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Cortex

Hippocampal and auditory contributions to speech segmentation

--Manuscript Draft--

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Abstract:	<p>Statistical learning has been proposed as a mechanism to structure and segment the continuous flow of information in several sensory modalities. Previous studies proposed that the medial temporal lobe, and in particular the hippocampus, may be crucial to parse the stream in the visual modality. However, the involvement of the hippocampus in auditory statistical learning, and specifically in speech segmentation is less clear. To explore the role of the hippocampus in speech segmentation based on statistical learning, we exposed seven pharmaco-resistant temporal lobe epilepsy patients to a continuous stream of trisyllabic pseudowords and recorded intracranial stereotaxic electro-encephalography (sEEG). We used frequency-tagging analysis to quantify neuronal synchronization of the hippocampus and auditory regions to the temporal structure of words and syllables of the stream. Results show that while auditory regions highly respond to syllable frequency, the hippocampus responds mostly to word frequency. These findings provide direct evidence of the involvement of the hippocampus in speech segmentation process and suggest a hierarchical organization of auditory information during speech processing.</p>
Response to Reviewers:	<p>Reviewer #1: Ramos-Escobar and colleagues presented continuous streams of auditory syllables to patients with intractable epilepsy followed by a forced choice recognition test on three-syllable words hidden in the streams. Using frequency tagging on intracranial EEG recordings on the surface of the auditory cortex and from depth electrodes in the medial temporal lobe, they measured statistical learning of syllables, two-syllables and three-syllable words. The authors report that the auditory cortex responds more to syllables than to words (i. e. shows a higher power in the frequency range at which syllables are presented than to the frequency at which words are presented), while the hippocampus responds more to words than to syllables (shows a higher power in the frequency range at which words are presented than to the frequency at which syllables are presented). Based on those findings the authors conclude that statistical learning is hierarchically organized in the brain, and that the hippocampus plays an important role in statistical learning of speech.</p> <p>The manuscript is well written and clear and shows interesting and compelling results.</p> <p>I have a few comments which need attention before I can recommend publication. Major comment: - The most puzzling issue is the finding that behavior shows a strong discrepancy to the neural responses. The authors mention that the force choice has low sensitivity to learning (page 11, line13). This may be true, but alternatively, the hippocampus may not be necessary for statistical learning (as was previously mentioned in line 1 of the same page). It would be good to discuss that possibility too in the context of learning</p>

speech sequences and in the context of the damage of the MTL in these patients. It would also be good to suggest alternative behavioral methods which would reveal learning.

We thank the reviewer for this comment. We have further developed this point in the discussion and also refer to other studies that have shown similar discrepancies (e.g. Henin et al., 2021). Most importantly, in relation to this point, we now report the analysis of sEEG data acquired during the test phase together with the corresponding figure (Figure 4). These results show that the event-related potentials (ERPs) to words and nonwords differ in the hippocampus. In other words, neurophysiological data show that 1) the hippocampus contributes to speech stream segmentation, as seen during the learning phase, 2) the hippocampus is sensitive to the familiarity of the items during the test phase (thus in a different dataset). Then, the absence of behavioural learning seems to be due to a high noise at the decision making level. We now further discuss this point in relation to possible weaknesses of the behavioural task and make reference to newly developed experimental designs (François et al., 2016, 2017). Finally, we would like to clarify that we do not make any causal statement in the manuscript and that our data only show that the hippocampus is involved in speech segmentation, but not that it is necessary for speech segmentation as these claims possibly require perturbation or lesion studies.

Results section:

Page 10, lines 235-241: "Importantly, however, as shown on Figure 4, the ERP data show a significant difference between words and nonwords in hippocampal channels in the 250-400 (beta = -18.8; CI = -33.3 -4.2; $p < .01$) and 550-700 ms (beta = -19.6, CI = -35.9 -3.2; $p < .01$) time-windows. A significant effect over a single 50ms time window, between 350 and 400 ms, is also found over auditory channels (beta = -8.4, CI = -16.5 -0.7; $p < .05$). Overall, these results confirm that patients did segment the words during the learning phase and that the hippocampus is particularly sensitive to the familiarity of the items."

Discussion section:

Page 12-13, lines 289-327: "In the current work, patients, most of whom had temporal lobe epilepsy, performed poorly in the explicit recognition test as patients with MTL lesions. By contrast, they presented robust neural tuning at target frequencies corresponding to different levels of the speech hierarchy (i.e., word, syllable, and pair of syllables) during the learning phase. This result indicates that learning did take place and that the hippocampus was functional with respect to statistical learning. It also confirms that implicit online measures of learning based on electrophysiological data are more sensitive than behavioural measures (François, Tillmann & Schön, 2012). Indeed, the analysis of the ERPs collected during the 2AFC task also revealed significant differences between words and nonwords over hippocampal channels. This result fits well with previous studies on speech segmentation based on SL showing functional activations of the hippocampus during speech segmentation tasks (Turk-Browne et al., 2009; Schapiro, Kustner, & Turk-Browne 2012; Schapiro et al., 2016; Barascud et al., 2016). A similar familiarity effect has been also reported when focusing on the 2AFC test (François & Schön, 2010, 2011; De Diego Balaguer et al., 2007). These studies used scalp EEG to show that healthy adults exhibited a larger negativity for unfamiliar than for newly learned. However, the percentage of correct explicit word recognition did not differ from chance level. Similar discrepancies between behavioural and neural data have been reported in previous neuroimaging studies of speech segmentation based on SL in healthy adults (François & Schön, 2010, 2011; McNealy et al., 2006; Turk-Browne et al., 2009; Sanders et al., 2002) and in patients with MTL damage (Henin et al., 2021; Schapiro et al., 2014; Covington, Brown-Schmidt & Duff, 2018). Moreover, the role of the hippocampus and MTL region during recognition memory tasks has largely been demonstrated in both healthy adults and patients with damage to the MTL (Brown & Aggleton, 2001; Düzel et al., 2001; Eldridge et al., 2000; Stark & Squire, 2000; Ranganath et al., 2004). Here, we used an implicit procedure during the learning phase and evaluated the learning using an explicit behavioural task that requires the conscious recognition of word-forms presented auditorily. While our approach has the advantage of being of a very short duration, the 2AFC task has been largely criticized for its low sensitivity due to different factors (François, Tillmann & Schön, 2012; Batterink et al., 2015; Siegelman, Bogaerts & Frost, 2017; Siegelman et al., 2018; Frost, Armstrong & Christiansen, 2019; Christiansen, 2019;). For instance,

the AFC task requires participants to make an explicit judgment on two presented items without feedback, which might be particularly challenging in the case of the relatively weak memory traces created during the implicit learning phase (Schön & François, 2011; Rodriguez-Fornells et al., 2009). Moreover, the design of the AFC test trials does not allow differentiating between word recognition and nonword rejection as it is the case when using a lexical decision task (François et al., 2016; Ramos-Escobar et al., 2021). Recent studies on speech segmentation based on SL have elegantly proposed innovative designs to overcome the weaknesses associated with the use of explicit tests. Of particular relevance is the use of implicit measures such as EEG, sEEG, or Reaction-Times collected during the learning or an online test phase (see for example François et al., 2016, 2017; de Diego Balaguer et al., 2007 for the analysis of ERPs to illegal items without explicit recognition) that seem more appropriate and sensitive to fully capture implicit learning processes (Kim, Seitz, Feenstra, & Shams, 2009; Kóbor et al., 2020; Turk-Browne et al., 2005; Batterink & Paller, 2017; Siegelman, Bogaerts & Frost, 2017)."

Minor comments:

- The experimental methods are very briefly described and it is difficult to understand the flow of events, particularly the duration of the trial or trials and the test phase. It would help to move the sentence from the stimuli section "Each word is presented 60 times ..." up to the experimental procedure section. Without the understanding that there is only one stream it is also difficult to understand the segmenting of the EEG signal.

We thank the reviewer for this comment. We agree that the experimental method should be developed further to facilitate the replication of the study. Therefore, we have added more details in the method section. We now also acknowledge that the procedure that we used here was similar to the one used in various studies of our group with healthy adults and children (François & Schön, 2010; 2011; François et al., 2013; 2014).

Page 6-7, lines 152-167: "We used a similar experimental design to the one used in our previous studies with healthy adults and children (Schön et al., 2008; François & Schön 2010; 2011; François et al., 2013; 2014). Specifically, the experimental procedure consisted of two consecutive phases, an implicit learning phase followed by an explicit 2-alternative forced-choice (2AFC) task. Before starting the implicit learning phase, patients were asked to listen carefully to one single auditory stream without explicit instructions of learning (see Stimuli section for a description of the speech streams). Importantly, we did our best to keep the entire procedure implicit. During the learning phase, patients were exposed to a single continuous speech stream that was composed of 4 pseudo-words presented 60 times each, thus leading to a single continuous stream of 240 words that lasted 4 min. Immediately after this learning phase, patients performed the behavioural 2AFC task that lasted 5 min. During each trial of the test, patients were presented with two consecutive auditory words and had to press one of two buttons to indicate which of two words (first or second item) most closely resembled what they had just heard in the continuous stream (see Figure 2). Importantly, one test item was a word from the learning stream while the other was a "nonword" that was never heard before the test. Each familiar word of the language (word) was presented with each unfamiliar word (nonwords), making up 16 pairs that were repeated twice, thus leading to 32 test trials."

"

- The authors mention that "epochs time-locked at the onset of each word were created by segmenting the recordings from 4 words before and 4 after the stimulus yielding epochs of 8-word length (lasting 7.2s)." I don't understand that sentence. Shouldn't 4+4+1 be 9 word length? Or is the word itself included in the "4 after the stimulus"?

We apologize for this misunderstanding. The epoch is defined with respect to the word onset, so it consists of 4 words before and four words after the onset. We have rephrased this sentence.

Page 8, lines 190-192: "Then, epochs time-locked to the onset of each word were created by segmenting the continuous EEG data from 4 words before and 4 after the stimulus yielding epochs of 8-word length (lasting 7.2s)."

- The syntax in the legend of Figure 3: "Black arrows indicate the bar where falls ..." should be corrected

We thank the reviewer for pointing this out. We have rephrased the legend as following:

"Black arrows indicate the bin where the hippocampal power response falls."

- Delete ; at the end of the citations on page 11 in line 16.

This has been done.

Reviewer #2: The authors provide an interesting examination of statistical learning using intracranial recordings in patients with epilepsy. Specifically, using frequency-tagged auditory stimuli they reported observing greater entrained responses in the hippocampus to artificial words and greater entrained responses in auditory cortex to phonemes. Studies with intracranial recordings (sEEG/ECOG) remain uncommon and valuable datasets for human neuroscience research. At present, however, the strength of the results is unclear to this reader, expanded on below, as it is possible that the pattern of results observed is unrelated to statistical learning, instead reflecting the particular set of analyses employed.

Primary Concerns

Statistical comparisons. The study examined significance within subjects by comparing power across electrodes. This is less commonly used than comparing power at each individual electrode to some baseline -- given the continuous nature of the stimulus in this experiment, I would expect the use of a prestimulus resting state period. The major weakness of the current approach is that non-baselined power will reflect a mixture of intrinsic power and evoked power, particularly because there was no temporal jitter between presentation of the 240 stimuli. Moreover, this measure of relative power across electrodes is dependent on where the other electrodes are located -- if a patient had auditory and hippocampal electrodes that each responded strongly to phonemes, then neither would be significant.

