FONDATION POUR L'AUDITION — À L'ÉCOUTE DE LA VIE

FINAL SCIENTIFIC REPORT

PROJECT NUMBER: RD-2021-12

TITLE of the PROJECT: New data-driven techniques for the diagnosis, prognosis and rehabilitation of impairments of speech prosody perception in brain-stroke survivors (DASHES)

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LAY SUMMARY

Understanding Speech Melody Impairments After Stroke: Project DASHES

After a stroke in the right side of the brain, over half of patients experience communication problems. One such issue is aprosodia—the difficulty in understanding or expressing the "melody" of speech, like rising tone for questions or emotional cues. Despite its impact on social interaction, aprosodia has been largely overlooked. Current tests are often too simple to detect it, and we don't fully understand what causes patients to struggle—making it hard to design effective therapies.

To address this, researchers from the FEMTO-ST Institute in Besançon and the Paris Brain Institute teamed up for a 3-year project called DASHES. They used an innovative method from hearing science called reverse correlation. This approach helps map how a person hears speech intonation and how internal factors, like mental noise or attention lapses, affect their responses. Though common in basic research with healthy people, reverse correlation had never been tried with stroke patients.

DASHES brought advances in several areas:

New Methods: The team adapted reverse correlation to better suit stroke patients, creating new algorithms. These include ways to estimate "internal noise" even without repeated tests, and a smart model (GLM-HMM) that adjusts for patients who repeat the same answers too often—a common issue after brain injury.

New Insights: Using these tools, researchers discovered that repeated or "perseverated" responses in stroke patients may be linked to problems with mental inhibition. These perseverations often follow long streaksof correctly repeated responses, and tend to stop when the correct answer is especially obvious—suggesting the perseverating brain isn't totally disconnected from the task.

Clinical Findings: The new method was tested on 63 patients (40 with stroke, 23 with brain tumors) in an ongoing clinical trial. Results show that the current standard test (called MEC) often misses aprosodia or mislabels it. In contrast, reverse correlation revealed hidden processing problems—even in patients labeled as "normal." The results also showed that different brain issues (like attention or hearing deficits) affect prosody perception in different ways.

Technology for Clinicians: DASHES tools have been packaged into three free, open-source programs now used by speech therapists: CLEESE helps create test sounds; JONES is an online platform used in hospitals for patient testing; PALIN analyzes the test results automatically

Training and Outreach: The project also helped train the next generation of auditory scientists, especially young women. It supported four speech-therapy theses, a PhD defense (Aynaz Adl Zarrabi, 2025), and led to a new faculty hire (Marie Villain, 2024). Results were shared in two workshops: one at a European neuroscience conference and another at the FEMTO-ST Institute in 2025.

In short, DASHES has advanced how we understand, diagnose, and eventually treat speech melody problems after stroke. It has also laid the groundwork for better tools and a stronger research community in this field.

PROJECT REPORT

A. Background and significance

The assessment and comprehension of of aprosodia after a right-hemisphere stroke

After a right hemisphere stroke, more than half of the patients present a communication disorder such as aprosodia, the impossibility to produce or comprehend speech prosody—or the "melody" of speech (Côté et al., 2007). Despite the social-cognitive implications for patients of not being able to process e.g. linguistic or emotional prosody, aprosodia following stroke has received scant attention (Stockbridge et al. 2022).

First, the existing assessment tools for impairments of prosodic processing are found to be lacking in several aspects. The gold standard in the French language, the *Montréal Evaluation de la Communication* (MEC) consists of a combination of listening and production tests which exhibit good inter-rater reliability (Joanette et al. 2004) but are suspected of limited sensitivity, failing to capture nuanced deficits in language processing in e.g. ecological situations (Benedetti et al. 2022). More generally, traditional pre-post assessments with listening batteries (ex. the 12-items of the MEC prosody task) suffer from test–retest effects, where participants might remember their responses, leading to learning effects. Additionally, assessments based on prosody production typically involve manual scoring by clinicians, which may generate issues of inter-rater variability and limits the potential for monitoring patients remotely. Finally, existing tools typically provide a binary score indicating the presence or absence of a pathology, but do not allow for an in-depth understanding of the mechanisms that explain why a specific error may occur.

Besides lacking sensitive assessment tools, the field is also lacking in its understanding the exact sensory/cognitive mechanisms that subtend aprosodia. On the one hand, a wealth of cognitive neuroscience research has linked linguistic and/or emotional prosody perception with a dominantly-right temporo-frontal network (Schirmer & Kotz, 2006)—although it should be noted that recent research has also implicated a wider variety of cortical and subcortical networks (Grandjean, 2021). One prominent explanation for such a specialization proposes that the bilateral auditory cortices differ in their temporal and spectral resolution, with left auditory regions responding preferably to fast changes in the type of spectral cues implicated in phonetic discrimination, and right auditory regions to slow variations of pitch as seen in speech prosody and music (Zatorre, Belin & Penhune, 2002). On the other hand, clinical patient data has also linked right hemisphere damage due to stroke with a wide multitude of cognitive-communication deficits, which not only include aprosodia, but also impairments of the interpersonal communication such as inappropriate pragmatics and humour, as well as domain-general deficits in attention, memory and executive function (Côté et al., 2007). It therefore remains poorly understood whether impairments of prosody perception result from specific damage in regions involved in speech representations, or in more generic mechanisms. Lacking a mechanistic understanding of why patients perform poorly on such tasks deprives health practitioners of practical therapeutic targets for their subsequent rehabilitation.

Psychophysical reverse correlation

When studying the neural mechanisms that relate physical stimuli to perception, the modern field of psychophysics has largely moved from simply measuring sensory thresholds and psychometric functions, and now provides a toolbox of techniques to measure and fit multi-staged models able to simulate participant behaviour (Read, 2015). Notably for the example of speech prosody, the psychophysical technique of reverse-correlation (Murray, 2011) allows estimating, at the individual level, not only what sensory representations (hereafter, “kernels”) subtend the normal or abnormal perception of e.g. interrogative prosody (Ponsot et al., 2018), but also “internal noise” parameters that capture aspects of behavioral variability that are of potential neurological relevance (Neri, 2010).

While the kernel + noise model has a rich history in healthy participants, with or without peripheral hearing impairment (De Boer & De Jongh, 1978), its use in participants with neurological or developmental disorders has received relatively little attention. Yet, from a theoretical point of view, reverse correlation offers the promise to improve our comprehension of the mechanistic bases of prosodic impairments in brain-stroke patients. Model parameters at the individual level can reveal both morphological (ex. patients attending to the wrong part of a word) and computational abnormalities (ex. correct mental representations, but large amounts of sensory noise), both of which can be related to the aetiology or location of the lesion.

From a clinical point of view, reverse correlation also offers the perspective of a new instrument to diagnose prosody impairments beyond existing gold standards, to provide a prognosis metric to quantify how well a patient reacts to speech therapy week after week, and inspire new audio-based health technology to rehabilitate prosody perception in these patients

B. Aims of the project

The proposed work plan of project DASHES included both methodological, theoretical, clinical and technological objectives.

The project’s **methodological objectives** aim to improve the efficiency of reverse correlation in terms of task duration/number of trials, and to improve the robustness of the calculations with respect to task-irrelevant impairments of executive functions such as perseveration.

→ This objective was completed beyond our expectations. We have introduced several key algorithms that address important limitations that arise when applying classical reverse correlation algorithms to stroke patients. These include 3 new techniques to estimate internal noise in the absence of double-pass data, as well as a GLM-HMM algorithm that allows estimating kernels in the presence of response perseveration. These new algorithms have resulted in a 5-fold improvement in estimation accuracy.

