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Author for correspondence:
Siloé Corvin
e-mail: siloe.corvin@yahoo.fr

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Nonlinear acoustic phenomena affect the perception of pain in human baby cries

Siloé Corvin[1,2], Mathilde Massenet[1], Angélique Hardy[2,3], Hugues Patural[4], Roland Peyron[2], Camille Fauchon[2,3] and Nicolas Mathevon[1,5,6]

[1]ENES Bioacoustics Research Lab, CRNL, CNRS, Inserm, University of Saint-Etienne, Saint-Etienne 42100, France
[2]NEUROPAIN Team, CRNL, CNRS, Inserm, University of Saint-Etienne, Saint-Etienne 42270, France
[3]Neuro-Dol, Inserm, University of Clermont Auvergne, University Hospital of Clermont-Ferrand, Clermont-Ferrand 63100, France
[4]Neonatal and Pediatric Intensive Care Unit SAINBIOSE Laboratory, Inserm, University Hospital of Saint-Etienne, University of Saint-Etienne, Saint-Etienne 42270, France
[5]Institut Universitaire de France, Paris 75005, France
[6]Ecole Pratique des Hautes Etudes, CHArt lab, EPHE - PSL University, Paris, France

SC, 0000-0002-9281-6087; MM, 0000-0002-0085-1871; HP, 0000-0002-5359-6544; RP, 0000-0002-2706-0594; CF, 0000-0002-5848-8681; NM, 0000-0003-0219-6601

What makes the painful cries of human babies so difficult to ignore? Vocal traits known as 'nonlinear phenomena' are prime candidates. These acoustic irregularities are common in babies' cries and are typically associated with high levels of distress or pain. Despite the vital importance of cries for a baby's survival, how these nonlinear phenomena drive pain perception in adult listeners has not previously been systematically investigated. Here, by combining acoustic analyses of cries recorded in different contexts with playback experiments using natural and synthetic cries, we show that baby cries expressing acute pain are characterized by a pronounced presence of different nonlinear phenomena, and that these nonlinear phenomena drive pain evaluation by adult listeners. While adult listeners rated all cries presenting any of these nonlinear phenomena as expressing more pain, they were particularly sensitive to the presence of chaos. Our results thus show that nonlinear phenomena, especially chaos, encode pain information in baby cries and may be critically helpful for the development of vocal-based tools for monitoring babies' needs in the context of paediatric care.

This article is part of the theme issue 'Nonlinear phenomena in vertebrate vocalizations: mechanisms and communicative functions'.

1. Introduction

The cry of the human baby is a vital communication signal produced in contexts associated with hunger, discomfort or pain and is meant to attract the attention of caregivers [1]. Hence, decrypting the information encoded in babies' cries and understanding how this information is captured by caregivers have become key objectives for improving parent–baby relationships [2–9]. On one hand, babies' cries carry relatively stable information, linked to idiosyncratic traits of the emitter, such as their identity, age, weight and height. This 'static' information enables a given baby to be vocally identified by human caregivers, notably their parents [2–4]. On the other hand, cries also carry 'dynamic' information related to the current physiological and emotional state of the baby, informing caregivers about the baby's immediate level of needs [5]. While cries do not seem to carry any evident information about their specific cause [4], they yet remain particularly informative regarding the baby's level of distress or pain.

Previous studies have shown that adult listeners, particularly those highly experienced with babies' care, such as parents of young children, are able to assess the level of pain conveyed by a cry and accurately distinguish between discomfort and pain cries [5,6]. Indeed, in both human and non-human mammals, an individual's emotional state strongly affects the configuration of the vocal apparatus and the mechanisms of vocal production responsible for the acoustic characteristics of the emitted vocalizations. Increasing distress typically results in a stronger airflow through the larynx, leading to faster and possibly irregular and unstable vibrations of the vocal folds [10,11]. This configuration of the vocal apparatus is often associated with an increase in the fundamental frequency (f_o corresponding to the rate at which the vocal folds vibrate and the perceived pitch), intensity and duration of vocalizations [12,13], as well as the production of acoustic irregularities, known as nonlinear phenomena.

These nonlinear phenomena are commonly observed in the distress calls of infant mammals ([14–16]; Massenet *et al.*, this issue [17]), including those of human babies ([5,18], and also see figure 1 and electronic supplementary materials for audio examples). Specifically, cries of human babies can contain several types of nonlinear phenomena: (i) *frequency jumps*, corresponding to abrupt changes in vocal fold vibrations resulting in a sudden jump in f_o , as in the breaking voices of teenage boys [19]; (ii) *subharmonics*, often resulting from a period-doubling or tripling in the vocal fold vibration, visible as parallel spectral bands that are harmonically related to the f_o (e.g. appearing at half f_o) and responsible for lowering the perceived pitch of vocalizations [10,11,20]; (iii) *deterministic chaos* (hereafter chaos), corresponding to aperiodic, irregular vibration of the vocal folds, visible as 'noisy' sections in vocalizations, as in very rough roars [10]; (iv) *vocal fry*, corresponding to relatively slow, irregular glottal pulses where the vocal folds typically vibrate below 70 Hz, as in low-pitched creaky voices, visible as pulses on spectrograms [21–23]; (v) *amplitude modulation*, corresponding to the modulation of the laryngeal frequency f_o by a lower supralaryngeal frequency j_o, visible as spectral bands at m*f_o ± n*j_o (where m and n are integers; Massenet *et al.*, this issue [17]), creating vocal roughness as in Louis Armstrong's voice; and (vi) *vibrato*, corresponding to both frequency and amplitude modulations of the laryngeal f_o, as in the bleats of a goat [24,25]. Nonlinear phenomena, and especially chaos, are responsible for the perceived roughness and instability of vocal signals [26,27]. Among these various types of nonlinear phenomena, chaos is the most commonly observed type in the distress calls of infant mammals, such piglets [28], infant giant pandas [15], infant elephants [14], kittens [16], puppies (Massenet *et al.*, this issue [17]) or marmot pups [29].