We understand the reviewer's concern. The choice of comparing power across electrodes was constrained by the absence of a sufficiently long baseline. Indeed, ideally, one would need a baseline as long as the learning phase in order to have an equivalent SNR. This was clearly not the case due to clinical constraints requiring to keep the experiment as short as possible. However, we would like to argue that our approach is actually more conservative than testing against a baseline. Indeed entrainment to auditory stimuli will be apparent in many regions (not limited to the auditory cortex, see Pesnot et al., 2021). Thus, thresholding using the distribution of the whole dataset is more conservative than using the baseline that will present NO entrainment but only intrinsic oscillatory activity. What we now tried to clarify, and that is important in this context, is the fact that by computing averages, we remove non time-locked activity (intrinsic oscillations) and only focus on evoked activity.

Page 8, lines 196-199: "Importantly, by computing averages, similarly to other frequency tagging studies (Nozaradan et al., 2021; Jonas et al., 2016), we remove non time-locked activity (intrinsic oscillations), enhance the signal-to-noise ratio of EEG activities time locked to the patterns and only focus on evoked activity."

Below, we computed the same power analysis on a surrogate data built by randomly picking non time-locked epochs for one patient. Such a surrogate distribution, possibly simulating a baseline thresholding strategy, shows extremely low values at the frequencies of interest compared to the real data (top panel). This shows that our approach is possibly more conservative than using a baseline approach: the probability of one single value (e.g., in the hippocampus) being above threshold by chance is smaller.

The reviewer has another related remark: whether this measure of relative power across electrodes is dependent on where the other electrodes are located; "if a patient had auditory and hippocampal electrodes that each responded strongly to phonemes, then neither would be significant". This is indeed correct, BUT we do systematically have many more contacts in regions outside the auditory and hippocampal areas than inside these areas. Patients have between ~140 and ~200 useful contacts and only a few of these (<10) are located in the hippocampus and auditory regions (<10).

Page 9, lines 209-211: "For each patient and for each target frequency (word, syllable & two syllables), we computed the distribution of power values across all contacts (between 140 and 200 per patient, spanning several brain regions beyond the primary auditory cortex and the hippocampus)."

Statistical learning. Patients did not demonstrate behavioral effects of statistical learning, and so it's possible that they were unaware which syllable groups formed word boundaries. It appears the test phase data was not analyzed, which could lend credibility to the authors' claim that subjects implicitly learned the statistical representation. More generally, 4 minutes of a stimulus may be too short a period for learning to occur in these patients. If the authors split their data in half, can they show that frequency-tagged responses to words increased whereas other syllable frequency stayed the same?

We thank the reviewer for this comment. We now report the neurophysiological data acquired during the behavioural task, namely the testing phase following the learning phase. These results show that the ERPs to words and pseudowords differ in the hippocampus. In other words, neurophysiological data show that 1) the hippocampus contributes to speech stream segmentation, as seen during the learning phase, 2) the hippocampus is sensitive to the familiarity of the items during the test phase (thus in a different dataset). Then, the absence of behavioural learning seems to be due to a high noise at the decision making level. We now discuss this point also in relation to some weaknesses of the behavioural task.

Page 12-13, lines 289-327: "In the current work, patients, most of whom had temporal lobe epilepsy, performed poorly in the explicit recognition test as patients with MTL lesions. By contrast, they presented robust neural tuning at target frequencies corresponding to different levels of the speech hierarchy (i.e., word, syllable, and pair of syllables) during the learning phase. This result indicates that learning did take place and that the hippocampus was functional with respect to statistical learning. It also confirms that implicit online measures of learning based on electrophysiological data are more sensitive than behavioural measures (François, Tillmann & Schön, 2012). Indeed, the analysis of the ERPs collected during the 2AFC task also revealed significant differences between words and nonwords over hippocampal channels. This result fits well with previous studies on speech segmentation based on SL showing functional activations of the hippocampus during speech segmentation tasks (Turk-Browne et al., 2009; Schapiro, Kustner, & Turk-Browne 2012; Schapiro et al., 2016; Barascud et al., 2016). A similar familiarity effect has been also reported when focusing on the 2AFC test (François & Schön, 2010, 2011; De Diego Balaguer et al., 2007). These studies used scalp EEG to show that healthy adults exhibited a larger negativity for unfamiliar than for newly learned. However, the percentage of correct explicit word recognition did not differ from chance level. Similar discrepancies between behavioural and neural data have been reported in previous neuroimaging studies of speech segmentation based on SL in healthy adults (François & Schön, 2010, 2011; McNealy et al., 2006; Turk-Browne et al., 2009; Sanders et al., 2002) and in patients with MTL damage (Henin et al., 2021; Schapiro et al., 2014; Covington, Brown-Schmidt & Duff, 2018). Moreover, the role of the hippocampus and MTL region during recognition memory tasks has largely been demonstrated in both healthy adults and patients with damage to the MTL (Brown & Aggleton, 2001; Düzel et al., 2001; Eldridge et al., 2000; Stark & Squire, 2000; Ranganath et al., 2004). Here, we used an implicit procedure during the learning phase and evaluated the learning using an explicit behavioural task that requires the conscious recognition of word-forms presented auditorily. While our approach has the advantage of being of a very short duration, the 2AFC task has been largely criticized for its low sensitivity due to different factors (François, Tillmann & Schön, 2012; Batterink et al., 2015; Siegelman, Bogaerts & Frost, 2017; Siegelman et al., 2018; Frost, Armstrong & Christiansen, 2019; Christiansen, 2019;). For instance,

the AFC task requires participants to make an explicit judgment on two presented items without feedback, which might be particularly challenging in the case of the relatively weak memory traces created during the implicit learning phase (Schön & François, 2011; Rodriguez-Fornells et al., 2009). Moreover, the design of the AFC test trials does not allow differentiating between word recognition and nonword rejection as it is the case when using a lexical decision task (François et al., 2016; Ramos-Escobar et al., 2021). Recent studies on speech segmentation based on SL have elegantly proposed innovative designs to overcome the weaknesses associated with the use of explicit tests. Of particular relevance is the use of implicit measures such as EEG, sEEG, or Reaction-Times collected during the learning or an online test phase (see for example François et al., 2016, 2017; de Diego Balaguer et al., 2007 for the analysis of ERPs to illegal items without explicit recognition) that seem more appropriate and sensitive to fully capture implicit learning processes (Kim, Seitz, Feenstra, & Shams, 2009; Kóbor et al., 2020; Turk-Browne et al., 2005; Batterink & Paller, 2017; Siegelman, Bogaerts & Frost, 2017).”

Concerning the possibility of splitting the data, we followed the reviewer suggestion. However, as the reviewer can see in the figure below, the effect is not clear cut, although there is a tendency for an increase at the word frequency. This is possibly due to different learning curves in the different patients that may prevent observing a clear increase. We also tried to have a more temporally resolved analysis to explore inter-individual differences, but the estimate became too noisy when using small data sets (e.g. 8 periods of 30 seconds). We eventually decided not to report this analysis in the manuscript.

Secondary Comments

4 ms is a very short baseline period which can introduce noise to the analysis. Do the authors have justification over a longer baseline (at least 100 ms)?

Sorry this was a typo error, it should be seconds and correspond to half of the window.

The authors mention normalization in the methods. How was power normalized? A common approach with frequency-tagging is to replot the data as signal-to-noise ratios, wherein power at the target frequency is compared against neighboring frequencies to cancel out the effects of the 1/f distribution.

We agree with the reviewer that some studies have used such a normalization procedure. However, we think that in the case of sEEG recordings the SNR is much higher than with scalp data. The suggested procedure that implicitly increases the local SNR may not be necessary in our case and we prefer not to use it and to show the ‘true’ FFT. Please also note that, as detailed above, we do not have the 1/f in the PSD because we work on averages. Further, recent studies have used similar approaches to study the neural mechanisms supporting the extraction of speech units based on SL in adults and children (see Jonas et al., 2016; Ordín et al., 2020; Ramos-Escobar et al., 2021).

Why was evoked power calculated as opposed to total power averaged across the entire time-range? Evoked power, when no jitter across trials, can lead to peaks at intrinsic oscillations. Moreover, total power would enable a plot of the 1/f distributions for electrodes and subjects which can be helpful in evaluating the quality of the recordings.

As we clarified above, the strategy of averaging is commonly used (see for instance Nozaradan et al., 2021; Jonas et al., 2016) in frequency tagging analysis to enhance the signal-to-noise ratio of EEG activities time locked to the patterns. Below, we computed the full range power spectral density for each patient (colored lines) for both hippocampal (top) and auditory (bottom) channels. On the left, the reviewer can appreciate that it is not easy to see much on the regular PSD of hippocampal channels. The scenario becomes a little bit better when normalizing by neighbours (dividing each value by two neighbour values), as can be seen on the right part of the figure. However, while for the auditory cortex, that has a very strong response to the syllabic

rate, the result is clear cut, for the hippocampal channels, have smaller responses, results are less clear and mostly visible in the first harmonic of the word frequency (2.2 Hz). We feel that this well illustrates the advantage of computing the FFT of a sliding average. Also, note that, as reported in the methods section, we cautiously use an overlap equal to twice the size of the word duration to ensure that possible artifacts would not lead to a spurious peak at the word frequency.

Assuming the power effects are driven by the stimuli, is it possible that the hippocampus tracked 'words' because the task required discrimination of 3 phoneme groups? Were subjects aware what they would be tested on?

We thank the reviewer for this comment. In this specific case, the answer is no. We used an implicit version of the SL paradigm in which the patients were not aware of the purpose of the task nor that they would be tested afterward. We agree that some studies have used explicit instructions of learning which may have triggered different cognitive mechanisms (Cunillera et al., 2006, 2009). Again, here, the patients were only instructed to listen carefully to an auditory stream without explicit instructions of learning. Importantly, the grouping of phonemes can only be done by statistical learning as there are no other (e.g., acoustic) cues to group the individual phonemes.

Hippocampal and auditory contributions to speech segmentation

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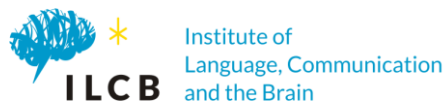
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Error!Error!Error!Error!

Marseille, 2nd of November 2021

Dear Editor,

Thank you for giving us with the opportunity to submit a revised version of our work. Please find attached the revised version of our manuscript entitled "*Hippocampal and auditory contributions to speech segmentation*", which we would like considered for publication in *Cortex*.

We are grateful to the two reviewers for all their helpful comments and interesting suggestions. We feel that we were able to address all the suggestions in an appropriate manner. You will find our detailed answers in the "responses to the reviewers" section but we would like to acknowledge some specific points that have been raised during the review.

Both reviewers had concern about the experimental procedure, the methods and the analyses we used. Therefore, we have provided further details about each of these points and have added new results with the corresponding figure in the new version of the manuscript. Based on the reviewers' comments, we have added new analyses focusing on the ERPs of the 2AFC test and discuss these new results in the discussion section. However, we have preferred not include the results comparing the two halves of the learning phase nor those obtained with the neighboring normalization. We will be delighted to add them in a new version of the manuscript if the editor considers these results important.