The project’s **theoretical objective** is to provide a better understanding of what neurophysiological variables are addressed and measured by “internal representations” and “internal noise” as extracted by reverse correlation. Our proposed way to address this objective was to conduct behavioral and brain-imaging experiments on patients and healthy participants, and to use patient MRI data to do lesion-symptom mapping.

→ This objective was addressed in unforeseen manners. On the one hand, although we did start data collection for healthy participant fMRI and patient MRI, data collection was delayed and has only provided pilot data so far (fMRI:N=3 ; MRI:N=9). On the other hand, the project has used other sources of data to provide two important insights into the neurological and cognitive bases of internal noise and perseverations. First, we have tested a sample of gliome patients (N=29), with some conclusions regarding the localization of internal noise impairments. Second, applying the GLM-HMM algorithm to prosody perception data has provided novel mechanistic insights into the phenomenon of perseverating response in right-hemisphere stroke patients.

Our **clinical objectives**, over the 3 year period of support, were to conduct a clinical study and recruit 60 right-hemisphere stroke patients on which the results of the reverse-correlation procedure can be compared to the clinical gold standard for evaluating receptive aprosodia (the *Montreal Evaluation of Communication* battery – MEC).

→ This objective was largely completed. By the end of the project's support period, we have recruited N=40 stroke patients, and an additional N=29 brain tumor patients, and clinical analyses have documented several key correlations between reverse correlation parameters and clinical scores. Patient recruitment is still ongoing, with separate clinical funding, and should be completed within a few months.

Finally, our **technological objectives** aimed to provide a remote means to administer the reverse-correlation task via a web or tablet app, so that speech pathologists now have access to both easy and accurate reverse-correlation procedures to evaluate their patients

→ This objective was largely completed. All our developped tools were integrated in open-source toolboxes, including JONES, an online plateform that is currently deployed in Hôpital Pitié-Salpêtrière to administer reverse correlation procedure to patients.

C. Methods: a primer on reverse correlation

We describe here our proposed procedure for assessing aprosodia in stroke patients using reverse correlation, including the state of art in parameter estimation available at the start of the project.

→ In the following sections, we will describe our methodological contributions to improve this procedure, as well as the theoretical and clinical insights generated by applying this procedure to our sample of patients.

Stimuli generation: We record a 426-ms utterance of the French word "vraiment" ("really"), and generate prosodic variations by dividing it into six segments of 71ms and randomly manipulating the pitch of each breakpoint independently using a normal distribution (SD = 70 cents; clipped at ± 2.2 SD), hereafter referred to as "stimulus noise". These values are linearly interpolated between time points and fed to an open-source pitch-shifting toolbox (CLEESE, Python language, v1.0, available at https://github.com/neuro-team-femto/cleese) developed for this purpose.

Procedure: We then present patients with 150 successive pairs of such manipulated utterances (really/really?) asking them to judge which, within each pair, sounded most interrogative. The sequence is divided into 3 blocks of 50 pairs. Without the participant's knowing, the first and last block of each sequence contains identical pairs of sounds (a procedure called double-pass, allowing us to examine response variability), but all other sounds in the sequence are otherwise distinct. Sounds are delivered using closed headphones (Beyerdynamics DT770) and presented dichotically (same signal in both ears) at an identical comfortable sound level (~ 70dB SPL) to all patients and healthy subjects. The inter-stimulus interval in each pair is 500ms, and the interval between successive pairs is 1s. The procedure takes about 15min to complete. The procedure is administered via a web plateform (JONES, GO language, available at https://github.com/neuro-team-femto/jones) developed for this purpose.

Parameter estimation: For each participant's response data, we then fit a 2-stage psychophysical model consisting, first, of a prosodic template (or "kernel") to which sound stimuli are compared and, second, of a level of "internal noise" which controls how consistently this representation is applied to incoming stimuli (Fig. 1).

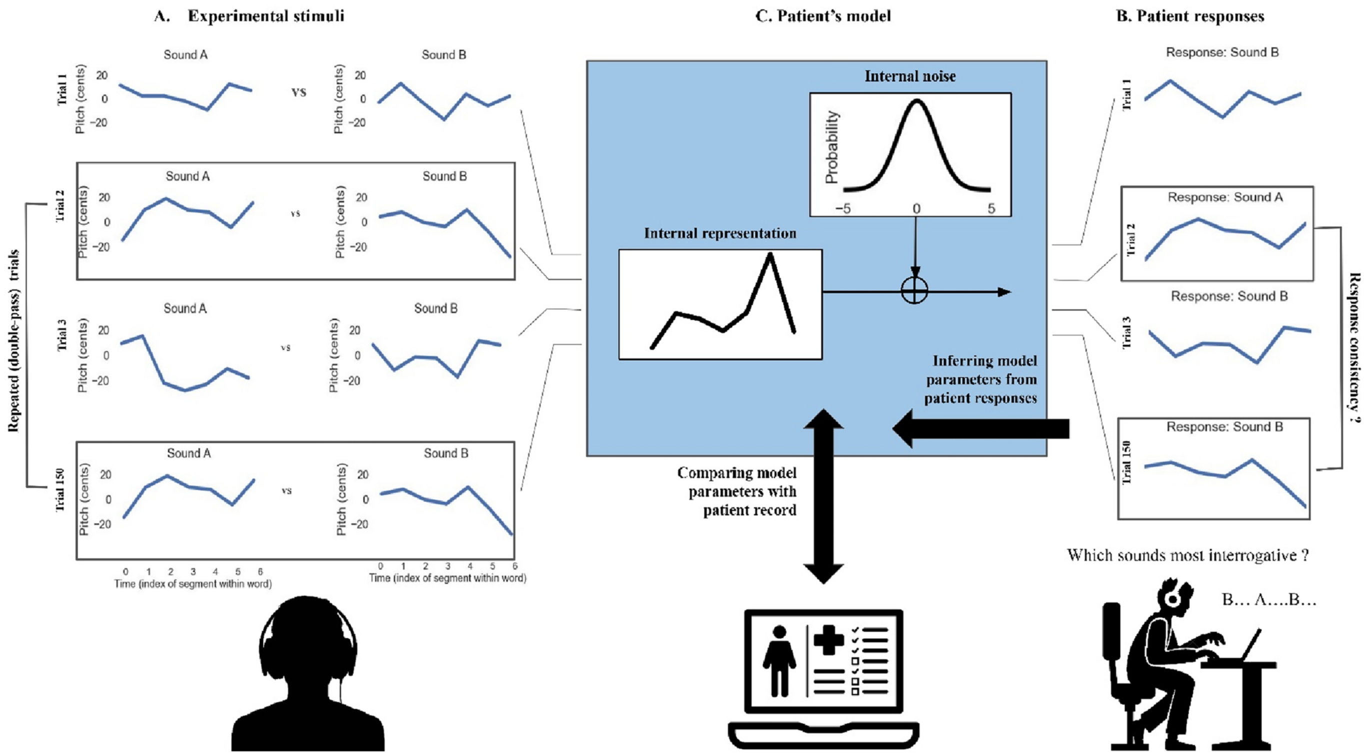

Figure 1: The kernel + noise model. Patients were presented with 150 successive trials consisting of pairs of manipulated prosodies (A) and asked to judge, within each pair, which sounded most interrogative (B). Patient responses in each trial were fitted with a 2-stage psychophysical model (C), consisting, first, of a prosodic template (or "internal representation") to which sound stimuli are compared and, second, of a level of "internal noise" which controls how consistently this representation is applied to incoming stimuli. See main text for details about the model-fitting procedure. In this work, we estimate the two model parameters (representation and noise) for each patient individually and compare them with patient records to test their value as markers of receptive aprosodia

Participants' internal representations (a time × pitch representation of an ideally interrogative pitch contour) are classically estimated using the weighted-sum "classification-image" technique.. We subtract the average pitch contour of non-interrogative classifications from that of interrogative classifications. To normalize this resultant representation, we divide it by the root mean square of its values—this method involves squaring each value of the representation, averaging these squared numbers, and then taking the square root of this average to scale the representation accordingly.