While previous work showed that the acoustic 'roughness' of a baby's cry signals the level of pain [5,30], to the best of our knowledge, there is no previous empirical study that has explored which of the different types of nonlinear phenomena encode pain information and experimentally tested how these affect pain perception in adult listeners. Here, we fill this gap by combining acoustic analyses of cries recorded in painful and discomfort contexts with playback experiments where parents and non-parents assessed the level of pain conveyed by natural cries (*Experiment 1*) and highly realistic synthetic cries (*Experiment 2*) for which we controlled the type of nonlinear phenomena using state-of-the-art sound synthesis tools ([26,31–33], Valente *et al.*, this issue [34]).

At the emitter's end, we predict that pain cries would be characterized by a greater amount and diversity of nonlinear phenomena than discomfort cries. At the receiver end, we also predict that listeners' assessment of the pain carried by a cry would depend on the type of nonlinear phenomenon. Specifically, given that chaos is the most common type of nonlinear phenomenon observed in the vocalizations of highly distressed animals ([1,14,15,26,29]; Massenet *et al.*, this issue [17], Valente *et al.*, this issue [34]), we expect chaos to be the predominant nonlinear phenomenon, both for pain coding by the baby and for assessment by adult receivers. Finally, we predict that parents, owing to their experience of babies cries, are more inclined than nonparents to consider nonlinear phenomena in cries as vocal indicators of pain [6].

2. Methods

Our experimental protocol includes (i) the selection of 304 sequences of baby cries (durations of 6.3 ± 1.1 s) recorded in contexts of discomfort and pain, (ii) analysing nonlinear phenomena in these cries, (iii) creating synthetic cries with and without nonlinear phenomena, and (iv) conducting two online psychoacoustic experiments, each testing a total of 40 parents and 40 non-parents.

Participants were presented with natural sequences of discomfort and pain cries (*Experiment 1*), or synthetic sequences of cries containing or not containing nonlinear phenomena whose nature was controlled (*Experiment 2*). Participants were asked to rate the level of pain conveyed by each of the cries they heard.

(a) Cries selection

We selected babies' cry sequences from a database at the ENES Bioacoustics Research Laboratory (see [5] for details on the methods used for the cry recordings). This database includes discomfort cries recorded during bathing, undressing or dressing the baby, and pain cries recorded during a scheduled routine vaccination in which each baby received two vaccine injections (n = 24 babies, 11 boys and 13 girls; age = 60.3 ± 3.3 days on the vaccination day; delay between recording sessions of discomfort and pain cries for a given baby = 6.8 ± 3.3 days). Pain cries refer to two types of cries: acute pain cries emitted at the vaccine injection and residual pain cries emitted around 6 s after the injection (as described in [5]).

Using Audacity open-source software (https://www.audacityteam.org/), we carefully inspected these recordings and extracted 304 cry sequences (of lengths 6.3 ± 1.1 s) that contained a low level of background noise, i.e. no overlapping voices, dripping water or slamming doors. These 304 sequences were distributed as follows: 210 sequences of discomfort cries (2–19