Thank you very much in advance for your consideration
Sincerely yours,

Neus Ramos-Escobar, Manuel Mercier, Agnès Trébuchon, Antoni Rodriguez-Fornells, Clément François & Daniele Schön

Reviewer #1: Ramos-Escobar and colleagues presented continuous streams of auditory syllables to patients with intractable epilepsy followed by a forced choice recognition test on three-syllable words hidden in the streams. Using frequency tagging on intracranial EEG recordings on the surface of the auditory cortex and from depth electrodes in the medial temporal lobe, they measured statistical learning of syllables, two-syllables and three-syllable words. The authors report that the auditory cortex responds more to syllables than to words (i. e. shows a higher power in the frequency range at which syllables are presented than to the frequency at which words are presented), while the hippocampus responds more to words than to syllables (shows a higher power in the frequency range at which words are presented than to the frequency at which syllables are presented). Based on those findings the authors conclude that statistical learning is hierarchically organized in the brain, and that the hippocampus plays an important role in statistical learning of speech.

The manuscript is well written and clear and shows interesting and compelling results.

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Major comment:

- The most puzzling issue is the finding that behavior shows a strong discrepancy to the neural responses. The authors mention that the force choice has low sensitivity to learning (page 11, line13). This may be true, but alternatively, the hippocampus may not be necessary for statistical learning (as was previously mentioned in line 1 of the same page). It would be good to discuss that possibility too in the context of learning speech sequences and in the context of the damage of the MTL in these patients. It would also be good to suggest alternative behavioral methods which would reveal learning.

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Results section:

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did segment the words during the learning phase and that the hippocampus is particularly sensitive to the familiarity of the items.”

Discussion section:

Page 12-13, lines 289-327: *“In the current work, patients, most of whom had temporal lobe epilepsy, performed poorly in the explicit recognition test as patients with MTL lesions. By contrast, they presented robust neural tuning at target frequencies corresponding to different levels of the speech hierarchy (i.e., word, syllable, and pair of syllables) during the learning phase. This result indicates that learning did take place and that the hippocampus was functional with respect to statistical learning. It also confirms that implicit online measures of learning based on electrophysiological data are more sensitive than behavioural measures (François, Tillmann & Schön, 2012). Indeed, the analysis of the ERPs collected during the 2AFC task also revealed significant differences between words and nonwords over hippocampal channels. This result fits well with previous studies on speech segmentation based on SL showing functional activations of the hippocampus during speech segmentation tasks (Turk-Browne et al., 2009; Schapiro, Kustner, & Turk-Browne 2012; Schapiro et al., 2016; Barascud et al., 2016). A similar familiarity effect has been also reported when focusing on the 2AFC test (François & Schön, 2010, 2011; De Diego Balaguer et al., 2007). These studies used scalp EEG to show that healthy adults exhibited a larger negativity for unfamiliar than for newly learned. However, the percentage of correct explicit word recognition did not differ from chance level. Similar discrepancies between behavioural and neural data have been reported in previous neuroimaging studies of speech segmentation based on SL in healthy adults (François & Schön, 2010, 2011; McNealy et al., 2006; Turk-Browne et al., 2009; Sanders et al., 2002) and in patients with MTL damage (Henin et al., 2021; Schapiro et al., 2014; Covington, Brown-Schmidt & Duff, 2018). Moreover, the role of the hippocampus and MTL region during recognition memory tasks has largely been demonstrated in both healthy adults and patients with damage to the MTL (Brown & Aggleton, 2001; Düzel et al., 2001; Eldridge et al., 2000; Stark & Squire, 2000; Ranganath et al., 2004). Here, we used an implicit procedure during the learning phase and evaluated the learning using an explicit behavioural task that requires the conscious recognition of word-forms presented auditorily. While our approach has the advantage of being of a very short duration, the 2AFC task has been largely criticized for its low sensitivity due to different factors (François, Tillmann & Schön, 2012; Batterink et al., 2015; Siegelman, Bogaerts & Frost, 2017; Siegelman et al., 2018; Frost, Armstrong & Christiansen, 2019; Christiansen, 2019;). For instance, the AFC task requires participants to make an explicit judgment on two presented items without feedback, which might be particularly challenging in the case of the relatively weak memory traces created during the implicit learning phase (Schön & François, 2011; Rodriguez-Fornells et al., 2009). Moreover, the design of the AFC test trials does not allow differentiating between word recognition and nonword rejection as it is the case when using a lexical decision task (François et al., 2016; Ramos-Escobar et al., 2021). Recent studies on speech*

segmentation based on SL have elegantly proposed innovative designs to overcome the weaknesses associated with the use of explicit tests. Of particular relevance is the use of implicit measures such as EEG, sEEG, or Reaction-Times collected during the learning or an online test phase (see for example François et al., 2016, 2017; de Diego Balaguer et al., 2007 for the analysis of ERPs to illegal items without explicit recognition) that seem more appropriate and sensitive to fully capture implicit learning processes (Kim, Seitz, Feenstra, & Shams, 2009; Kóbor et al., 2020; Turk-Browne et al., 2005; Batterink & Paller, 2017; Siegelman, Bogaerts & Frost, 2017)."

Minor comments:

- The experimental methods are very briefly described and it is difficult to understand the flow of events, particularly the duration of the trial or trials and the test phase. It would help to move the sentence from the stimuli section "Each word is presented 60 times ..." up to the experimental procedure section. Without the understanding that there is only one stream it is also difficult to understand the segmenting of the EEG signal.

We thank the reviewer for this comment. We agree that the experimental method should be developed further to facilitate the replication of the study. Therefore, we have added more details in the method section. We now also acknowledge that the procedure that we used here was similar to the one used in various studies of our group with healthy adults and children (François & Schön, 2010; 2011; François et al., 2013; 2014).

Page 6-7, lines 152-167: *"We used a similar experimental design to the one used in our previous studies with healthy adults and children (Schön et al., 2008; François & Schön 2010; 2011; François et al., 2013; 2014). Specifically, the experimental procedure consisted of two consecutive phases, an implicit learning phase followed by an explicit 2-alternative forced-choice (2AFC) task. Before starting the implicit learning phase, patients were asked to listen carefully to one single auditory stream without explicit instructions of learning (see Stimuli section for a description of the speech streams). Importantly, we did our best to keep the entire procedure implicit. During the learning phase, patients were exposed to a single continuous speech stream that was composed of 4 pseudo-words presented 60 times each, thus leading to a single continuous stream of 240 words that lasted 4 min. Immediately after this learning phase, patients performed the behavioural 2AFC task that lasted 5 min. During each trial of the test, patients were presented with two consecutive auditory words and had to press one of two buttons to indicate which of two words (first or second item) most closely resembled what they had just heard in the continuous stream (see Figure 2). Importantly, one test item was a word from the learning stream while the other was a "nonword" that was never heard before the test. Each familiar word of the language (word) was presented with each unfamiliar word (nonwords), making up 16 pairs that were repeated twice, thus leading to 32 test trials."*

"

- The authors mention that "epochs time-locked at the onset of each word were created by segmenting the recordings from 4 words before and 4 after the stimulus yielding epochs of 8-word length (lasting 7.2s)." I don't understand that sentence. Shouldn't 4+4+1 be 9 word length? Or is the word itself included in the "4 after the stimulus"?

We apologize for this misunderstanding. The epoch is defined with respect to the word onset, so it consists of 4 words before and four words after the onset. We have rephrased this sentence.

Page 8, lines 190-192: *"Then, epochs time-locked to the onset of each word were created by segmenting the continuous EEG data from 4 words before and 4 after the stimulus yielding epochs of 8-word length (lasting 7.2s)."*

- The syntax in the legend of Figure 3: "Black arrows indicate the bar where falls ..." should be corrected

We thank the reviewer for pointing this out. We have rephrased the legend as following: *"Black arrows indicate the bin where the hippocampal power response falls."*

- Delete ; at the end of the citations on page 11 in line 16.

This has been done.

Reviewer #2: The authors provide an interesting examination of statistical learning using intracranial recordings in patients with epilepsy. Specifically, using frequency-tagged auditory stimuli they reported observing greater entrained responses in the hippocampus to artificial words and greater entrained responses in auditory cortex to phonemes. Studies with intracranial recordings (sEEG/ECOG) remain uncommon and valuable datasets for human neuroscience research. At present, however, the strength of the results is unclear to this reader, expanded on below, as it is possible that the pattern of results observed is unrelated to statistical learning, instead reflecting the particular set of analyses employed.

Primary Concerns

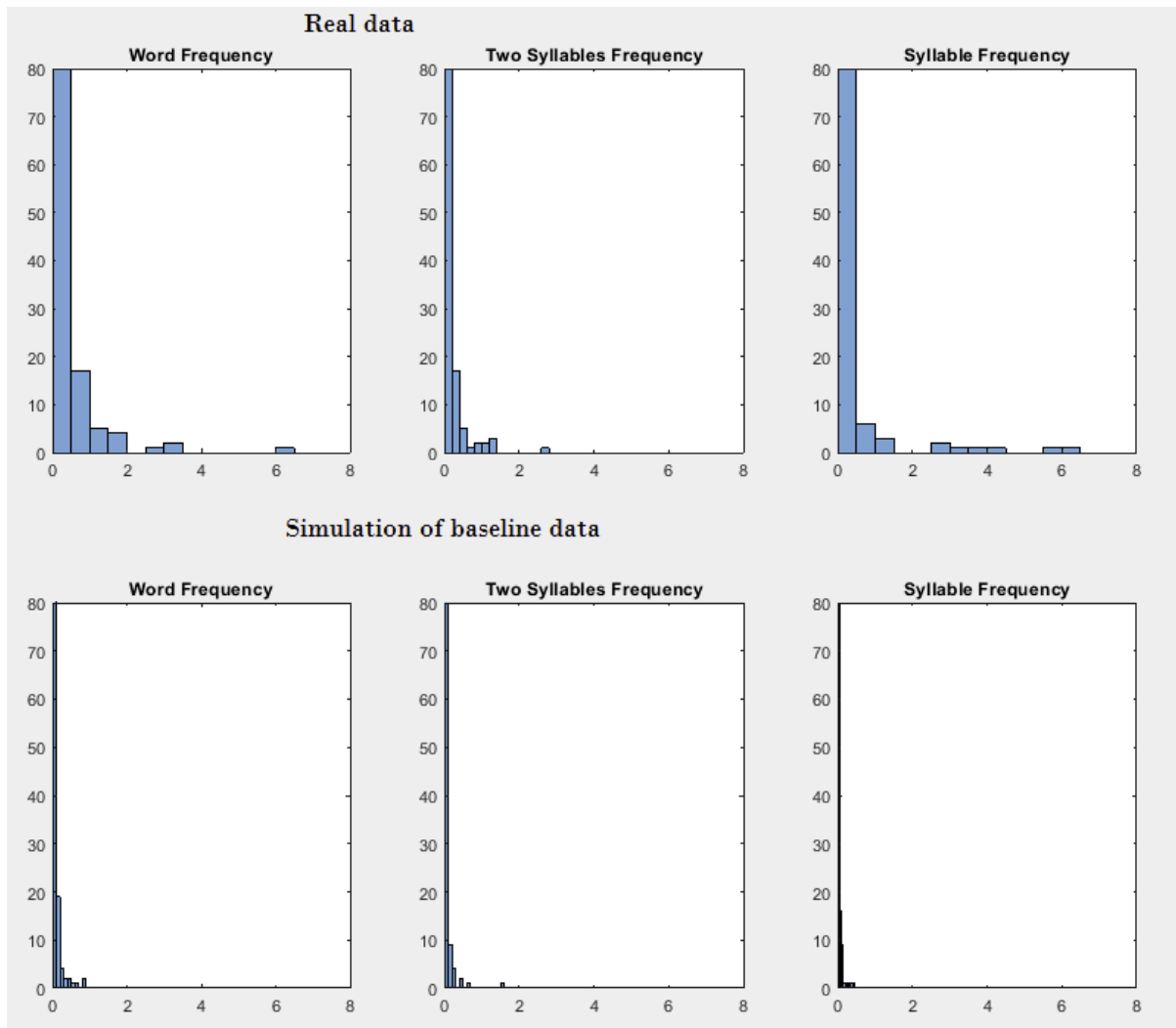
Statistical comparisons. The study examined significance within subjects by comparing power across electrodes. This is less commonly used than comparing power at each individual electrode to some baseline -- given the continuous nature of the stimulus in this experiment, I would expect the use of a prestimulus resting state period. The major weakness of the current approach is that non-baselined power will reflect a mixture of intrinsic power and evoked power, particularly because there was no temporal jitter between presentation of the 240 stimuli. Moreover, this measure of relative power across electrodes is dependent on where the other electrodes are located -- if a patient had auditory and hippocampal electrodes that each responded strongly to phonemes, then neither would be significant.