→ As will be seen below, the classification image method suffers from imprecision when participants/patients alternate between phases of task engagement and disengagement (perseveration), and one of the project's contributions is to provide a new method (GLM-HMM) that's more appropriate to this situation.

Participants' internal noise (expressed in units of the standard deviation of stimulus noise) is classically inferred from response consistency and response bias across the repeated double-pass trials, using the simulation procedure of Neri. In short, we compute an idealized participant model responding to repeated stimuli pairs of various sensory evidence, perturbed its response with additive gaussian noise ("internal noise"), and estimate the probability for that model to give the same response for identical trials (i.e. response consistency) and the probability of giving the first response option (i.e. response bias), for different standard deviations of that internal noise. For each participant, we then invert that model and obtained the value of internal noise (by exhaustive search between 0 and + 5 std) that minimizes the error between the observed and predicted values for that participant's consistency and bias.

→ As seen below, the double-pass procedure suffers from imprecision with small numbers of double-pass trials (as is the case here ; reverse correlation experiments typically involve 1000s of trials). One of the project's contributions is to provide new methods to estimate internal noise that do not require double-pass trials and are more appropriate to this situation.

D. Results

We describe here project results regarding to all four methodological, theoretical, clinical and technological objectives.

D.1. Methodological contributions

From a methodological point of view, we have introduced several key algorithms that address important limitations that arise when applying classical reverse correlation algorithms to stroke patients. These include 3 new techniques to estimate internal noise in the absence of double-pass data, as well as a GLM-HMM algorithm that allows estimating kernels in the presence of response perseveration.

a. Three new analysis methods to estimate internal noise in data-driven experiments, in the absence of double-pass measurements

While one of the important methodological interests of data-driven reverse-correlation experiments is to allow estimating internal noise, the dominant strategy to do so, double-pass, is plagued with important practical limitations, among which its lack of precision for short experiments, its vulnerability to local perturbations, and its assuming that noise is stationary throughout the experiment. These limitations are particularly salient in the case of stroke patients, who are both fatiguable and have a tendency to perseverate (i.e. to stop engaging with the task and contributing long series of identical responses that are seemingly unrelated to the stimuli).

Project DASHES introduced 3 simple alternative analytical techniques (Intercept, Accuracy and GLM) to estimate internal noise from data-driven experiments in the absence of double-pass measurements. The first method, Intercept, provides a heuristic to estimate the double-pass probability of agreement by extrapolating the agreement of pairs of imperfectly repeated trials over the single-pass experiment. The second method, Accuracy, estimates a proxy of probability of agreement based on the observer's agreement with an ideal observer over the same data. The third method, GLM, is a model-based approach that estimates internal noise as a function of normalized confidence interval around GLM kernel weights. All three methods extract information about response consistency from trial and response variability in single-trial data, without requiring the availability of double-pass data. This is important because, in typical experiments, single-pass trials are more numerous than double-pass trials, so there exists a compromise between the accuracy of double-pass estimation of internal noise, and the single-pass estimation of kernel.

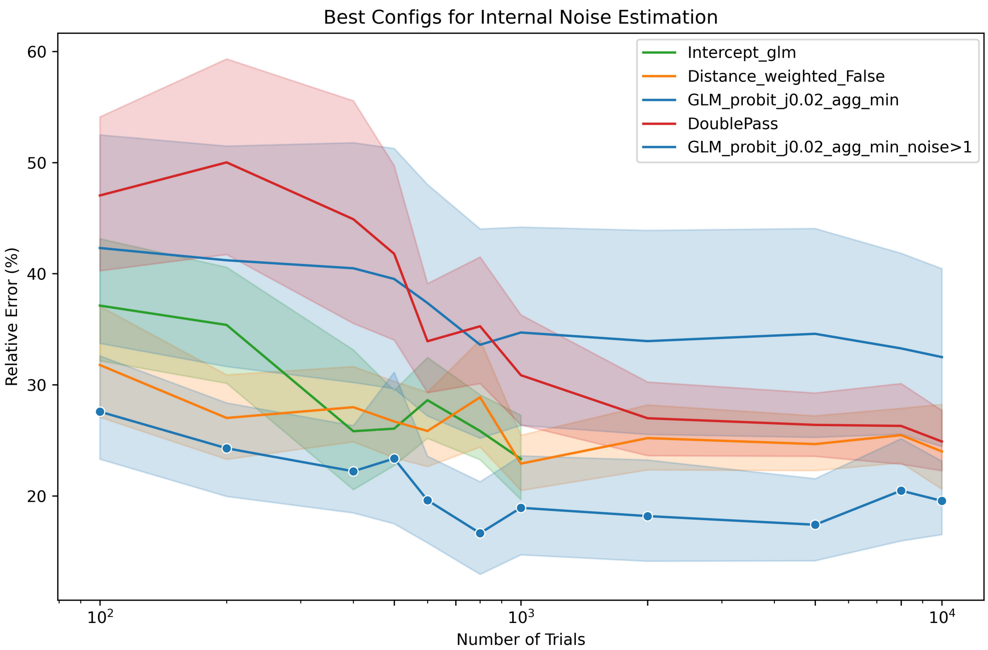

Figure 2: Relative error of internal noise estimation across methods and trial counts [100,10000]. Intercept (Intercept glm) and Accuracy (Distance not weighted) show consistently lower error than Double pass across all trials counted up to 1000. GLM overestimates internal noise at low levels, but it performs best among all methods when the noise level is restricted to σn >1.

Using computer simulations with a specially-developed toolbox (PALIN, see below), we showed that the three techniques consistently outperform double-pass estimation for experiments with low number of trials (<1000), often more than halving percentage error (Figure 2).

These results were reported on in the format of a preprint, co-written with by project participants AAZ, MV and JJA, and in collaboration with Ladislas Nalborczyk (Laboratoire Parole et Langage, Aix-en-Provence), which is intended for submission at a methodological journal such as Behaviour Research Methods or Quantitative Methods for Psychology **(→ Adl Zarrabi et al., preprint, 2025)**

b. Joint estimation of perseverations and reverse-correlation parameters with the GLM-HMM model

The fact that stroke patients tend to perseverate disrupts both the stimulus-response relation and response variability, leading to large estimation errors in both kernel and noise. First, when patients perseverate for an important proportion of an experiment, kernels estimated with the classification-image method are trying to infer a stimulus-response relation based on data which does not reflect such a decision strategy. Second, if patients perseverate during one or both double-pass blocks, the probability of agreement may be severely under- or over-estimated, leading to internal noise estimates which do not have a direct relation with the patient's perceptual decision process.

One approach to detecting perseveration in behavioral responses is to only analyze choice history, i.e., measure the tendency to repeat the same response across an arbitrary number of consecutive trials (e.g., 15) without considering whether the response was actually appropriate to the stimulus. While this approach is simple, it is likely to both falsely label as perseverated streaks of trials which, by chance, genuinely warranted similar responses and also miss shorter episodes of perseverations. At the same time, like internal noise, perseverating episodes is not only a source of "estimation noise" that one want to mitigate but also a symptom of cognitive deficits after stroke. Detecting it accurately (e.g., estimating a true probability of perseverating) may therefore provide crucial insights into post-stroke cognitive impairments and potentially another candidate for biomarkers that can help their diagnosis, prognosis or therapy.