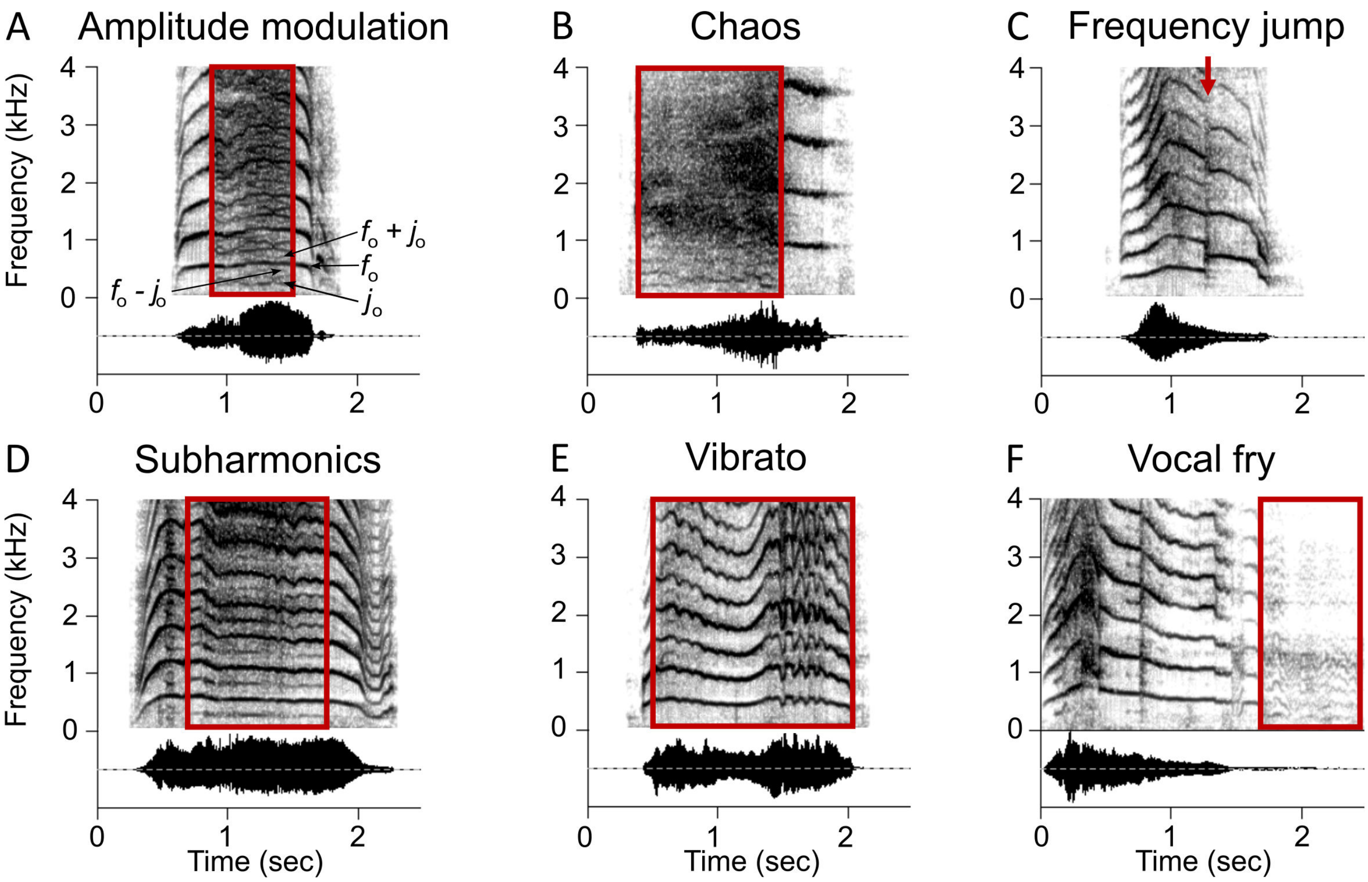

Figure 1. Nonlinear phenomena in babies' cries. The nonlinear phenomena present in natural baby cries are of six different types: amplitude modulation (A), chaos (B), frequency jump (C), subharmonics (D), vibrato (E) and vocal fry (F). The moment of the cry characterized by a nonlinear phenomenon is marked with a rectangle or arrow on each spectrogram.

sequences/baby), 46 sequences of residual pain cries (1–2 sequences/baby) and 48 sequences of acute pain cries (2 sequences/baby).

(b) Acoustic analyses

We quantified the presence of nonlinear phenomena in each of the 304 selected cry sequences, and then compared the nature and quantity of these nonlinear phenomena between the different conditions (discomfort, acute pain, residual pain). We characterized the presence of nonlinear phenomena, namely frequency jumps, chaos, vocal fry, subharmonics, amplitude modulation and vibrato, by visually inspecting and annotating spectrograms provided by Praat software (frequency range 0.2–10 kHz and window length 0.05–0.08 s [35]).

Specifically, within each of the 304 cry sequences, we identified between 1 and 12 cry syllables, a syllable being defined as a vocal utterance produced during a single exhalation and separated from the other syllables by silences [36]. For each syllable of each cry sequence, we measured the occurrence and proportion relative to the total syllable duration of each of the nonlinear phenomena. As frequency jumps correspond to sudden changes in the fundamental frequency, there is no duration associated with these events and we only measured their occurrence.

(c) Natural and synthetic cry stimuli

To test whether the presence of nonlinear phenomena in babies' cries modulates pain perception by adult listeners, we prepared sound stimuli for two psychoacoustic acoustic experiments.

In *Experiment 1*, these stimuli corresponded to unmodified natural cry sequences, with amplitudes normalized to 100% of the maximal amplitude ('normalize' function of tuneR package; https://cran.r-project.org/web/packages/tuneR/index.html). In *Experiment 2*, we aimed to test the perceptual effects of nonlinear phenomena, independently of any other acoustic features. To achieve this, we used highly realistic synthetic cry stimuli with or without nonlinear phenomena. Specifically, to create these synthetic stimuli, we first selected 10 sequences of discomfort cries produced by 10 different babies (5 boys, 5 girls), with an average f_0 that fell within the observed natural distribution to limit strong inter-individual variation in cry f_0 and its possible effect on pain ratings (electronic supplementary material, figure S1). We then used the selected natural cry sequences as templates to create their fully synthetic copies without nonlinear phenomena (= synthetic cry prototypes) with the R package Soundgen [31]). Finally, we derived these synthetic cry prototypes into variants containing the different types of nonlinear phenomena. We did not consider adding vocal fry to cry prototypes because our acoustic analyses revealed that its presence does not considerably vary between discomfort and pain cries (figure 2A) and playbacks of natural cry sequences showed that this phenomenon is not strongly correlated with listeners' rating of pain (*Experiment 1*, see figure 2B). The timing of insertion and the proportion of nonlinear phenomena affecting the synthetic cries were informed by our acoustic analyses. Thus, we synthesized naturalistic variants, i.e. with acoustic characteristics in terms of nonlinear phenomena that remained within the range of variation of natural cries. In total, we created 60 stimuli for *Experiment 2*: 10 prototypes x 6 conditions (no nonlinear phenomenon, chaos, frequency jump, amplitude modulation, subharmonics and vibrato; figure 3A,B). All the sound stimuli used for *Experiments 1* and *2*, as well as R codes used to synthesize the stimuli, are available at [37].