We understand the reviewer's concern. The choice of comparing power across electrodes was constrained by the absence of a sufficiently long baseline. Indeed, ideally, one would need a

baseline as long as the learning phase in order to have an equivalent SNR. This was clearly not the case due to clinical constraints requiring to keep the experiment as short as possible. However, we would like to argue that our approach is actually more conservative than testing against a baseline. Indeed entrainment to auditory stimuli will be apparent in many regions (not limited to the auditory cortex, see Pesnot et al., 2021). Thus, thresholding using the distribution of the whole dataset is more conservative than using the baseline that will present NO entrainment but only intrinsic oscillatory activity. What we now tried to clarify, and that is important in this context, is the fact that by computing averages, we remove non time-locked activity (intrinsic oscillations) and only focus on evoked activity.

Page 8, lines 196-199: *“Importantly, by computing averages, similarly to other frequency tagging studies (Nozaradan et al., 2021; Jonas et al., 2016), we remove non time-locked activity (intrinsic oscillations), enhance the signal-to-noise ratio of EEG activities time locked to the patterns and only focus on evoked activity.”*

Below, we computed the same power analysis on a surrogate data built by randomly picking non time-locked epochs for one patient. Such a surrogate distribution, possibly simulating a baseline thresholding strategy, shows extremely low values at the frequencies of interest compared to the real data (top panel). This shows that our approach is possibly more conservative than using a baseline approach: the probability of one single value (e.g., in the hippocampus) being above threshold by chance is smaller.



The reviewer has another related remark: whether this measure of relative power across electrodes is dependent on where the other electrodes are located; “if a patient had auditory and hippocampal electrodes that each responded strongly to phonemes, then neither would be significant”. This is indeed correct, BUT we do systematically have many more contacts in regions outside the auditory and hippocampal areas than inside these areas. Patients have between ~140 and ~200 useful contacts and only a few of these (<10) are located in the hippocampus and auditory regions (<10).

Page 9, lines 209-211: “For each patient and for each target frequency (word, syllable & two syllables), we computed the distribution of power values across all contacts (between 140 and 200 per patient, spanning several brain regions beyond the primary auditory cortex and the hippocampus).”

Statistical learning. Patients did not demonstrate behavioral effects of statistical learning, and so it's possible that they were unaware which syllable groups formed word boundaries. It appears the test phase data was not analyzed, which could lend credibility to the authors' claim that subjects implicitly learned the statistical representation. More generally, 4 minutes of a stimulus may be too short a period for learning to occur in these patients. If the authors

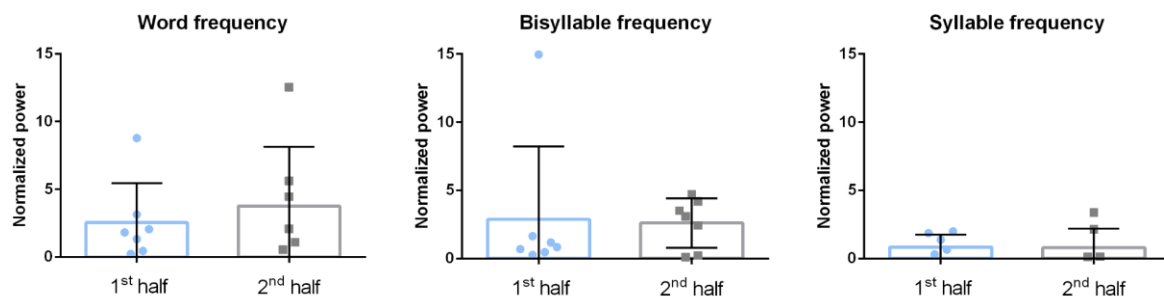
split their data in half, can they show that frequency-tagged responses to words increased whereas other syllable frequency stayed the same?

We thank the reviewer for this comment. We now report the neurophysiological data acquired during the behavioural task, namely the testing phase following the learning phase. These results show that the ERPs to words and pseudowords differ in the hippocampus. In other words, neurophysiological data show that 1) the hippocampus contributes to speech stream segmentation, as seen during the learning phase, 2) the hippocampus is sensitive to the familiarity of the items during the test phase (thus in a different dataset). Then, the absence of behavioural learning seems to be due to a high noise at the decision making level. We now discuss this point also in relation to some weaknesses of the behavioural task.

Page 12-13, lines 289-327: *“In the current work, patients, most of whom had temporal lobe epilepsy, performed poorly in the explicit recognition test as patients with MTL lesions. By contrast, they presented robust neural tuning at target frequencies corresponding to different levels of the speech hierarchy (i.e., word, syllable, and pair of syllables) during the learning phase. This result indicates that learning did take place and that the hippocampus was functional with respect to statistical learning. It also confirms that implicit online measures of learning based on electrophysiological data are more sensitive than behavioural measures (François, Tillmann & Schön, 2012). Indeed, the analysis of the ERPs collected during the 2AFC task also revealed significant differences between words and nonwords over hippocampal channels. This result fits well with previous studies on speech segmentation based on SL showing functional activations of the hippocampus during speech segmentation tasks (Turk-Browne et al., 2009; Schapiro, Kustner, & Turk-Browne 2012; Schapiro et al., 2016; Barascud et al., 2016). A similar familiarity effect has been also reported when focusing on the 2AFC test (François & Schön, 2010, 2011; De Diego Balaguer et al., 2007). These studies used scalp EEG to show that healthy adults exhibited a larger negativity for unfamiliar than for newly learned. However, the percentage of correct explicit word recognition did not differ from chance level. Similar discrepancies between behavioural and neural data have been reported in previous neuroimaging studies of speech segmentation based on SL in healthy adults (François & Schön, 2010, 2011; McNealy et al., 2006; Turk-Browne et al., 2009; Sanders et al., 2002) and in patients with MTL damage (Henin et al., 2021; Schapiro et al., 2014; Covington, Brown-Schmidt & Duff, 2018). Moreover, the role of the hippocampus and MTL region during recognition memory tasks has largely been demonstrated in both healthy adults and patients with damage to the MTL (Brown & Aggleton, 2001; Düzel et al., 2001; Eldridge et al., 2000; Stark & Squire, 2000; Ranganath et al., 2004). Here, we used an implicit procedure during the learning phase and evaluated the learning using an explicit behavioural task that requires the conscious recognition of word-forms presented auditorily. While our approach has the advantage of being of a very short duration, the 2AFC task has been largely criticized for its low sensitivity due to different factors (François, Tillmann & Schön, 2012; Batterink et al., 2015; Siegelman, Bogaerts & Frost, 2017; Siegelman et al., 2018; Frost, Armstrong & Christiansen, 2019;*

Christiansen, 2019;). For instance, the AFC task requires participants to make an explicit judgment on two presented items without feedback, which might be particularly challenging in the case of the relatively weak memory traces created during the implicit learning phase (Schön & François, 2011; Rodriguez-Fornells et al., 2009). Moreover, the design of the AFC test trials does not allow differentiating between word recognition and nonword rejection as it is the case when using a lexical decision task (François et al., 2016; Ramos-Escobar et al., 2021). Recent studies on speech segmentation based on SL have elegantly proposed innovative designs to overcome the weaknesses associated with the use of explicit tests. Of particular relevance is the use of implicit measures such as EEG, sEEG, or Reaction-Times collected during the learning or an online test phase (see for example François et al., 2016, 2017; de Diego Balaguer et al., 2007 for the analysis of ERPs to illegal items without explicit recognition) that seem more appropriate and sensitive to fully capture implicit learning processes (Kim, Seitz, Feenstra, & Shams, 2009; Kóbor et al., 2020; Turk-Browne et al., 2005; Batterink & Paller, 2017; Siegelman, Bogaerts & Frost, 2017).”

Concerning the possibility of splitting the data, we followed the reviewer suggestion. However, as the reviewer can see in the figure below, the effect is not clear cut, although there is a tendency for an increase at the word frequency. This is possibly due to different learning curves in the different patients that may prevent observing a clear increase. We also tried to have a more temporally resolved analysis to explore inter-individual differences, but the estimate became too noisy when using small data sets (e.g. 8 periods of 30 seconds). We eventually decided not to report this analysis in the manuscript.



Secondary Comments

4 ms is a very short baseline period which can introduce noise to the analysis. Do the authors have justification over a longer baseline (at least 100 ms)?

Sorry this was a typo error, it should be seconds and correspond to half of the window.

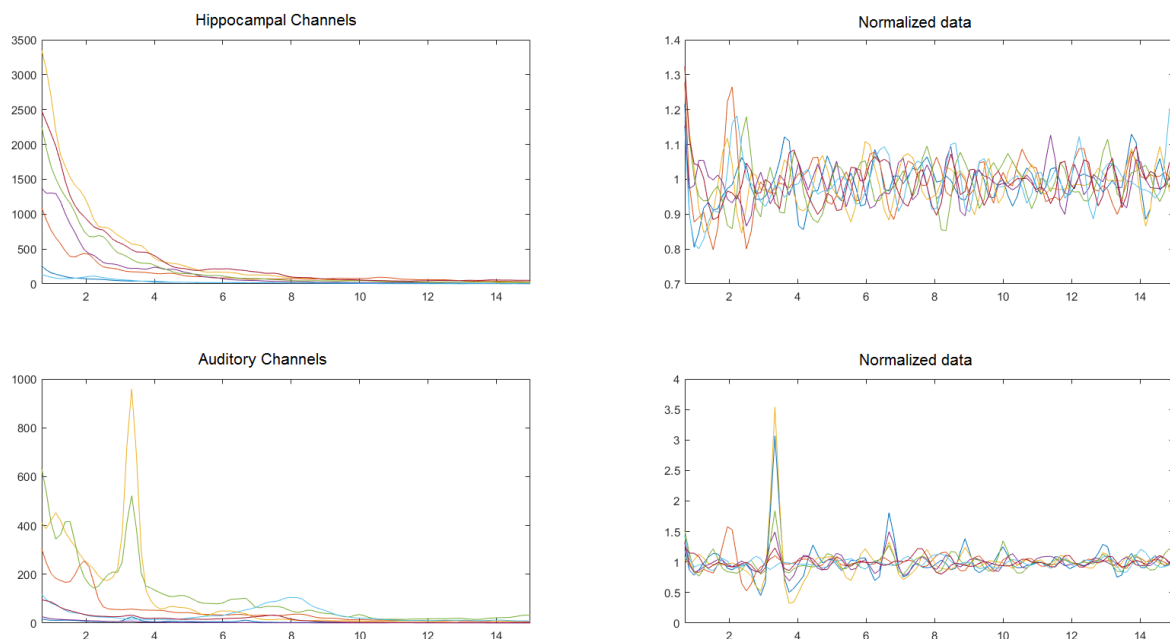
The authors mention normalization in the methods. How was power normalized?