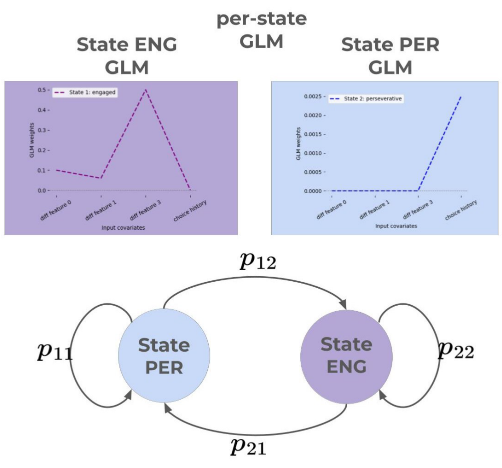

Figure 3: The GLM-HMM model. Top: GLM weights for each hidden state: the engaged (ENG) state (left, purple) exhibits flexible weights across stimulus features and minimal influence from previous choices, while the perseverative (PER) state (right, blue) demonstrates a dominant weight on previous response and negligible weights on stimulus features. Bottom: State transition matrix of the GLM-HMM, where p11 and p22 represent the probabilityof remaining in the same state, and p12 and p21 denote switching between states. Accurate inference of these parameters enables the model to capture dynamic switching between engaged and perseverative behaviors during the task.

Project DASHES introduced a new method to conjointly estimate both linear-observer parameters and perseverating episodes, using a joint model with two latent states (input-output hidden Markov model, or GLM-HMM): one engaged state, which response rule corresponds to the usual kernel + noise model, and one perseverating state, which response rule is simply to repeat the response to the previous trial (Figure 3). We provided a new training procedure, based on a maximum-a-posteriori criteria with priors learned with Bayesian optimization, that is able to fit model parameters to observer responses. We showed that this model is able to recover perseverating episodes with good accuracy, which not only improves the accuracy of kernel and noise estimates across non-perseverated episodes (Figure 4), but also provides a novel way to analyse factors leading to perseveration (see *D.2 Theoretical contributions*, below)

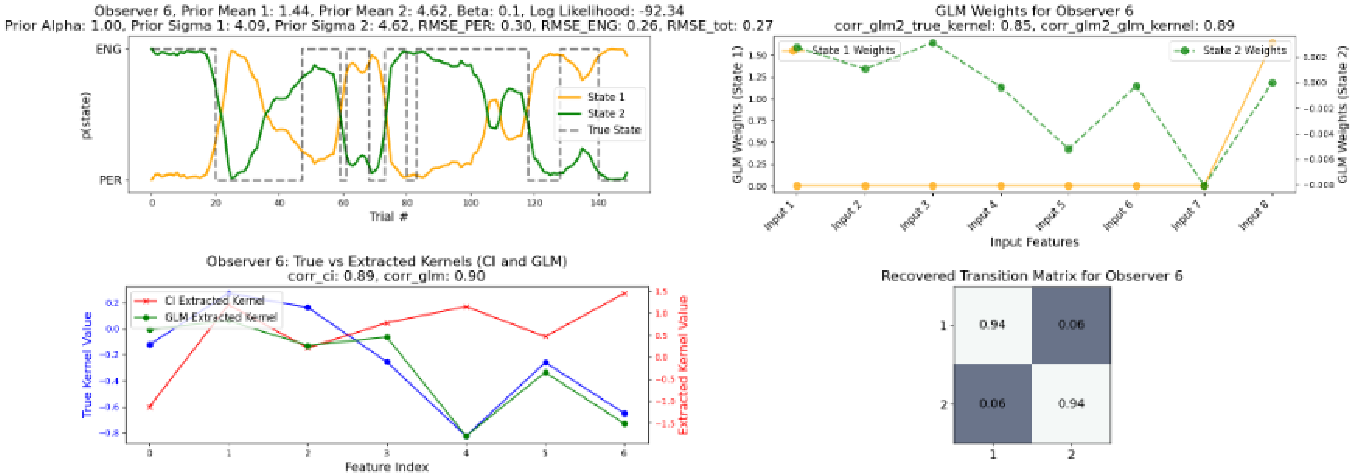

Figure 4: Illustration of GLM-HMM parameter fitting on one simulated perseverating observer. Top left: Posterior state probabilities (green: engaged, orange: perseverative) with the true latent state (gray). Top right: State-specific GLM weights across eight input features (stimulus features and previous choice input). Bottom left: Comparison of true kernel (blue), engaged-state kernel from GLM-HMM (green), and kernel from single-state GLM-HMM (red). Bottom right: Recovered transition matrice between states.

These results were reported on as a chapter in AAZ's PhD thesis **(→ Adl Zarrabi, PhD thesis, 2025)**, and will be prepared for publication together with theoretical results about the analysis of patient perseveration, tentatively in a neurology journal such as Brain or Stroke.

D.2. Theoretical contributions

The project's theoretical objectives was to provide a better understanding of what neurophysiological variables are addressed and measured by parameters extracted by reverse correlation. These parameters include not only kernels and internal noise but also, via our newly developed GLM-HMM method, transition probabilities and the characteristics of perseverated trials. The project has provided two main theoretical results: first, we have tested a sample of gliome patients pre- and post-surgery, to test an association between tumour localization and internal noise impairments; second, we applied the GLM-HMM algorithm to provide novel insights into the characteristics of perseverated trials in right-hemisphere stroke patients. In addition, we have also initiated two additional experiments for which data collection is still ongoing, and which we also describe below.

a. Glioma surgery: a model to study how lesions in different brain regions impact kernels and noise

One important question when interpreting abnormal kernel and noise values from reverse correlation in a neurological context is to be able to relate such impairments to neurophysiological variables. In particular, there is debate in the literature whether internal noise measured by reverse correlation corresponds to neuronal noise active at the level of sensory cortices (Vilidaite, Marsh & Baker, 2019), decision noise linked to prefrontal cortices (Findling & Wyart, 2021), or a more anatomically distributed phenomenon.

To investigate this issue, we have started a new collaboration with the neuropsychology department of Hôpital Pitié-Salpêtrière (Paris) to investigate the impact of glioma surgery on revcor performed pre- and post-surgery. While different from our target condition (brain stroke), glioma surgery offers a quasi-experimental model to study how lesions in different brain regions (notably: frontal vs temporal) impact representation and noise. We have collected revcor data on N=29 glioma patients (50% astrocytoma, 50% oligodendroglioma; 60% in frontal, 25% in temporal regions), as well as N=29 controls. By comparing internal noise values pre- and post-surgery, we found evidence that internal noise was associated not with frontal regions, but temporal regions bilaterally (Figure 5).

These results were reported on in the speech-therapy thesis of Célia Chauche-Lombard and Aude Warnery, and presented at the ESCAN conference in May 2024 **(→ Chauche-Lombard, ESCAN 2024)**. They will be prepared for publication as a journal article, tentatively in Journal of Neurology, Neurosurgery and Psychiatry.