(d) Psychoacoustic experiments

The two online psychoacoustic experiments involved a total of 160 participants (n = 80 listeners aged 32.3 ± 5.7 years old (range 23-43) in *Experiment 1*; n = 80 listeners aged 31.0 ± 6.9 years old (range 19-49) in *Experiment 2*). Via the online platform Prolific (https://www.prolific.com/), we recruited 40 parents and 40 non-parents for each experiment, distributed equally between the sexes (40 men, 40 women). When parents participated to the experiments, they had at least one child under the age of 2 (mean child age = 11.6 ± 5.9 months in *Experiment 1*, 9.0 ± 5.4 months in *Experiment 2*). The recruited non-parent participants had no experience of caring for babies. We excluded paediatric care professionals such as nannies, midwives and paediatricians, as well as people who occasionally babysat or were in contact with a baby in their close circle. All participants reported having normal hearing.

Once recruited on the Prolific platform, participants were directed to the LabVanced online platform ([38], https://www.labvanced.com/) where the playback experiments were conducted. Before starting an experiment, participants were asked to complete a short questionnaire about their age, sex and experience with babies. Participants were asked to take part in the experiment in a quiet room, with headphones, and with a sound volume set at a high but still comfortable level.

In each of the two playback experiments, participants were presented with a total of 60 sequences of natural or synthetic cries. Specifically, in *Experiment 1*, we exposed participants to natural cry sequences randomly selected from three conditions (discomfort, acute pain, residual pain). For each participant, 20 cry sequences from 20 different babies were selected for each condition. In *Experiment 2*, participants were exposed to sequences of synthetic cry, chosen at random from six conditions: no nonlinear phenomena, chaos, frequency jump, amplitude modulation, subharmonics, vibrato (each condition balanced across synthetic cry prototypes).

After each cry exposure, participants were asked to rate the level of pain that they perceived pain in the cries by answering the question 'How does this baby feel?' with a continuous scale ranging from 0 (no pain and no distress) to 100 (worst pain imaginable). A 'pain threshold' at 40/100, as used in studies on pain neurophysiology [39,40], was also indicated visually by adding a mark to the scale. Participants were neither informed about the type of cry (discomfort, residual pain, acute pain cries in *Experiment 1*; condition type in *Experiment 2*), nor the cry quality (natural or synthetic). After completion of the experiment, participants were paid at the recommended rate of £8.00 (GBP) per hour.

(e) Statistical analysis

We performed statistical analyses using Bayesian mixed models fitted with the brms R package ([41], R (v.4.2.2)). The advantages of using the Bayesian approach are manifold, including its high flexibility, quantification of uncertainty in estimates, use of priors for regularization, intuitive interpretation of confidence intervals and ability to handle unbalanced datasets and complex models [41–43].

Our first aim was to test whether the context of crying and the presence of nonlinear phenomena are correlated. We first ran a statistical model including the presence of any nonlinear phenomena (i.e. independently from the nonlinear phenomena type, absence/presence coded as 0/1) as a response variable modelled by a logistic function (Bernouilli family), and the crying context (discomfort, residual pain, acute pain) as a fixed factor. We then ran another similar model, adding the type of nonlinear phenomena (i.e. amplitude modulation, chaos, frequency jumps, subharmonics, vibrato and vocal fry) as fixed factor. We then built additional models to investigate how the proportion of non-discrete nonlinear phenomena (chaos, vocal fry, amplitude modulation, subharmonics and vibrato) and the number of discrete frequency jump events vary in cries with zero-one-inflated beta and zero-inflated Poisson distributions, respectively [44]. Finally, in a last model, we used lognormal distribution to investigate whether the duration of pain cries differ from discomfort cries. All models examining acoustic data also included the baby's identity as random factor.

Our second aim was to test whether the presence of nonlinear phenomena drives how adult listeners rate the pain expressed by babies' cries. We built two independent statistical models, the first using pain ratings of natural cry sequences (*Experiment 1*) and the second using pain ratings of synthetic cry sequences (*Experiment 2*). In each of the two models, response variables were the ratings (expressed as percentages) recoded from 0 to 1 to model our data as a zero-one-inflated beta distribution. These models included parental status (parent or non-parent) and the condition (no nonlinear phenomena and all nonlinear phenomena types except vocal fry for the second model) as fixed factors. The identity of the participant and the identity of the baby (i.e. the origin of the stimulus) were included as random factors.