A common approach with frequency-tagging is to replot the data as signal-to-noise ratios, wherein power at the target frequency is compared against neighboring frequencies to cancel out the effects of the 1/f distribution.

We agree with the reviewer that some studies have used such a normalization procedure. However, we think that in the case of sEEG recordings the SNR is much higher than with scalp data. The suggested procedure that implicitly increases the local SNR may not be necessary in our case and we prefer not to use it and to show the 'true' FFT. Please also note that, as detailed above, we do not have the $1/f$ in the PSD because we work on averages. Further, recent studies have used similar approaches to study the neural mechanisms supporting the extraction of speech units based on SL in adults and children (see Jonas et al., 2016; Ordin et al., 2020; Ramos-Escobar et al., 2021).

Why was evoked power calculated as opposed to total power averaged across the entire time-range? Evoked power, when no jitter across trials, can lead to peaks at intrinsic oscillations. Moreover, total power would enable a plot of the $1/f$ distributions for electrodes and subjects which can be helpful in evaluating the quality of the recordings.

As we clarified above, the strategy of averaging is commonly used (see for instance Nozaradan et al., 2021; Jonas et al., 2016) in frequency tagging analysis to enhance the signal-to-noise ratio of EEG activities time locked to the patterns. Below, we computed the full range power spectral density for each patient (colored lines) for both hippocampal (top) and auditory (bottom) channels. On the left, the reviewer can appreciate that it is not easy to see much on the regular PSD of hippocampal channels. The scenario becomes a little bit better when normalizing by neighbours (dividing each value by two neighbour values), as can be seen on the right part of the figure. However, while for the auditory cortex, that has a very strong response to the syllabic rate, the result is clear cut, for the hippocampal channels, have smaller responses, results are less clear and mostly visible in the first harmonic of the word frequency (2.2 Hz). We feel that this well illustrates the advantage of computing the FFT of a sliding average. Also, note that, as reported in the methods section, we cautiously use an overlap equal to twice the size of the word duration to ensure that possible artifacts would not lead to a spurious peak at the word frequency.



Assuming the power effects are driven by the stimuli, is it possible that the hippocampus tracked 'words' because the task required discrimination of 3 phoneme groups? Were subjects aware what they would be tested on?

We thank the reviewer for this comment. In this specific case, the answer is no. We used an implicit version of the SL paradigm in which the patients were not aware of the purpose of the task nor that they would be tested afterward. We agree that some studies have used explicit instructions of learning which may have triggered different cognitive mechanisms (Cunillera et al., 2006, 2009). Again, here, the patients were only instructed to listen carefully to an auditory stream without explicit instructions of learning. Importantly, the grouping of phonemes can only be done by statistical learning as there are no other (e.g., acoustic) cues to group the individual phonemes.

Credit Author statement.

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Project administration: Daniele Schön, Clément François,

Supervision: Daniele Schön, Clément François

Data curation: Neus Ramos-Escobar, Manuel Mercier

Writing - original draft: Neus Ramos-Escobar, Clément François, Daniele Schön

Writing - review & editing: Manuel Mercier, Antoni Rodriguez-Fornells, Agnès Trébuchon-Fonséca, Clément François, Daniele Schön

Hippocampal and auditory contributions to speech segmentation

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17 **Abstract**

18 Statistical learning has been proposed as a mechanism to structure and segment the continuous flow of
19 information in several sensory modalities. Previous studies proposed that the medial temporal lobe, and
20 in particular the hippocampus, may be crucial to parse the stream in the visual modality. However, the
21 involvement of the hippocampus in auditory statistical learning, and specifically in speech segmentation
22 is less clear. To explore the role of the hippocampus in speech segmentation based on statistical
23 learning, we exposed seven pharmaco-resistant temporal lobe epilepsy patients to a continuous stream
24 of trisyllabic pseudowords and recorded intracranial stereotaxic electro-encephalography (sEEG). We
25 used frequency-tagging analysis to quantify neuronal synchronization of the hippocampus and auditory
26 regions to the temporal structure of words and syllables of the learning stream. *We also analyzed the
27 event-related potentials (ERPs) of the test to evaluate the role of both regions in the recognition of newly
28 segmented words.* Results show that while auditory regions highly respond to syllable frequency, the
29 hippocampus responds mostly to word frequency. *Moreover, ERPs collected in the hippocampus show
30 clear sensitivity to the familiarity of the items.* These findings provide direct evidence of the
31 involvement of the hippocampus in the speech segmentation process and suggest a hierarchical
32 organization of auditory information during speech processing.

33 **Keywords:** Hippocampus, statistical learning, frequency tagging, SEEG, speech segmentation

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47 **Introduction**

48 Humans are daily exposed to a massive amount of information. Finding a structure in the
49 sensory flow is necessary to make sense of the world. A structure can emerge thanks to regularities in
50 the input tracked by computing low-order statistics (Reber, 1967; Frost et al., 2015). Statistical learning
51 (SL) is a domain-general learning mechanism through which learners track statistical regularities of
52 motor (Hunt & Aslin, 2001), visual (Fisher & Aslin, 2002), and auditory sequences (Saffran et al., 1996,
53 1999; see Frost et al., 2015 for a review).

54 Speech segmentation is one of the first problems that language learners must deal with when
55 learning a new language (Graf-Estes et al., 2007; François et al., 2017). SL has been proposed as a
56 possible mechanism that allows segmenting words from fluent speech (Cutler & Butterfield, 1992;
57 Saffran et al., 1996). This process can occur incidentally and without effort via simple exposure, as in
58 the case of infants (Saffran et al., 1997; Turk-Browne et al., 2005; Saffran et al., 1999). Although several
59 behavioral (Cutler & Butterfield, 1992; Saffran et al., 1996; Schön et al., 2008) and electrophysiological
60 studies (Sanders et al., 2002; Cunillera et al., 2006; de Diego-Balaguer et al., 2007; Ablá et al., 2008;
61 François et al., 2014; 2017) have explored the bases of SL, the underlying precise brain network
62 dynamics are not clear yet.

63 Capitalizing on a high spatial resolution, functional magnetic resonance imaging (fMRI) studies
64 have allowed to decipher the brain regions supporting SL in the auditory and visual modalities. Results
65 showed activations of modality-specific brain regions during exposure to learning streams (Turk-
66 Browne et al., 2009; Bischoff-Grethe et al., 2000; McNealy et al., 2006; Cunillera et al., 2009; Karuza
67 et al., 2013). Specifically, fMRI speech segmentation studies consistently observed functional
68 activations of typical language areas such as the middle and superior temporal regions (MTG & STG)
69 and the inferior frontal gyrus (IFG; McNealy et al., 2006; Cunillera et al., 2009; Karuza et al., 2013).
70 However, activations of the hippocampus were also observed in a few SL studies (Turk-Browne et al.,
71 2009; Schapiro, Kustner, & Turk-Browne 2012; Schapiro et al., 2016; Barascud et al., 2016). The
72 interplay between cortical and subcortical structures during SL fits well with cognitive models
73 proposing that complementary neural systems may account for human learning abilities (Davis &
74 Gaskell, 2009; McClelland et al., 1995). Specifically, these models suggest that learning and memory
75 processes may occur in two different stages. The medial temporal structures would support the initial
76 acquisition and formation of memory traces, while neocortical regions may participate in their long-
77 term storage. Interestingly, the hippocampus has been proposed to play a crucial role in segmenting

78 continuous sensory inputs into discrete events (Radvansky & Zacks, 2017). Recent studies on event
79 memory formation propose that the interplay between sensory regions and the hippocampus may
80 support the creation of boundaries between events. Specifically, while sensory areas seem to be
81 responsible for fine-grained boundaries, the hippocampus instead supports cortical information binding
82 into memory traces (Baldassano et al., 2017; Ben-Yakov & Dudai, 2011; Zacks et al., 2001; Speer et
83 al., 2007). Further, recent studies on vocabulary acquisition based on associative or contextual learning
84 consistently show functional activations of the hippocampus during the early stages of learning
85 (Bartolotti et al., 2017; Breitenstein et al., 2005; Covington & Duff, 2016; Ripollés et al., 2016; Züst et
86 al., 2019). However, direct human electrophysiological evidence for the role of the hippocampus in
87 extracting pattern regularities in speech is still missing.

88 Recently, electrophysiological studies have capitalized on the brain property to oscillate at the
89 frequency of a continuous auditory stimulus to explore the neural mechanisms supporting the
90 hierarchical processing of speech and music (Nozaradan et al., 2014; Giraud & Poeppel, 2012; Poeppel
91 & Teng, 2020). Specifically, frequency tagging analysis have been successfully applied to surface EEG
92 or MEG recordings to quantify the amount of neural synchronization to syllable, pairs of syllables and
93 words during speech segmentation tasks (Buiatti et al., 2009; Ding et al., 2016; Batterink & Paller,
94 2017). In a recent study, Henin and colleagues (2020) collected intracortical brain responses from
95 human epileptic patients during an auditory and a visual SL task. They applied frequency-tagging to
96 electrocorticography (EcoG) data to show that neural response in the STG synchronized to both
97 syllables and word frequency. They also found synchronized neural response to word frequency in the
98 IFG and Anterior Temporal Lobe. However, no evidence of neural synchronization was observed in the
99 hippocampus possibly due to a limited access provided by EcoG probes. Nonetheless, using a more
100 indirect method based on multivariate pattern similarity analysis, they were able to show the
101 involvement of the hippocampus in word identity during learning.

102 Here, we gathered intracranial recordings from 7 patients with pharmaco-resistant temporal
103 lobe epilepsy implanted with depth electrodes to directly assess the contribution of the auditory cortex
104 and the hippocampus during a speech segmentation task based on SL. Participants passively listened to
105 4 minutes of an artificial statistically structured speech stream and were tested on their ability to
106 recognize the newly segmented words. We used frequency-tagging to quantify the level of neural
107 synchronization in auditory and hippocampal regions to the constitutive elements of the inputs, namely
108 syllables, pairs of syllables and tri-syllabic words during the learning phase. We expected auditory
109 regions to show a peak in the power spectrum corresponding to the syllable rate reflecting phonological
110 processing, while the hippocampus was expected to exhibit high neural synchronization to pairs of
111 syllables and word frequencies, reflecting its role in speech segmentation. [Moreover, previous reports](#)
112 [studying memory have extensively shown the involvement of the hippocampus \(Ripollés et al., 2016;](#)

113 Brown & Aggleton, 2001; Düzel et al., 2001; Eldridge et al., 2000; Stark & Squire, 2000; Ranganath et
 114 al., 2004). Therefore, we also analyzed the event-related potentials (ERPs) collected during the
 115 behavioural test to evaluate the contribution of both regions during the recall of newly segmented words.