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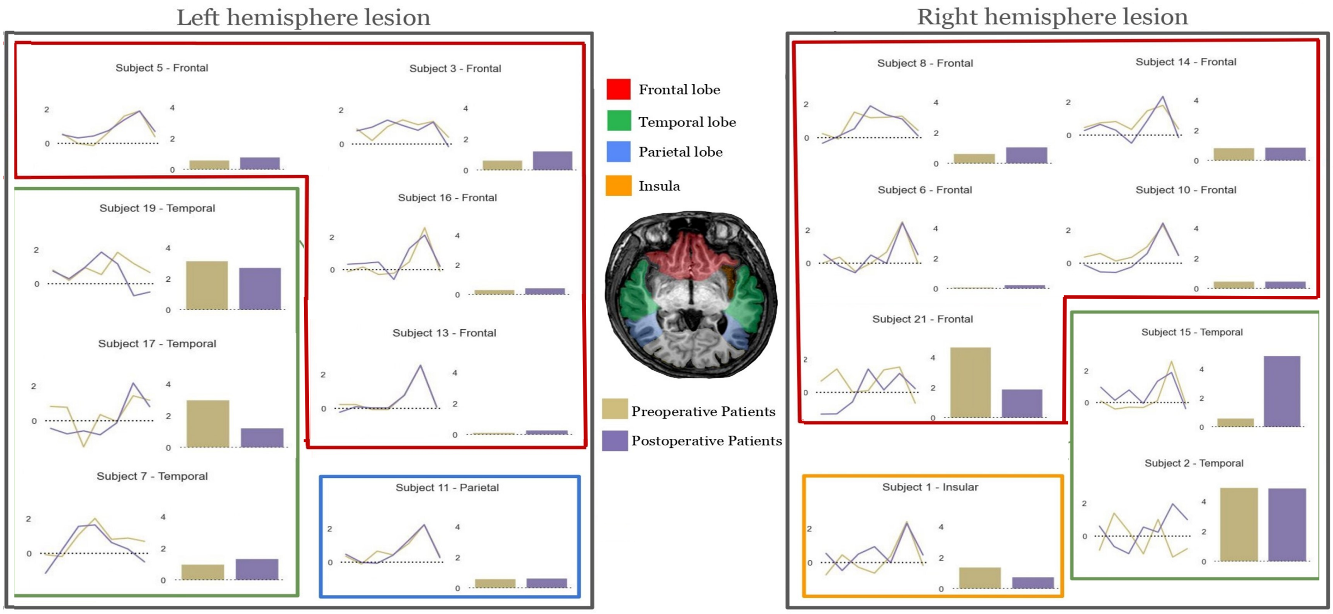

Figure 5: Kernels and noise for the revcor task performed pre and post glioma surgery. Large noise values are mostly found for temporal glioma

b. Novel insights into the characteristics of perseverated trials in right-hemisphere stroke patients

The GLM-HMM model developped in the project (D.1.b, above) opens the opportunity to explore the characteristics of perseveration in stroke patients, and in particular whether we can link state switching to certain characteristics of the stimuli or responses in the vicinity of the switch. To do do, we can exploit the fact that fitting the GLM-HMM model provides labels (i.e., posterior state probabilities) for the most probable state at each trial, and that the characteristics of these trials (stimuli, responses, response times) are random but known. Using our collected data on N=40 stroke patients (see D.3, below), we have investigated whether specific parameters influence the likelihood of patients entering and exiting the perseverative state.

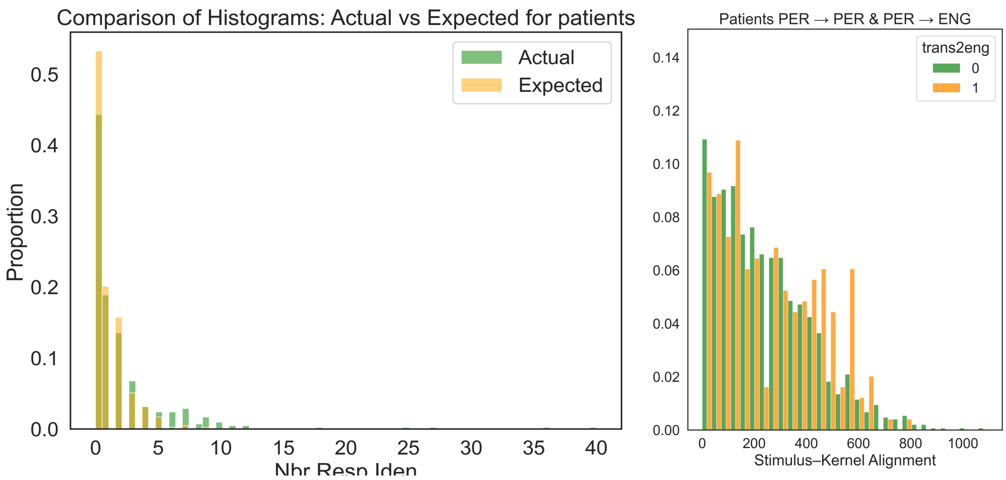

Figure 6: Left: Comparison of the expected and observed distribution of consecutive identical responses before a perseveration switch for patients. Right: Comparison of the distribution of stimulus alignment over perseverative trials that either transitioned to the engaged state (orange) or remained perseverative (green).

First, we found that perseverations tend to occur after long streaks of (correctly) repeated responses. To do so, we extracted all trials in engaged state that immediately preceded a switch to perseveration (i.e., the last trial in every sequence of successive engaged trials), and computed the empirical distribution of the number of consecutive identical responses that was ongoing at these trials, before the switch. Because all trials are random, the mode of that distribution is likely equal to 1, but it may be larger either because of a un/lucky sequence of stimuli or response tendencies. We then compared this empirical distribution with the expected theoretical distribution, which is the cumulated density of a binomial distribution with probability p = 0.5. The distribution over the group of patients differed statistically from the expected distribution (Kolmogorov–Smirnov test, p = 0.0036), with some switches occurring after 10 or more successive identical responses (Figure 6). This suggests that, before a switch to perseveration, patients exhibit more repetitive responses than what would be expected with random binary choice. This pattern of results is consistent with the view that perseverating participants have difficulties inhibiting a response once it is established.

Second, using a similar analysis strategy, we found that perseverations often end on trials for which the correct answer is particularly obvious (i.e. for the stimulus was well aligned with the participant's kernel). This suggests that this brain state is not entirely disconnected from task-related information processing.

While they are only correlational, such effects are interesting for several reasons. First, to test for a possible causal effect, one could imagine artificially introducing sequences of trials that warrant identical responses and seeing if these make patients more likely to enter perseveration; conversely, when patients are found to be perseverating, one could imagine a closed-loop procedure where they are presented easier trials to test if this drive them back to task engagement. Second, these effects may suggest a possible strategy to avoid perseverating behaviour in patients, by avoiding to prevent long sequences of trials that warrant identical responses. Further experimental work will be needed to test the causality of this possible relation.

These results were reported on as a chapter in AAZ's PhD thesis **(→ Adl Zarrabi, PhD thesis, 2025)**, and will be prepared for publication together with methodological results on GLM-HMM model, tentatively in a neurology journal such as Brain or Stroke.

c. Ongoing experiment: do participants have metacognitive access to internal noise ?

To investigate the link between kernels, internal noise and participant's metacognition, we we have collected reverse-correlation data from N=25 healthy participants. Participants took part in four successive tasks, of varying difficulty, incl. the same interrogative task as patients but also comparable tasks requiring more difficult prosodic judgements. Importantly, on each trial, participants not only indicated their response but also their degree of confidence in this response, on a 4-point Likert scale.