All models were fitted with mildly informative conservative priors. Four thousand iterations were run over four MCMC chains (Markov Chain Monte Carlo), the first 500 of each chain being used to adjust the algorithm. Convergence was checked [41] and achieved for every model. Model predictions expressed from 0 to 1 were reconverted into percentages for an easier interpretation of our results. We summarized our results with the medians of the posterior distributions and their 95% credible

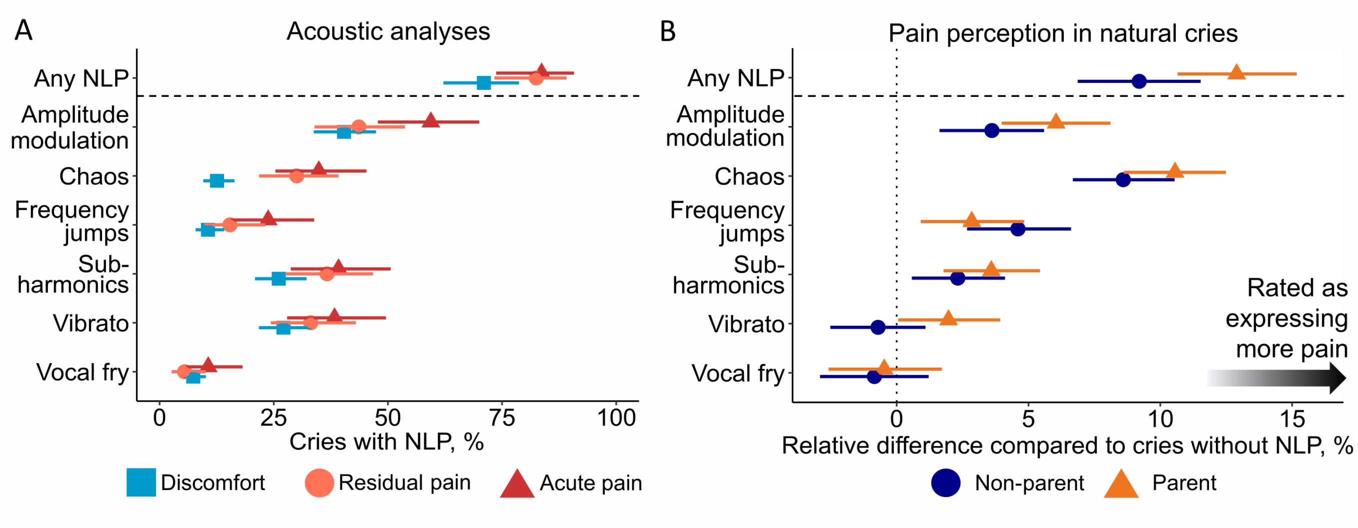

Figure 2. Nonlinear phenomena as markers of pain expressed by babies' cries. (A) Proportion of cries presenting nonlinear phenomena as a function of the recording context (blue square: discomfort; orange circle: residual pain; red triangle: acute pain). Any NLP: any type and combination of nonlinear phenomena. (B). Pain perception by adult listeners as a function of the type of nonlinear phenomenon present in natural cries. The graph illustrates the differences in pain perception between cries containing different types of nonlinear phenomena and cries without nonlinear phenomena. Listeners were either non-parents (blue circle) or parents (orange triangle). Solid markers represent medians of posteriors distributions, with bars indicating the 95% credible intervals (CIs). NLP = Nonlinear phenomena.

intervals (CIs). CIs contain the parameter values of highest probability and span the 95% most probable value. CIs for estimates that do not include zero (or any threshold value of interest) indicate a credible effect given the observed data and model structure. In the same way, distribution of posteriors value over a given threshold can be quantified and indicate a credible difference when more than 97.5% of the posteriors are over the threshold value. When contrasting two conditions, CIs of this difference excluding the null value (i.e. only positive values or only negative values within the CI) indicate a credible difference between the conditions [43]. We present either the median and CIs of parameter values (figure 2A) or contrasts between two conditions (figures 2B and 3C, differences between cries with and without nonlinear phenomena).

3. Results

(a) Pain cries are longer and characterized by nonlinear phenomena

From the 304 cry sequences, we identified a total of 1085 cry syllables distributed as follows: 831 of discomfort, 148 of residual pain and 106 of acute pain. The duration of these syllables increases with the level of pain expressed by the baby. Specifically, cry syllables of acute pain cries lasted 2.1 s [1.7, 2.7] (median and 95% CI), and were longer by 0.62 s [0.29, 1.01] and 0.86 s [0.55, 1.24] than residual pain cry syllables (1.5 s [1.2, 1.9]) and discomfort cry syllables (1.3 s [1.0, 1.5]), respectively. Residual pain cry syllables were also 0.24 s [0.06, 0.45] longer than discomfort cry syllables.

