whereas such approaches may be successful for stroke survivors with damage to other areas (including other areas of the left hemisphere such as the temporal lobe). Overall, our findings suggest that word segmentation learning is sensitive both to aging and to damage to the specific brain regions underlying this process in healthy individuals.

Notes

1. Note that we selected only two non-words to minimise the imbalance in the test between "legal" sequences in the language (the four words) and "illegal" sequences (four part-words and two non-words).
2. In one experiment, Toro and colleagues (2005) did find reduced statistical learning when participants were asked to attend to pitch changes in the speech stream itself. However, exposure was only 7 minutes, participants were told their goal was to detect the pitch changes (not to learn anything about the language), and pitch changes occurred often, approximately every 10 syllables.
3. A reviewer points out that there could be circumstances in which lesions to frontal regions may actually convey an implicit learning advantage. Frontal regions are known to be involved in cognitive control, which has been shown to interfere with implicit learning under some circumstances (see Friederici et al., 2013 for a discussion of this issue). Therefore, one could generate the hypothesis that impairments to cognitive control mechanisms might lead to improvements in implicit learning abilities. While we have not tested this proposal directly here, we agree that more work is needed to understand precisely what these brain regions contribute to the statistical learning mechanism.

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