Our initial analyses, which will have to be confirmed using our newly developped measures of internal noise (D.1), suggest an almost total lack of metacognitive access to internal noise. If confirmed, such results would have consequences both for understanding the neurophysiological substrate of internal noise, and for subsequent rehabilitation strategies. This line of research will be continued as part of project participant Marie Villain's ANR JCJC on anosognosia (lack of metacognitive awareness of symptoms), funded this year.

d. Ongoing experiment: the functional localization of prosody kernels

Finally, to investigate the brain localization of prosody kernels, we have started a collaboration with the team of Prof. Pascal Belin (Institut des Neurosciences de la Timone, Marseille), in which participants are scanned with fMRI while they passively listen to 700 vowels with randomized pitch contours. By computing a prosody kernel for each voxel, we can investigate whether there exist systematic cortical representations (i.e. a tonotopy) of dynamic pitch contours. Only one other study has looked at this question, using intracranial EEG and only 4 types of pitch contours (Tang, Hamilton & Chang, Science 2017). We have validated the protocol on N=3 healthy participants (Figure 7), and are now including our complete sample.

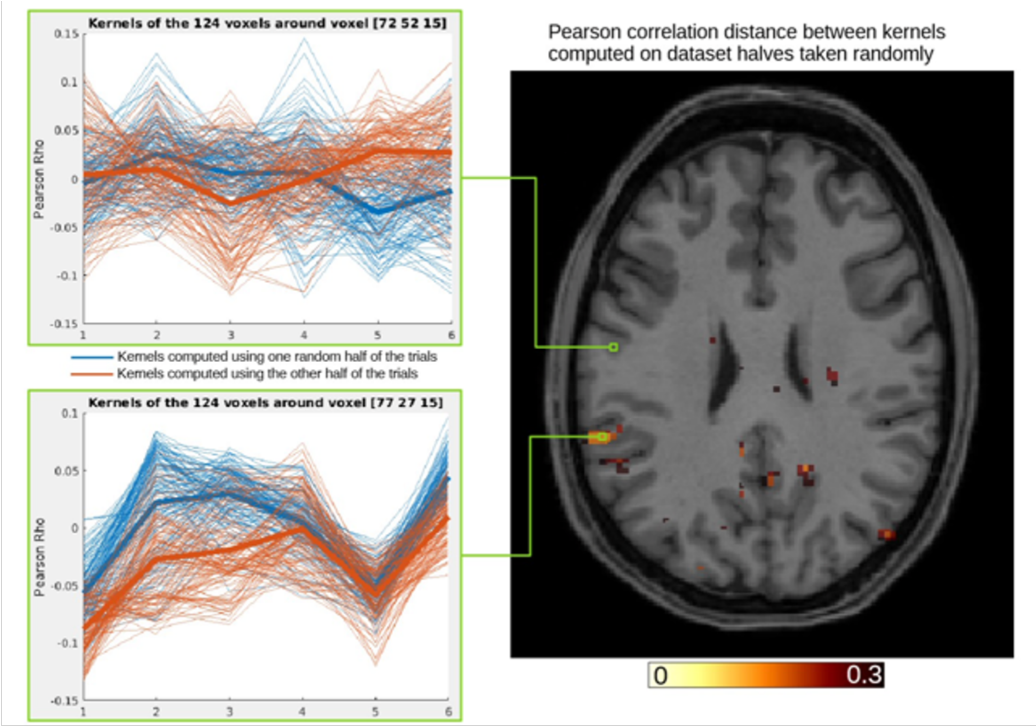

Figure 7: Reverse correlating the prosodic sensitivity of individual voxels in the auditory cortex (pilot data, N=1)

D.3. Clinical contributions

From a clinical perspective, we have applied our newly-developed technique on N=40 brain-stroke patients in a clinical trial that is still ongoing. Our results have shown that the current gold-standard for evaluating aprosodia (the Montreal Evaluation of Communication procedure, or MEC) lacks both sensitivity and specificity.

First, reverse correlation kernels show significant alterations of prosodic sensory processing in patients who are yet classified as non-pathological by MEC. Internal representations of interrogative prosody in the control group exhibited a typical final-rise contour, characterized by a marked pitch increase at the end of the second syllable. In contrast, patients' kernel had lower amplitude, indicating reduced discriminative power, and displayed greater variability across individuals. (Figure 8)

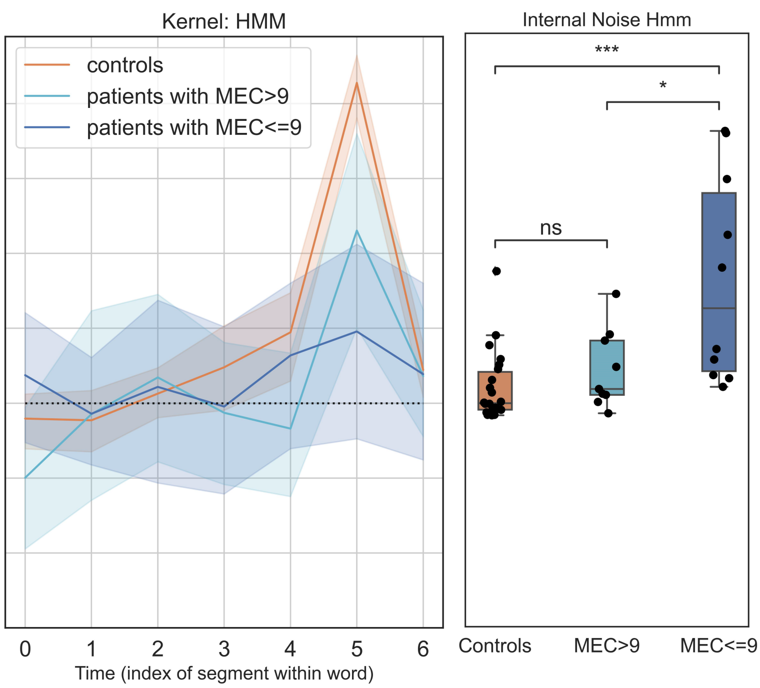

Figure 8: Kernel and internal noise estimated by reverse correlation separate controls from patients above and below the pathological cut-off (9/12) on the MEC clinical tool. Left: internal representations (kernels) of interrogative prosody. Right: control participants were able to apply these representations remarkably consistently across trials with internal noise values < 1 standard deviations of stimulus noise. In contrast, patients' internal noise levels were larger and more variable, and scaled with prosodic difficulties measured by MEC

Second, altered kernels and increased internal noise do not directly correlate with pathological MEC scores, but rather to different cognitive subprocesses – kernels with central auditory deficits (as measured with AIRTAC), and internal noise with auditory attention (as measured with LAMA).