116 **Methods**

117 **Participants**

118 Seven patients with pharmaco-resistant temporal lobe epilepsy (4 females, mean age = 29; range 18-
 119 45) participated in the study (see **Table 1**). Patients were implanted with depth electrodes for clinical
 120 reasons to determine the epileptic zone before they underwent neurosurgical treatment at the La Timone
 121 Hospital in Marseille (France). The location of the implanted electrodes was solely determined by
 122 clinical criteria. Patients provided informed consent prior to the experimental session, and the study was
 123 approved by the Institutional Review Board of the French Institute of Health (IRB00003888). No part
 124 of the study procedures was pre-registered prior to the research being conducted.

125 **Table 1:** Patients clinical description

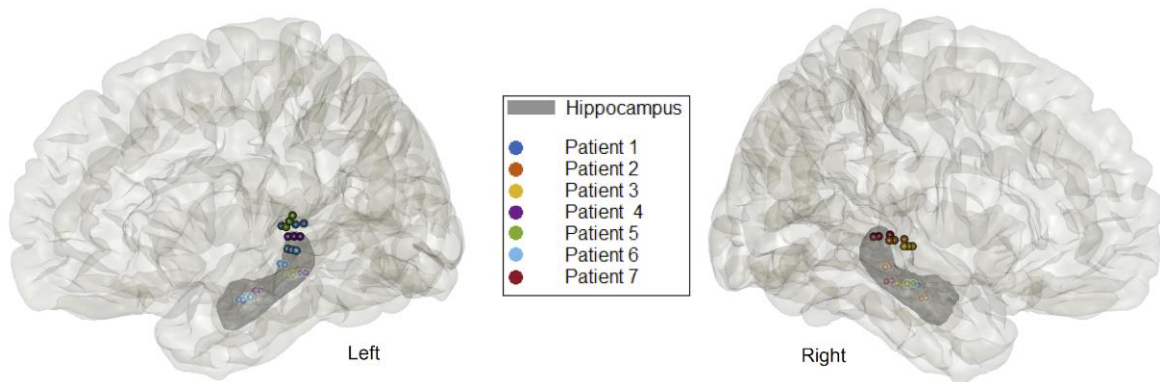
Patients	Gender	Age (years)	Hemispheric dominance	Epileptogenic zone	Depth electrodes	Hippocampal electrodes
P1	F	29	L	L temporal	4R + 10L	Both
P2	F	45	L	R temporal	10R + 2L	Both
P3	F	18	L	R temporal	5R + 4L	Both
P4	F	23	Atypical	L temporal	1R + 12L	L
P5	M	19	L	L temporal	2R + 11L	R
P6	M	42	L	L Frontal	1R + 13L	L
P7	M	33	L	R Frontal & Parietal	14R	R

126 *M* male, *F* female, *L* left, *R* right

127 **Data acquisition & electrode localization**

128 The sEEG signal was recorded using depth electrodes of 0.8 mm diameter containing 10 to 15 electrodes
129 contacts (Alcis, Besançon, France). The electrode contacts were 2 mm long and were spaced from each
130 other by 1.5 mm. Data was recorded using a BrainAmp amplifier system (Brain Products GmbH,
131 Munich, Germany), sampled at 1000 Hz and high-passed filtered at 0.016 Hz. During the acquisition,
132 recordings were referenced to a single scalp-electrode located at Cz. Contact data was offline converted
133 to virtual channels using a bipolar montage approach (closest-neighbor contact reference) to increase
134 spatial resolution and reduce passive volume diffusion from neighboring areas (Mercier et al., 2017).

135 To precisely localize the channels, a procedure similar to the one used in the iELVis toolbox was applied
136 (Groppe et al., 2017). First, we manually identified the location of each channel centroid on the post-
137 implant CT scan using the Gardel software (Medina et al., 2018). Second, we performed volumetric
138 segmentation and cortical reconstruction on the pre-implant MRI with the Freesurfer image analysis
139 suite (documented and freely available for download online <http://surfer.nmr.mgh.harvard.edu/>). Third,
140 we mapped channel locations to the pre-implant MRI brain (processed with FreeSurfer) and to the MNI
141 template, using SPM12 methods (Penny et al., 2011), through the FieldTrip toolbox (Oostenveld et al.,
142 2011). The co-registration to the patient brain was done via a rigid, affine transformation to respect
143 individual anatomy. The normalization to the MNI template was done through a non-linear
144 transformation to map channels to a standardized space and allow brain regions labeling using the
145 Destrieux atlas (Destrieux et al., 2010). The definition of hippocampal and primary auditory channels
146 was determined using a combination of automatic atlas labeling and visual inspection of the anatomical
147 data in 2D and 3D representations (see **Figure 1**).



148
149 **Figure 1.** sEEG channel location. Colored dots indicate the channel location for each patient in auditory (dark-colored) and
150 hippocampal (light-colored) regions. Light gray represents the cortical sheet of the FreeSurfer brain template. The shaded area
151 depicts the hippocampus.

152 **Experimental procedure**

153 We used a similar experimental design to the one used in our previous studies with healthy adults and
154 children (Schön et al., 2008; François & Schön 2010; 2011; François et al., 2013; 2014). Specifically,

155 the experimental procedure consisted of two consecutive phases, an implicit learning phase followed
 156 by an explicit 2-alternative forced-choice (2AFC) task. Before starting the implicit learning phase,
 157 patients were asked to listen carefully to one single auditory stream without explicit instructions of
 158 learning (see Stimuli section for a description of the speech streams). Importantly, we did our best to
 159 keep the entire procedure implicit. During the learning phase, patients were exposed to a single
 160 continuous speech stream that was composed of 4 pseudo-words presented 60 times each, thus leading
 161 to a single continuous stream of 240 words that lasted 4 min. Immediately after this learning phase,
 162 patients performed the behavioural 2AFC task that lasted 5 min. During each trial of the test, patients
 163 were presented with two consecutive auditory words and had to press one of two buttons to indicate
 164 which of two words (first or second item) most closely resembled what they had just heard in the
 165 continuous stream (see Figure 2). Importantly, one test item was a word from the learning stream while
 166 the other was a “nonword” that was never heard before the test. Each familiar word of the language
 167 (word) was presented with each unfamiliar word (nonwords), making up 16 pairs that were repeated
 168 twice, thus leading to 32 test trials.

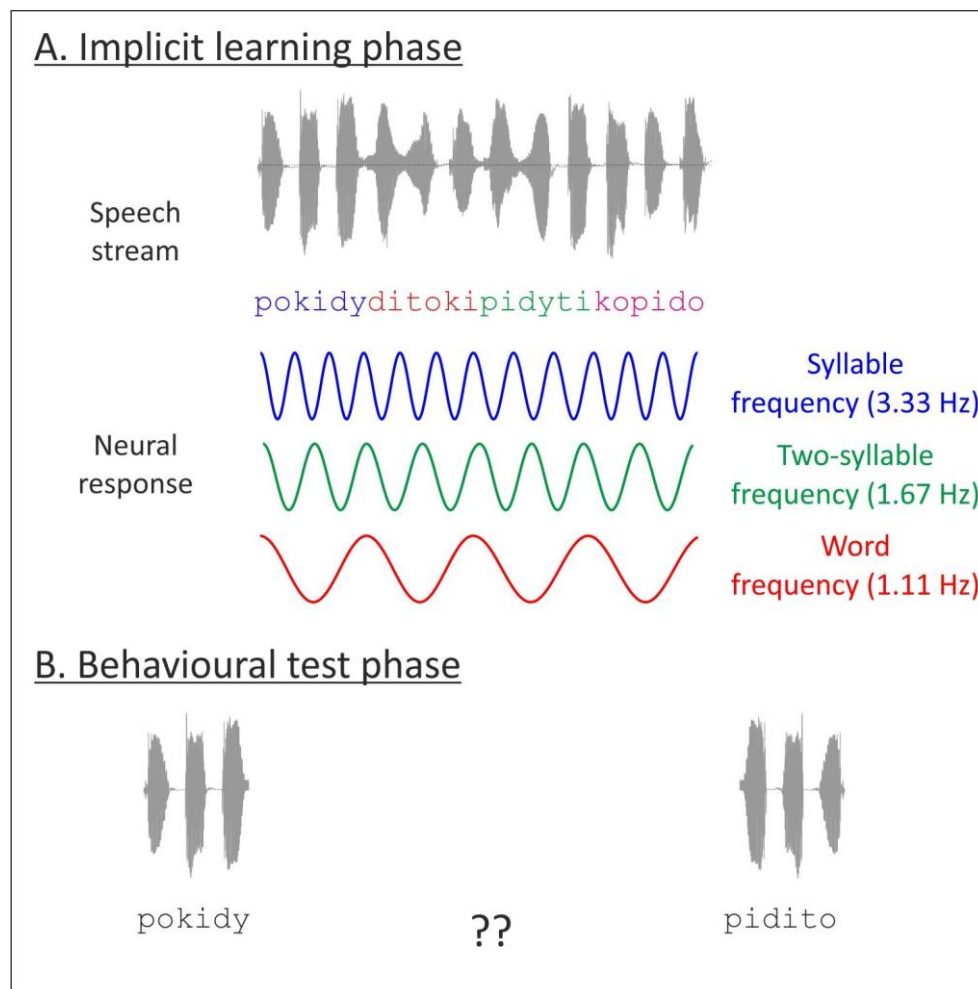


Figure 2. Illustration of the experimental procedure. After being exposed to a continuous stream of statistically structured syllables/words without instruction of learning (A), participants performed a 2AFC task to assess the level of learning (B). The auditory cortex should preferentially respond to the syllable frequency reflecting the tracking of low-order speech structure.

173 The hippocampus should preferentially respond to the word frequency reflecting the creation of event boundaries during the
174 learning.

175

176 **Stimuli**

177 The language consisted of four consonants ('p', 't', 'k', 'd') and three vowels ('o', 'i', 'y'), which were
178 combined into a set of eleven syllables. The exact syllable length was set to 300 ms. These syllables
179 were then combined to give rise to 4 tri-syllabic words (POKIDY, DITOKI, PIDYTI, and KOPIDO).
180 The stream was built by random concatenation of the four pseudowords and synthesized using Mbrola
181 (<http://tcts.fpms.ac.be/synthesis/mbrola.html>). More precisely, the speech stream was built by
182 concatenating seven minimal sequences of non-coarticulated syllables respecting the constraint of not
183 repeating the same word twice in a row. Importantly, no acoustic cues have been inserted at word
184 boundaries. In the test, the items consisted of the four words used in the learning phase and four
185 nonwords created by pseudo-randomly mixing the syllables of the words from the language TOPIDY,
186 DYPOKI, KOKITI, and PIDITO.