We observed nonlinear phenomena in the majority of syllables of all cry types: 71.0% [62.1, 78.7] of discomfort cries, 82.5% [73.3, 89.1] of residual pain cries, 83.7% [73.7, 90.8] of acute pain cries. However, nonlinear phenomena were more present in residual pain cries and acute pain cries compared with discomfort cries (+11.3% [4.1, 18.6] and +12.5% [4.3, 20.5] respectively; these CIs excluding the null value correspond to a credible difference between the conditions; see table 1 for details). Specifically, when comparing with the presence of nonlinear phenomena in discomfort cries, chaos and subharmonics were more present in residual and acute pain cries. Frequency jumps, amplitude modulation and vibrato were more present in acute pain cries but not in residual pain cries, compared with discomfort cries. Acute pain cries were also characterized by an increased presence of amplitude modulation compared with residual pain cries (figure 2A; see table 1 for details of model data and electronic supplementary material, table S1 for raw data). Finally, we found only marginal or no variation in the duration of episodes of nonlinear phenomena between the three types of cries (see electronic supplementary material, table S2).

Together, our results suggest that, the mere presence of nonlinear phenomena, rather than their duration, is positively correlated with the pain expressed by the baby. Residual pain cries are predominantly characterized by chaos, subharmonics and amplitude modulation, whereas acute pain cries exhibit various types of nonlinear phenomena (except vocal fry).

(b) Nonlinear phenomena drive the perception of babies' pain in adult listeners

In *Experiment 1*, we played natural cries with and without nonlinear phenomena to parents and non-parents. Our results show that natural cries without nonlinear phenomena led to a pain rating of 33.7% (95% CI [30.3, 37.4]) on a perceptual scale ranging from 0 to 100%. This score was statistically below the pain threshold of 40% specified to the listeners (99.9% of the posterior distribution below the 40% threshold), suggesting that they perceived cries without nonlinear phenomena as expressing relatively low pain levels. In contrast, listeners rated natural cries with any combination of nonlinear phenomena