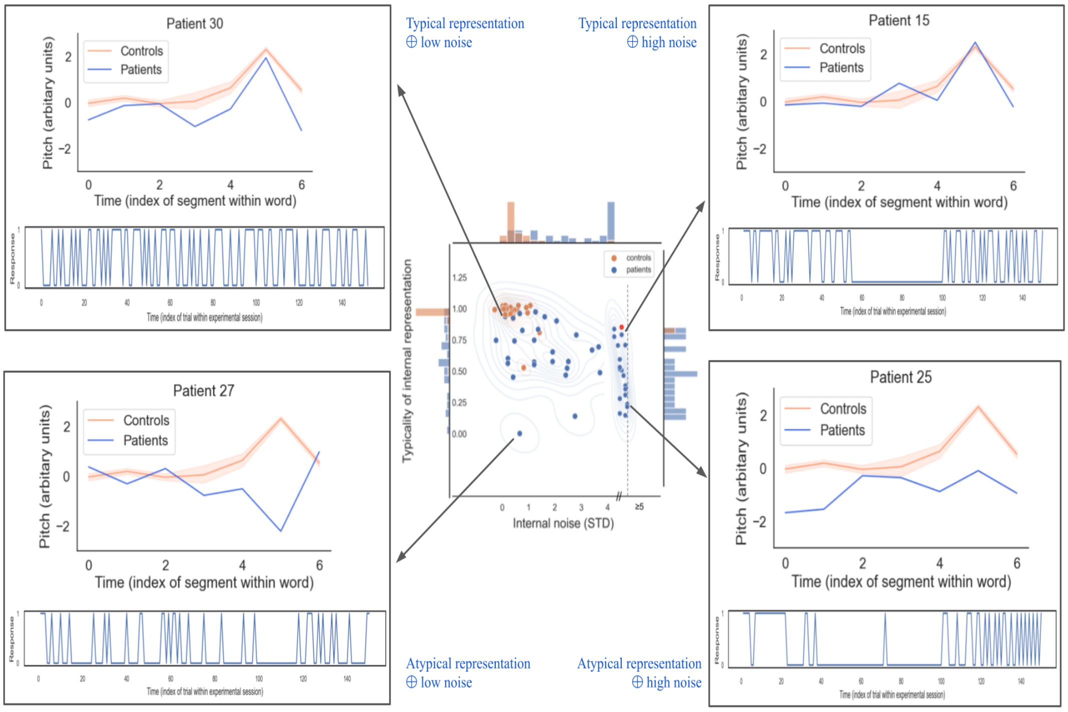

Figure 9: The representation + noise model captures a rich diversity of sensory/cognitive mechanisms underlying impairments of prosody processing after stroke. Center: distribution of representation typicality and internal noise for controls and patients, overlaid with by kernel density estimate. Histograms on the marginal axes show univariate distributions for each variable in the patient group. Corners: corner boxes show internal representations (top) and behavioral series of responses (bottom) for 4 illustrative patients. Patients in top corners have internal representations (blue) that are similar to controls (orange), but vary in amounts of internal noise (e.g: high level of internal noise in top right). Patients in bottom corners have atypical representations, but some nevertheless retain healthy levels of internal noise (bottom left).

Taken together, the kernel + noise model paints a simple yet potent portrait of the variety of sensory/cognitive mechanisms that can explain impairments of prosody processing after stroke: patients may differ from controls by having altered representations but a healthy level of internal noise (e.g., being normally consistent in wrongly expecting e.g. question phrases to decrease rather than increase in pitch—Fig. 9-left); by having normal representations but abnormal levels of internal noise (e.g. showing excessive response perseveration and suboptimal executive control on top of otherwise normal sensory processing—Fig. 9-right); or both.

An initial analysis of a subset of this data (N=22) was published using classical methods (classification image and double-pass) in Scientific Reports **(→ Adl Zarrabi et al., Scientific Reports, 2024)**. A reanalysis of the complete dataset using the updated methods (D.1) is reported on in Adl Zarrabi's PhD thesis **(→ Adl Zarrabi, PhD thesis, 2025)**, and will be prepared for publication together with methodological results on GLM-HMM model and theoretical results on perseveration, tentatively in a neurology journal such as Brain or Stroke.

D.4. Technological contributions

Finally, from a technological point of view, these newly developed suite of tools has been integrated in open-source toolboxes (CLEESE, PALIN and JONES), and deployed online, so that speech pathologists now have access to both easy and accurate reverse-correlation procedures to evaluate their patients.

Toolbox CLEESE automates the creation of reverse-correlation stimuli. It is available as an open-source github package programmed in Python on https://github.com/neuro-team-femto/cleese, and documented on https://neuro-team-femto.github.io/cleese. Since the start of the project, CLEESE has received increasing interest from the neuroscience community and is now being used by a number of other labs for similar experiments (*University of Reading, UK; University of Quebec, CA; University of Potsdam, DE; Neurospin, FR*).

JONES is an online plateform that is currently deployed in Hôpital Pitié-Salpêtrière to administer reverse correlation procedure to patients. It is available as an open-source Golang package on https://github.com/neuro-team-femto/jones. JONES allows the rapid implementation (via text configuration files) of reverse correlation experiments, and their deployment over the web and/or secure hospital networks. The plateform was designed to be robust to loss of connection (with data caching), and designed in coordination with DPO at the APHP hospitals to be GDPR compliant.

Finally, **PALIN** automates the analysis of kernel and internal noise from patient data. The toolbox enables the flexible simulation of reverse-correlation experiments by varying key parameters such as internal noise, decision bias, and observer kernel, as well as the analysis of experimental data into the same variables. It incorporates not only the classical estimation methods (classification images, double-pass), but also the methods newly developed in the project; we ambition that it will also become the receptacle for future developments by us and others. The toolbox is implemented in both the Python and R programming languages, and available open-source at https://github.com/neuro-team-femto/palin .

A previous version of the CLEESE Toolbox was published in PLOS One as Burred et al, 2019. During the scope of the project, CLEESE was publicized at a symposium session at the 2024 European Society for Cognitive and Affective Neuroscience (ESCAN) meeting in Ghent, May 2024 **(→ Aucouturier & Tuttosi, ESCAN 2024)**. We are preparing three submissions for each toolbox at Journal of Open-Source Software, as well as a joint tutorial paper describing the complete suite of software in a journal like Tutorials in Quantitative Methods for Psychology.

D.5. Training and Outreach

Beyond science, the project was also instrumental for the career development of several new (incidentally, all young women) researchers entering the French community of auditory science.

First, the project provided support for 6 speech-therapy theses (memoire d'orthophonie), Pauline Bardet, Pauline Commère, Romane Legendre, Anne-Victoire Ogeron supervised by MV, and Célia Chauche-Lombard and Aude Warnery co-supervised by MV and Viviane Luherne-du Boullay (APHP). Pauline Bardet and Pauline Commère's theses (completed I 2019, but analysed in the project) assessed the prosodic perception of 13 right-hemisphere stroke patients and 12 control subjects. Their results were compared with those obtained using voice audiometry, a mood and anxiety self-assessment scale, and tests assessing various cognitive functions. Romane Legendre (2025) investigated the performance of left-hemisphere stroke patients. She found that aphasic patients also show deficits in prosodic perception. Anne-Victoire Ogeron (2025) studied the link between amusia and aprosody after stroke. Her study involved 9 post-stroke patients and revealed links between auditory attention and aprosody. Finally, Célia Chauche-Lombard and Aude Warnery (2023) studied prosody perception pre- and post-tunmour resection surgery in 29 glioma patients.

Second, project PhD student Aynaz Adl Zarrabi successfully defended her PhD thesis (Reverse-correlation modeling of deficits of prosody perception in right-hemisphere stroke) in July 2025, before a committee consisting of Dr Léo Varnet (LSP, Paris), Prof. Anahita Basirat (Univ. Lille), Dr Charlotte Jacquemot (NPI, Paris), Dr Ladislas Nalborczyk (LPL, Aix-en-Provence) and Dr Emmanuel Ponsot (STMS, Paris).

Finally, project postdoc Marie Villain was recruited in Oct. 2024 as an Assistant Professor (maitresse de conférence) in Sorbonne Université / Institut du Cerveau.

Project results were disseminated in two dedicated workshops, one organized as a special session at the 2024 conference of the European Society for Cognitive and Affective Neuroscience, and one workshop on auditory reverse correlation at the FEMTO-ST Institute in July 2025 (https://neuro-team-femto.github.io/revcor25).