187 **SEEG Data analysis: Frequency tagging (learning phase)**

188 For each patient, sEEG data, [in a bipolar montage](#), were visually inspected using AnyWave software
189 (Colombet et al., 2015), and channels with artifacts or epileptic activity were excluded from the analysis.
190 Continuous sEEG recordings acquired during the learning task were filtered using a 0.5 Hz high pass
191 filter to remove slow drifts in the recorded signal. [Then, epochs time-locked to the onset of each word](#)
192 [were created by segmenting the continuous EEG data from 4 words before and 4 after the stimulus](#)
193 [yielding epochs of 8-word length \(lasting 7.2 s\)](#). Epochs were partially overlapping, yet we took care to
194 use an overlap equal to twice the size of the word to ensure that possible artifacts would not lead to a
195 spurious peak at the word frequency. A baseline correction was applied (-3.6 to 0 s). Epochs with high
196 amplitude values were excluded (threshold: mean +2 SD). Epochs were averaged and transformed to
197 the frequency domain using a discrete Fourier transformation (Matlab; Natick, MA). [Importantly, by](#)
198 [computing averages, similarly to other frequency tagging studies \(Nozaradan et al., 2021; Jonas et al.,](#)
199 [2016\), we remove non time-locked activity \(intrinsic oscillations\), enhance the signal-to-noise ratio of](#)
200 [EEG activities time locked to the patterns and only focus on evoked activity](#). We extracted the power
201 values for each target frequency (word frequency: 1.11 Hz; two-syllables frequency: 1.67 Hz; syllable
202 frequency: 3.33 Hz). Power values at the target frequencies were obtained for each patient and channel.

203 **SEEG Data analysis: ERP analysis (Test phase)**

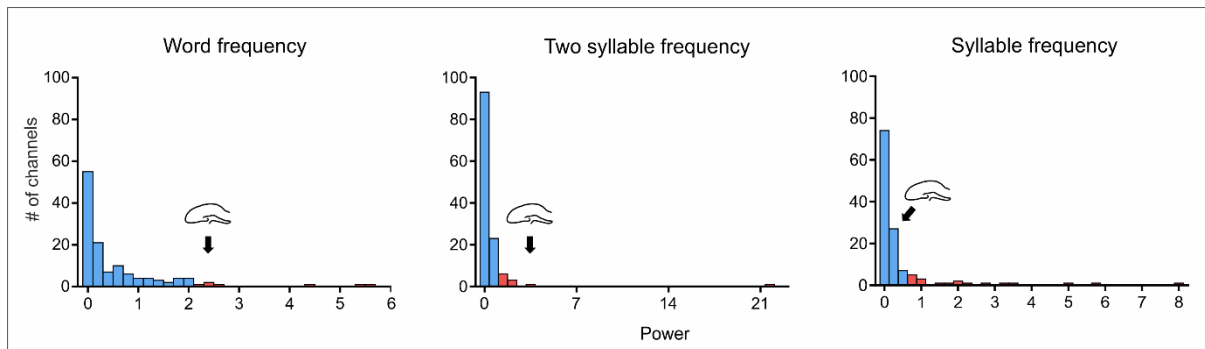
204 We used a similar strategy with the sEEG data collected during the 2AFC test. First, we changed to a
205 bipolar montage to increase spatial resolution, high-pass filtered at 0.5 Hz and low-pass filtered at 20

206 Hz. Then, we created epochs time-locked to the item onset using a -100 ms 1200 ms time-window. A
207 baseline correction was applied (-100 to 0 ms). We only report analyses of channels in the hippocampus
208 and the primary auditory cortex.

209 Statistical analyses

210 For each patient and for each target frequency (word, syllable & two syllables), we computed the
211 distribution of power values across all contacts (between 140 and 200 contacts per patient, spanning
212 several brain regions beyond the primary auditory cortex and the hippocampus). Since the distribution
213 was not normal, we used a non-parametric threshold (median + 2.5 interquartile range, IQR) to
214 determine whether hippocampal and auditory contacts showed a significant response at the target
215 frequencies, as compared to overall channels (see **Figure 3**).

216 Whenever more than one channel was present in the same region (primary auditory or hippocampus),
217 the average power values of the two channels was used. For patients with bilateral implantation and
218 artifact free hippocampi, the average power values of channels located in both hemispheres was used.
219 Finally, to assess the power differences between hippocampal and auditory channels for each patient at
220 word, two-syllable, and syllable frequencies, we normalized the data across channels for each frequency
221 and patient and applied the Wilcoxon test.

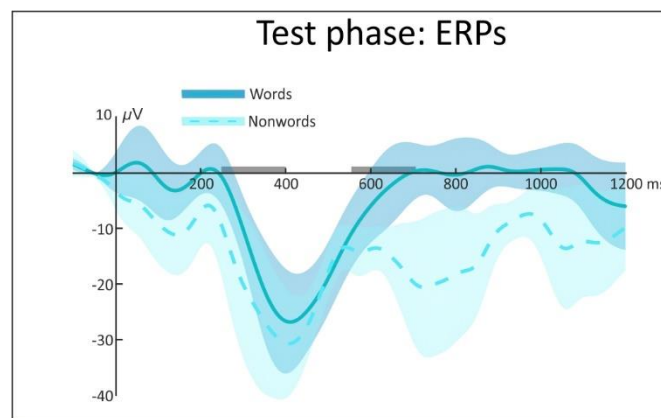


223 **Figure 3.** Example of the methodology used to define significant hippocampal implication. Histograms of power response of
224 all contacts (N ~ 150) to word, two-syllable, and syllable target frequencies for Patient 6. Power values above the threshold
225 (median plus 2.5 IQR) are represented by red bars. Black arrows indicate the frequency bins where the hippocampal power
226 response falls. In this example, the hippocampal response is significant at the word and two-syllable frequencies (arrow on red
227 bars) but not at the syllable frequency (arrow on blue bars).

228 To analyze the ERP data of the test phase, we first compared the amplitude of the ERPs to words and
229 nonwords using mean amplitude values in successive 50 ms time-windows between 250 and 700 ms
230 post-stimulus onset. Then, we computed a mixed-model including each trial (one value per trial per
231 condition per patient: $\text{val} \sim \text{conditions} + \text{trials} + (1 | \text{subjects})$).

232 Results

233 *Test phase:* The level of performance in the 2AFC test reveals that the percentage of correct explicit
 234 word recognition did not differ from chance level (range: 25-56%, $p > .05$, wilcoxon signed-rank) thus
 235 confirming previous results of impaired explicit word recall in patients with epilepsy (Schapiro et al.,
 236 2014; Henin et al., 2021). Importantly, however, as shown on **Figure 4**, the ERP data show a significant
 237 difference between words and nonwords in hippocampal channels in the 250-400 (beta = -18.8; CI = -
 238 33.3 -4.2; $p < .01$) and 550-700 ms (beta = -19.6, CI = -35.9 -3.2; $p < .01$) time-windows. A significant
 239 effect over a single 50 ms time window, between 350 and 400 ms, is also found over auditory channels
 240 (beta = -8.4, CI = -16.5 -0.7; $p < .05$). Overall, these results confirm that patients did segment the words
 241 during the learning phase and that the hippocampus is particularly sensitive to the familiarity of the
 242 items.



243
 244 **Figure 4.** ERPs to words and nonwords in hippocampal contacts (bipolar montage) averaged across 6 patients obtained during
 245 the 2AFC task. The thick and dashed lines show the mean of ERPs to words and nonwords respectively. The shaded areas
 246 correspond to the standard error of the mean in each condition. The grey areas depict the two time-windows showing significant
 247 differences between the two conditions.

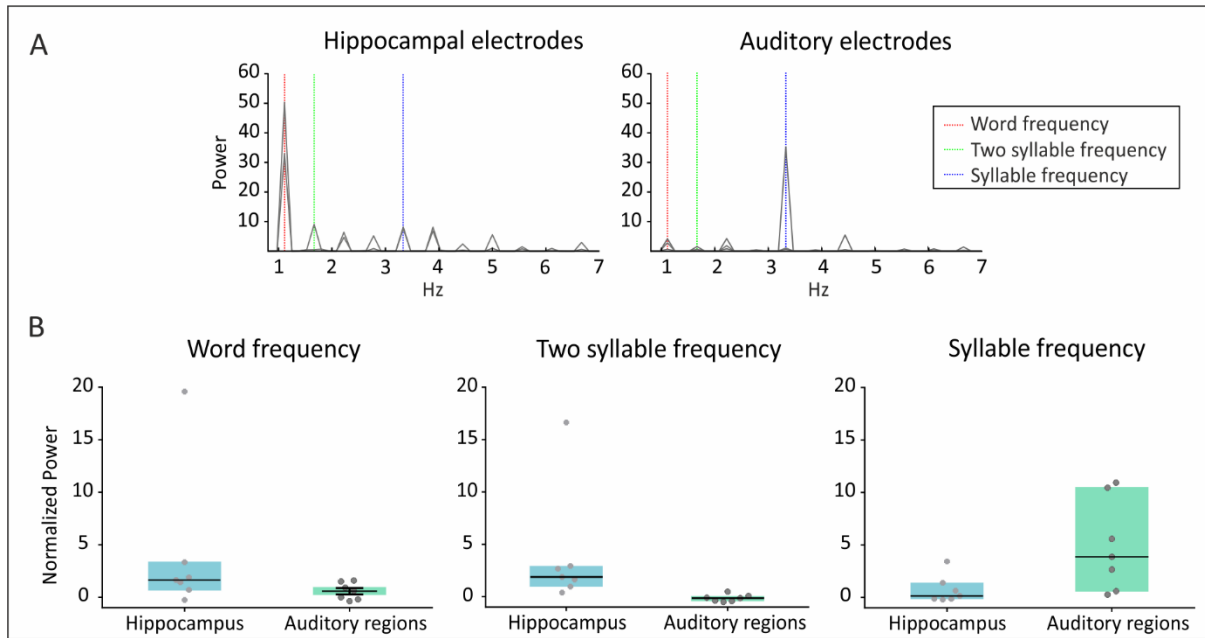
248
 249 *Learning phase:* Clear power spectrum peaks at word and syllable frequencies are visible over auditory
 250 and hippocampal contacts (see **Figure 5A**).

251 For the syllable frequency, all patients except one exhibited a clear peak in contacts located within the
 252 primary auditory cortex (raw data median = 12.24; IQR = 315.69). Five patients also showed significant
 253 responses at this target frequency in hippocampal contacts although much smaller than auditory
 254 responses (raw data median = 1.62; IQR = 2.76).

255 For the word-frequency, all patients except one (Patient 4) showed a significant response in
 256 hippocampal contacts (raw data median = 3.86; IQR = 15.95). Three patients also showed a significant
 257 response to word-frequency in auditory contacts although smaller than hippocampal responses (raw
 258 data median = 1.62; IQR = 8.73).

259 For the two-syllable frequency, all patients showed a significant response at hippocampal contacts (raw
 1 260 data median = 4.79; IQR = 5.87). By contrast, none of the patients showed a significant response to the
 2 261 two-syllable frequency in auditory contacts (raw data median = 0.59; IQR = 0.71).

6 262 The amplitude of the peaks in the power spectrum of the hippocampus differed from that in auditory
 7 263 regions across all target frequencies (word frequency: Cohen $d = 0.5$; $p = .01$; two-syllable frequency:
 8 264 $d = 0.46$; $p = .01$; syllable frequency: $d = 0.7$; $p = .03$).



266 **Figure 5.** A) Example of a patient (Patient 7) power response of hippocampal and auditory electrodes to word frequency (red),
 267 two-syllable frequency (green) and syllable frequency (blue). B) Average of all patients' neural responses to word, two-
 268 syllables and syllable frequencies in hippocampus and auditory regions (z-score normalized data). Black lines indicate the
 269 median of all patients and box plots indicate the interquartile range.