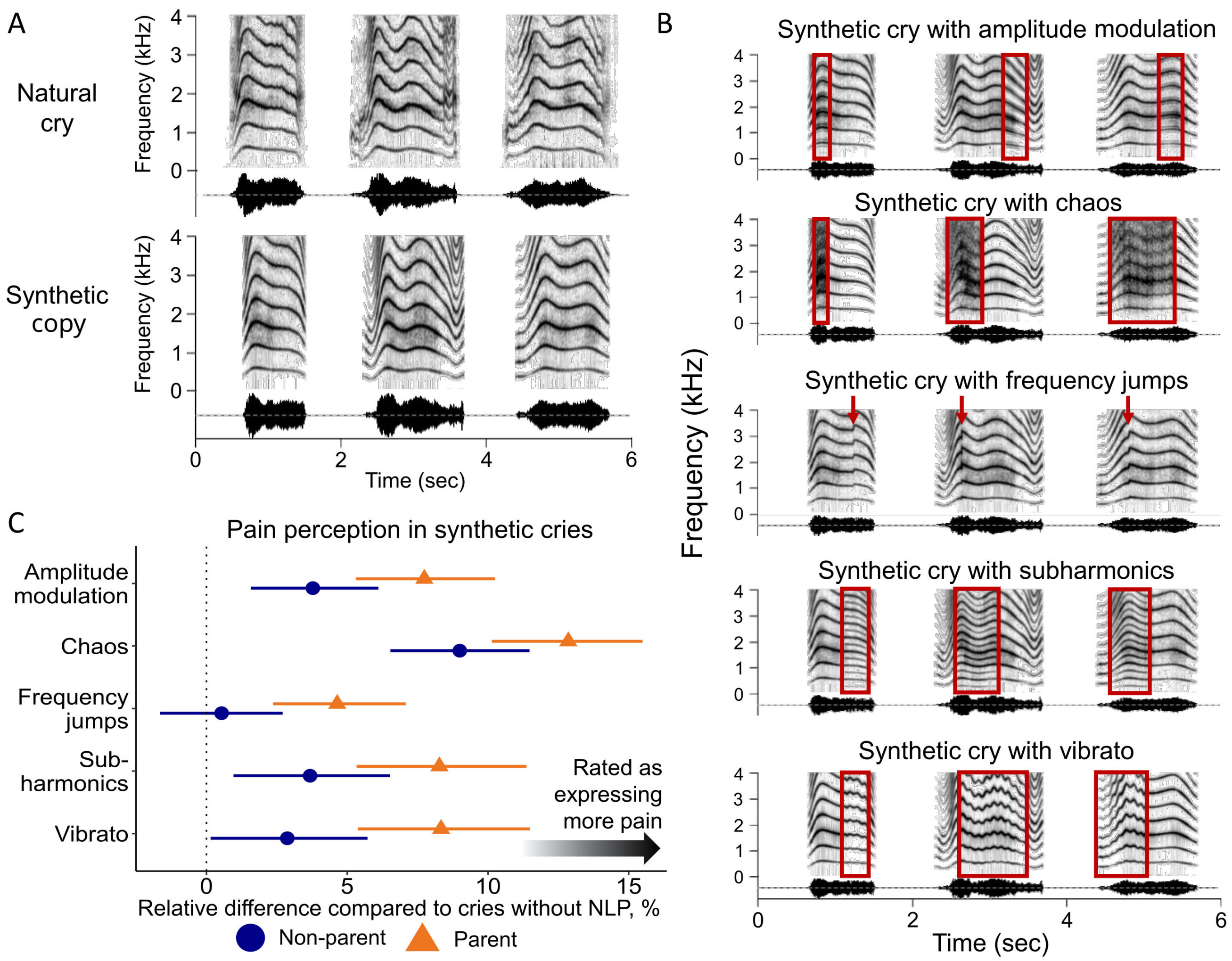

Figure 3. Nonlinear phenomena drive pain assessment by adult listeners. (A) Top: Example of a natural discomfort cry without nonlinear phenomena. Bottom: Synthetic copy of this natural cry. The synthetic copies of natural cries are used in *Experiment 2* as control stimuli (synthetic cries without nonlinear acoustic phenomena) and as prototypes for the synthesis of stimuli with nonlinear phenomena. (B) Variants of a prototype synthetic cry to which different types of nonlinear phenomena have been added (from top to bottom: amplitude modulation, chaos, frequency jumps, subharmonics and vibrato). (C) Results of *Experiment 2* (listening to synthetic cries). Nonlinear phenomena modulate the perception of pain by non-parents (blue circles) and parents (orange triangles). Overall, parents are more sensitive to nonlinear phenomena than non-parents. Solid shapes represent the medians of the posterior distributions, with bars indicating the 95% CIs. NLP = Nonlinear phenomena.

Table 1. Pairwise comparisons of nonlinear acoustic phenomena presence across the three types of cries (i.e. discomfort, residual pain and acute pain cries). Results are summarized by the median of the posterior distributions and their 95% credible interval. NLP = nonlinear phenomena. Values in bold correspond to comparisons for which more than 97.5% of the posteriors are positive and indicate a credible difference in the presence of nonlinear phenomena between two types of cries.

nonlinear phenomena presence	residual pain vs discomfort	acute pain vs discomfort	acute pain vs residual pain
any NLP	**11.3 [4.1, 18.6]**	**12.5 [4.3, 20.5]**	1.1 [−8.2, 10.4]
amplitude modulation	3.3 [−5.5, 12.3]	**18.9 [8.5, 28.8]**	**15.6 [2.8, 28.1]**
chaos	**17.4 [10.2, 25.3]**	**22.2 [13.8, 31.4]**	4.8 [−5.8, 15.7]
frequency jump	4.8 [−0.8, 12.0]	**13.1 [5.2, 22.4]**	8.2 [−1.5, 18.6]
subharmonics	**10.5 [2.2, 19.5]**	**13.1 [3.4, 23.3]**	2.5 [−9.8, 14.7]
vibrato	6.0 [−2.1, 14.7]	**11.1 [1.5, 21.2]**	5.1 −7.0, 17.3]
vocal fry	−1.9 [−5.3, 2.6]	3.3 [−1.7, 10.4]	5.1 [−1.1, 12.7]

as expressing pain above the 40% threshold (average rating across all nonlinear phenomena 44.8% [41.2, 48.4], 99.5% of the posterior distribution was above the 40% threshold), which was statistically higher than for cries without nonlinear phenomena (11.1% higher, 95% CI [9.4, 12.8], 100% of the posterior distribution of the difference was positive). Specifically, both parents and non-parents rated natural cries with chaos, frequency jumps, subharmonics or amplitude modulation as expressing more pain. They indeed attributed higher scores to cries with nonlinear phenomena compared with cries without nonlinear phenomena (cries with chaos: 9.6% [8.1, 11.0], frequency jumps: 3.7 % [2.3, 5.2], subharmonics: 3.0% [1.6, 4.3], amplitude modulation: 4.8%

[3.3, 6.4]; coefficients averaged between parents and non-parents; figure 2B see table 2 for model data; electronic supplementary material, figure S2, table S3 for raw data). Furthermore, our results suggest that parents tend to show greater sensitivity to cries with nonlinear phenomena than do non-parents, especially for cries with vibrato (table 2).

Experiment 2, which was carried out with synthetic cries, clarifies the effect of nonlinear phenomena on the perception of pain expressed by babies' cries. In line with the results of *Experiment 1*, synthetic cries without nonlinear phenomena were rated as expressing little pain (median pain rating = 30.8% [23.1, 39.1]). In contrast, synthetic cries with nonlinear phenomena were rated as expressing greater pain level (median pain rating = 37.0% [28.5, 45.8]), confirming that nonlinear phenomena are indeed responsible for the perception of pain expressed by cries. While this perceptual effect is observed in all listeners, parents are more sensitive to nonlinear phenomena than non-parents when assessing pain in synthetic cries (table 3). In parents, the experimental addition of any type of nonlinear phenomenon increased pain perception compared with cries without nonlinear phenomena in parents (figure 3C and table 3 for model data details on the perceptual effects of each type of nonlinear phenomena; electronic supplementary material, figure S3, table S4 for raw data)—the addition of chaos causing the strongest perceptual effect (perceived pain increased by +12.9% [10.1, 15.5]). In non-parents, similar perceptual effects were observed in non-parents, but to lesser extent: for them, the presence of frequency jumps in cries did not affect perception of pain (0.5% [–1.6, 2.7]; table 3).

4. Discussion

By combining acoustic analysis of natural signals and playback experiments with natural and artificial stimuli, the present study clarifies how nonlinear phenomena encode pain in babies' cries. Our analyses show that various types of nonlinear phenomena are frequent in babies' cries, and that their presence is more pronounced when cries are recorded in a painful context. Our playback experiments show that adult listeners—both parents and non-parents—argely rely on the presence and nature of nonlinear phenomena in cries to assess the level of pain expressed by the baby.