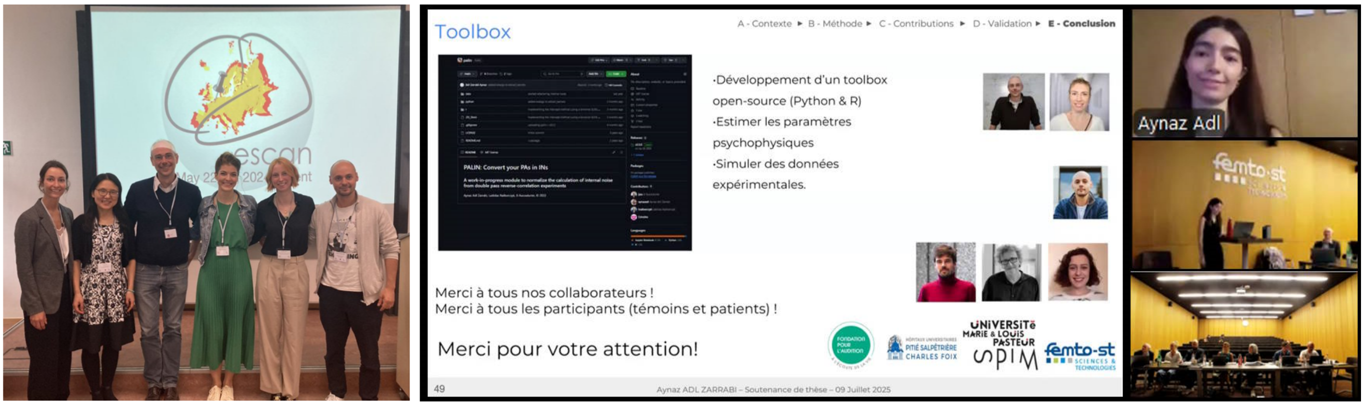

Figure 10: Some of the outreach events organised during the project. Left: CLEESE symposium at the 2024 conference of the European Social Cognitive and Affective Neuroscience society in Ghent, BE; Middle, Right: PhD defense of project PhD AAZ, FEMTO-ST Institute, July 2025.

Discussion

In short, project DASHES has advanced how we understand, diagnose, and eventually treat speech melody problems after stroke. It has also laid the groundwork for better tools and a stronger research community in this field.

From a methodological point of view, our new developments (new methods for internal noise without double pass, and GLM-HMM) have applications that reach far beyond the project. In particular, with a 4-5 fold improvement on the accuracy of internal noise estimation with our new methods, this may call for a re/analysis of the published literature where double-pass internal noise estimates were calculated with small number of trials, e.g. in the case of fatigable patients or online participants. In studies investigating internal noise and its link to individual traits (e.g., autistic characteristics - Merchie et al., 2024) the lack of observed correlation may partly arise from the imprecision of the traditional double-pass method. The fact that our results were presented in presence of a large share of the French reverse correlation community at the occasion of the AAZ's PhD defense should help in organizing such an initiative.

From a theoretical point of view, our results have raised the intriguing possibility to control perseveration in stroke patients by manipulating either trials with correctly identical responses (to control the entry in perseveration) or trials that aligh with the participant's kernels (to control the exit from perseveration). While the evidence is so far correlational, we anticipate that we will try directly manipulating these factors in an experimental design to test their causal influence. In addition, two of the project's studies are still ongoing (analysis for the metacognition study, data collection for fMRI), and we will follow up on their completion.

Our clinical contributions have lead to a practical implementation of an optimized reverse correlation protocol, shown both more sensitive and more specific than the field's gold standard (MEC). Our perspectives at the end of the project is to assist its continuous adoption in the project's partner hospital (APHP), which will be facilitated by the faculty hire of project postdoc MV. While our clinical trial (currently at N=40/60 patients) is expected to establish the technique's value for diagnosis, our future work will focus on prognosis and therapeutic uses: first, we will test the value of repeated revcor assessment during the course of speech therapy; second, we will investigate whether the knowledge of impaired kernel and/or internal noise warrants different rehabilitation strategies. As these perspectives are clinical in nature, they will probably be investigated in the format of speech-therapy theses.

Finally, at the outset of the project, we have several publications in preparation, which we will endeavour to submit and publish in the next few months:

- one manuscript on internal noise methods, already available as a preprint, to be submitted at a methodological journal such as Behaviour Research Methods or Quantitative Methods for Psychology **(→ Adl Zarrabi et al., preprint, 2025)**
- one manuscript on the analysis of perseveration, based on chapters 8-9 of AAZ's PhD Thesis **(→ Adl Zarrabi, PhD thesis, 2025)**, to be submitted in a neurology journal such as Brain or Stroke.

- one manuscript on the association of glioma tumour localization and reverse correlation parameters, to be adapted from the speech-therapy thesis and ESCAN poster of of Célia Chauche-Lombard **(→ Chauche-Lombard, ESCAN 2024)**, to be submitted in Journal of Neurology, Neurosurgery and Psychiatry
- three submissions for each toolbox at Journal of Open-Source Software, as well as a joint tutorial paper describing the complete suite of software in a journal like Tutorials in Quantitative Methods for Psychology.

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PUBLICATIONS, ABSTRACTS, PATENTS, ETC.

Articles:

- Aynaz Adl Zarrabi, Jean-Julien Aucouturier, Ladislas Nalborczyk, Marie Villain (2025) Three new analysis methods to estimate internal noise in data-driven experiments, in the absence of double-pass measurements, preprint [pdf included below]
- Adl Zarrabi, A., Jeulin, M., Bardet, P., Commère, P., Naccache, L., Aucouturier, J. J. & Villain, M. (2024). A simple psychophysical procedure separates representational and noise components in impairments of speech prosody perception after right-hemisphere stroke. Scientific Reports, 14(1), 15194. [pdf download link: https://www.nature.com/articles/s41598-024-64295-y]

Collaboration not funded by the project:

- Annabelle Merchie, Zoé Ranty, Aynaz Adl Zarrabi, Frédérique Bonnet-Brilhault, Emmanuelle Houy-Durand, Jean-Julien Aucouturier, Marie Gomot (2025) Intact representation of vocal smile in autism: A reverse correlation approach, Research in Autism Vol. 124 [pdf download link: https://www.sciencedirect.com/science/article/pii/S3050656525000719]

Posters:

- Chauche-Lombard, C., Adl Zarrabi, A., Warnery, A., Aucouturier, JJ., Luherne-du Boullay, V., Villain, M. Exploring Prosody Recognition in Glioma Patients: A reverse-correlation Study, poster presented at European Society for Cognitive and Affective Neuroscience 2024.

Talks:

- Adl Zarrabi, Une nouvelle procédure psychoacoustique pour caractériser la perception de la prosodie après AVC de l'hémisphère droit, 9ème Journée de Phonétique Clinique, Juin 2023
- JJ Aucouturier & Paige Tuttosi, CLEESE A step by step example, European Society for Cognitive and Affective Neuroscience 2024

Organized workshops:

- Cracking the code of the social cognition of face and voice with the CLEESE Python toolbox. European Society for Cognitive and Affective Neuroscience, Ghent, BE, July 2024.
- Recent advances in auditory reverse correlation, FEMTO-ST Institute, July 2025 (https://neuro-team-femto.github.io/revcor25).

PhD Thesis:

- Aynaz Adl Zarrabi (2025) Reverse-correlation modeling of deficits of prosody perception in right-hemisphere stroke. Thèse de l'Université Marie et Louis Pasteur, Besançon, FR. Soutenue le 9 Juillet 2025. [pdf download link: https://neuro-team-femto.github.io/articles/2025/adl_zarrabi_phd_2025.pdf]

Software:

- CLEESE, a toolbox to automate the creation of reverse-correlation stimuli. https://neuro-team-femto.github.io/cleese.
- JONES, an online plateform to administer reverse correlation procedures to patients. https://github.com/neuro-team-femto/jones.
- PALIN, a toolbox to automate the analysis of kernel and internal noise from patient data. https://github.com/neuro-team-femto/palin .

OVERALL EVALUATION – For internal use