271 Discussion

272 In the present study, we directly assessed the contribution of auditory regions and the
 273 hippocampus during speech segmentation based on SL. Pharmaco-resistant epileptic patients implanted
 274 with sEEG depth electrodes listened to a continuous stream of statistically organized syllables. The
 275 frequency-tagging analysis reveals that the hippocampus preferentially responds to word-frequency. By
 276 contrast, auditory regions preferentially tune their response to syllable frequency (see **Figure 5B**).
 277 Although previous studies have suggested the involvement of MTL regions and especially the
 278 hippocampus in SL based on indirect measures, we provide the first direct evidence for its role during
 279 speech segmentation based on SL.

280 Previous neuropsychological studies showed that patients with lesions of the MTL are impaired
 281 in extracting auditory and visual statistical patterns (Schapiro et al., 2014; Covington, Brown-Schmidt

282 & Duff, 2018). In a single case study, a patient with complete bilateral loss of hippocampus and
283 extensive damage to surrounding MTL regions could not recall familiar sequences in a visual SL task
284 (Schapiro et al., 2014). However, Covington and colleagues (2018) showed that patients with
285 hippocampal damage could perform above chance level in SL tasks, although they were overall
286 impaired in comparison to healthy controls. Therefore, although the hippocampus might participate and
287 to a certain extent facilitate statistical learning by strengthening associations between input elements,
288 its participation might not be strictly necessary and other non-hippocampal cortical regions could
289 support SL.

290 In the current work, patients, most of whom had temporal lobe epilepsy, performed poorly in
291 the explicit recognition test as patients with MTL lesions. By contrast, they presented robust neural
292 tuning at target frequencies corresponding to different levels of the speech hierarchy (i.e., word,
293 syllable, and pair of syllables) during the learning phase. This result indicates that learning did take
294 place and that the hippocampus was functional with respect to statistical learning. It also confirms that
295 implicit online measures of learning based on electrophysiological data are more sensitive than
296 behavioural measures (François, Tillmann & Schön, 2012). Indeed, the analysis of the ERPs collected
297 during the 2AFC task also revealed significant differences between words and nonwords over
298 hippocampal channels. This result fits well with previous studies on speech segmentation based on SL
299 showing functional activations of the hippocampus during speech segmentation tasks (Turk-Browne et
300 al., 2009; Schapiro, Kustner, & Turk-Browne 2012; Schapiro et al., 2016; Barascud et al., 2016). A
301 similar familiarity effect has been also reported when focusing on the 2AFC test (François & Schön,
302 2010, 2011; De Diego Balaguer et al., 2007). These studies used scalp EEG to show that healthy adults
303 exhibited a larger negativity for unfamiliar than for newly learned. However, the percentage of correct
304 explicit word recognition did not differ from chance level. Similar discrepancies between behavioural
305 and neural data have been reported in previous neuroimaging studies of speech segmentation based on
306 SL in healthy adults (François & Schön, 2010, 2011; McNealy et al., 2006; Turk-Browne et al., 2009;
307 Sanders et al., 2002) and in patients with MTL damage (Henin et al., 2021; Schapiro et al., 2014;
308 Covington, Brown-Schmidt & Duff, 2018). Moreover, the role of the hippocampus and MTL region
309 during recognition memory tasks has largely been demonstrated in both healthy adults and patients with
310 damage to the MTL (Brown & Aggleton, 2001; Düzel et al., 2001; Eldridge et al., 2000; Stark & Squire,
311 2000; Ranganath et al., 2004). Here, we used an implicit procedure during the learning phase and
312 evaluated the learning using an explicit behavioural task that requires the conscious recognition of
313 word-forms presented auditorily. While our approach has the advantage of being of a very short
314 duration, the 2AFC task has been largely criticized for its low sensitivity due to different factors
315 (François, Tillmann & Schön, 2012; Batterink et al., 2015; Siegelman, Bogaerts & Frost, 2017;
316 Siegelman et al., 2018; Frost, Armstrong & Christiansen, 2019; Christiansen, 2019;). For instance, the
317 AFC task requires participants to make an explicit judgment on two presented items without feedback,

318 which might be particularly challenging in the case of the relatively weak memory traces created during
319 the implicit learning phase (Schön & François, 2011; Rodriguez-Fornells et al., 2009). Moreover, the
320 design of the AFC test trials does not allow differentiating between word recognition and nonword
321 rejection as it is the case when using a lexical decision task (François et al., 2016; Ramos-Escobar et
322 al., 2021). Recent studies on speech segmentation based on SL have elegantly proposed innovative
323 designs to overcome the weaknesses associated with the use of explicit tests. Of particular relevance is
324 the use of implicit measures such as EEG, sEEG, or Reaction-Times collected during the learning or an
325 online test phase (see for example François et al., 2016, 2017; de Diego Balaguer et al., 2007 for the
326 analysis of ERPs to illegal items without explicit recognition) that seem more appropriate and sensitive
327 to fully capture implicit learning processes (Kim, Seitz, Feenstra, & Shams, 2009; Kóbor et al., 2020;
328 Turk-Browne et al., 2005; Batterink & Paller, 2017; Siegelman, Bogaerts & Frost, 2017).

329 Previous studies with surface EEG or MEG have successfully used frequency tagging to track
330 the patterns of cortical synchronization supporting the hierarchical processing of speech (Buiatti et al.,
331 2009; Ding et al., 2016; Batterink & Paller., 2017; see Poeppel & Teng, 2020 for a review). Importantly
332 however, while functional activations of the hippocampus have been consistently reported during visual
333 SL tasks (Turk-Browne et al., 2009; Schapiro, Kustner & Turk-Browne 2012), this was not the case
334 using sequences of syllables (McNealy et al., 2006; Cunillera et al., 2009; Karuza et al., 2013). Further,
335 in a recent study, Henin and colleagues gathered brain responses to statistically structured auditory and
336 visual sequences in 26 patients with MTL epilepsy (Henin et al., 2021). Using similar frequency tagging
337 analysis applied to EcoG data, they found clear neural response at both two-syllable and word
338 frequencies over multiple cortical regions. However, evidence for a contribution of the hippocampus
339 was only observed with a more indirect analysis based on representational similarities (dissimilarity
340 measures). Here, instead of using grid electrodes located at the surface of the cortex (referenced to
341 subdural/skull contacts), we used depth sEEG electrodes and in particular bipolar montages that allow
342 a high spatial resolution and directly quantifying neural response at the population level in the auditory
343 cortex and in the hippocampus. Results are clear cut in showing that auditory regions significantly
344 respond to syllable frequency but not to word frequency. Crucially, we observe an opposite pattern in
345 the hippocampus with an ample response to longer units (i.e., pairs of syllables and words, see **Figure**
346 **5B**).

347 These results strongly corroborate a hierarchical organization of auditory information during
348 speech segmentation. Moreover, the hippocampal response to both pairs of syllables and word
349 frequencies sheds light on the neural validity of speech segmentation models. According to the
350 PARSER model, continuous speech is segmented by extracting small chunks of increasing size based
351 on the computation of temporal proximity and associative learning mechanisms. Through repetition,
352 these chunks are consolidated and stored, allowing explicit behavioural recognition of the newly learned

353 items (Perruchet & Vinter, 1998). More recent work on event memory formation for spatial or temporal
1 354 sequences proposes that sensory regions and the hippocampus hierarchically contribute to creating
2 boundaries between events contained in long passages (Baldassano et al., 2017; Radvansky & Zacks,
3 355 2017; Ben-Yakov & Dudai, 2011; see also Zacks & Swallow, 2007). For instance, the encoding and
4 recall of narratives may involve the encoding of small temporal chunks in primary sensory regions.
5 356 Long events encoding would occur in higher-level brain regions, including cortical areas and the
6 357 hippocampus (Baldassano et al., 2017). Importantly, Schapiro and colleagues (2017) recently proposed
7 a neuroanatomically plausible model of hippocampal functioning during continuous sequence learning
8 358 such as SL. Specifically, they exposed an artificial neural network mimicking the functional and
9 anatomical properties of the hippocampus to continuous sequences of items with different temporal
10 359 regularities. Results suggested the existence of complementary learning systems in the hippocampus
11 where specific neural pathways differently contribute to learning depending on the type of input. Our
12 360 findings are in line with the idea that the hippocampus is sensitive to pattern regularities found in the
13 environment. It seems reasonable to think that the hippocampus is also sensitive to the co-occurrence
14 361 of syllable pairs as for visual sequences (Schapiro et al., 2017; Turk-Browne et al., 2009). Taken
15 362 together, our data suggest a hierarchical organization of auditory information during speech processing,
16 363 where both cortical and hippocampal regions contribute to language learning. While the clear response
17 at syllable frequency in primary auditory areas may reflect the tracking of the phonological structure,
18 364 the hippocampus would be involved in the encoding and storage of larger units as previously proposed
19 in different neurocomputational models of chunking (Baldassano et al., 2017; Schapiro et al., 2017).
20 365 Taken together, our data suggest that the hippocampus plays an important role in speech segmentation
21 and language learning using a more direct measure of neural activity than previously described
22 366 (Schapiro et al., 2014; Covington, Brown-Schmidt & Duff, 2018; Duff & Brown-Schmidt, 2012;
23 367 Kepinska et al., 2018).

41 377 Nonetheless, our study presents methodological limitations that prevent us from drawing
42 definite conclusions on the role of the hippocampus in speech segmentation in the general population.
43 378 First, the complex clinical history of these temporal lobe epileptic patients may affect verbal memory
44 379 storage and executive functions thus, explaining impaired performance at test (Zamarian et al., 2011;
45 Saling, 2009; Squire et al., 2004). Second, while there is evidence for left lateralized activations in the
46 380 Inferior and Superior Temporal Gyri during speech segmentation based on SL (Cunillera et al., 2009;
47 McNealy et al., 2006; Karuza et al., 2013), it is still unclear as to whether asymmetric processing also
48 381 takes place in the hippocampus. In our small population, only one of the patients (P4), implanted over
49 the left hemisphere, did not significantly respond to word frequency in the hippocampus. Clinical
50 382 exploration revealed that this patient had an atypical language dominance to the right hemisphere,
51 383 probably induced by a disease-related atypical functioning of the hippocampus. Thus, further work on
52 a larger sample and possibly bilateral implantations is needed to explore the possibility of a hippocampal
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389 asymmetry. Finally, Schapiro and colleagues (2017) showed that the anterior part of the hippocampus
390 where the monosynaptic pathway connects the entorhinal cortex to the “*cornu ammonis I*” is more
391 involved in SL than the posterior part. Again, determining possible functional differences related to
392 topographical gradients in hippocampal structures will require further investigations with a larger
393 number of patients.

394 **Conclusion**

395 Here, we directly assessed the role of the hippocampus in speech segmentation based on SL.
396 We showed that the hippocampus neural response synchronizes with the word-level time scale but not
397 with the syllable-level time scale. Conversely, auditory regions consistently responded to syllable
398 frequency but not to word frequency. [Moreover, we found clear neural evidence for the contribution of](#)
399 [the hippocampus in the recall of newly segmented words.](#) These findings provide preliminary but direct
400 evidence in humans for the involvement of the hippocampus in the brain network that orchestrates
401 auditory speech segmentation based on SL.

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