Pain cries, whether acute (i.e. at the time of a vaccine injection) or residual (i.e. a few seconds after the vaccine injection), more often contain episodes of chaos and subharmonics than cries recorded in a situation of discomfort (e.g. at the time of the baby's bath). Cries indicating acute pain are also more likely to contain episodes of amplitude modulation, vibrato and frequency jumps than other cries (residual pain cries and discomfort cries). In contrast, vocal fry, which occurs less in cries compared with the other types of nonlinear phenomena, does not considerably vary with the baby's level of discomfort or pain. Taken together, the diversity of these nonlinear phenomena therefore contributes to make the baby's cry a graded signal, expressing the baby's distress according to a continuous variation. Such gradation of pain encoded by nonlinear phenomena is also found in vocalizations emitted during the different phases of epidural-free childbirth, where women produced more chaos and amplitude modulation during the final stages of labour [34]. The variability in the type of nonlinear phenomena in pain cries can probably be explained by the physiological modulations that a baby undergoes during a pain episode, with activation of the autonomic nervous system and a decrease of the vagal tone [45]. This results in increased subglottal pressure, laryngeal constriction, and increased tension in the vocal folds, a vocal configuration often associated with irregular or asynchronous vibration of the vocal folds from which nonlinear phenomena derive [11,46].

Importantly, and echoing the increased presence of nonlinear phenomena in pain cries, both parents and nonparents rated natural cries with nonlinear phenomena as expressing more pain compared with natural cries without nonlinear phenomena. Particularly, chaos, which is key acoustic feature of pain cries, is also the nonlinear phenomenon associated with the greatest perceived pain in natural cries. In contrast, the occurrence of vocal fry, which does not considerably vary across all types of cries, is not associated with an increase in listeners' ratings of pain. In the same way, vibrato episodes show the smallest difference in presence between pain and non-pain cries, and is linked to an increased pain perception as observed in parents only. While the results of our acoustic analyses and first playback experiment suggest that nonlinear phenomena are strong candidates to signal pain via babies' cries, this is further confirmed by our second playback experiment, in which we used synthetic cries. Indeed, the use of synthetic cries eliminates any confounding effect that might be caused by any acoustic feature other than a nonlinear phenomenon. By independently adding each type of nonlinear phenomenon to synthetic copies of natural cries, and comparing pain ratings between these stimuli, we demonstrate that the presence of nonlinear phenomena increases pain ratings by adult listeners. As with natural cries, the results of our playback experiments with synthetic cries show that chaos is responsible for the strongest perceptual effect of pain.

In both playback experiments, parents and non-parents were highly sensitive to the presence of nonlinear phenomena when rating the level of pain conveyed by cries. Specifically, both parents and non-parents judged cries with chaos, and to a lesser extent, those with amplitude modulation, subharmonics and vibrato, as expressing more pain than cries without nonlinear phenomena. While this result indicates that parenthood is not a prerequisite for being able to use nonlinear phenomena to assess pain level, in a previous study, we also showed that the ability to identify a pain or discomfort cry from a familiar or unfamiliar baby is highly correlated with the listener's level of prior experience with babies [6]. In the experiments we report here, non-parents showed some ability at identifying pain in cries with nonlinear phenomena, but parents tended to rate the same cries as expressing more pain, thus suggesting that baby caring experience may strengthen the effect of nonlinear phenomena on perceived pain.

While our experiments demonstrate that the presence of nonlinear phenomena in baby cries drives pain ratings in adult listeners, we cannot rule out the possibility that, in real-life conditions with natural cries, other acoustic features, such as f_o, duration of cry syllable or sound intensity, may also modulate this rating. Interactions between these acoustic features and nonlinear phenomena might also change perception. In addition, non-parents may be particularly sensitive to these other

Table 2. Comparison between pain levels estimated by adult listeners listening to natural cries without nonlinear phenomena and natural cries with nonlinear phenomena. Results are summarized by the median of the posterior distributions and their 95% credible interval. NLP = nonlinear phenomena. Values in italic correspond to comparisons for which 95 to 97.5% of the posteriors are positive and indicate a tendency of higher pain estimation in parents compared with non-parents. Values in bold correspond to comparisons for which more than 97.5% of the posteriors are positive and indicate a credible difference.

comparisons with natural cries without nonlinear phenomena	rating by all participants	rating by parents	ratings by non-parents	difference between parents and non-parents
cries with any combination of NLP types	**11.1 [9.4, 12.8]**	**12.9 [10.7, 15.2]**	**9.2 [6.9, 11.5]**	**3.7 [0.6, 6.7]**
cries with amplitude modulation	**4.8 [3.3, 6.4]**	**6.0 [4.0, 8.1]**	**3.6 [1.6, 5.6]**	*2.4 [−0.2, 5.1]*
cries with chaos	**9.6 [8.1, 11.0]**	**10.6 [8.6, 12.5]**	**8.6 [6.7, 10.5]**	2.0 [−0.6, 4.5]
cries with frequency jumps	**3.7 [2.3, 5.3]**	**2.8 [0.9, 4.8]**	**4.6 [2.7, 6.6]**	−1.8 [−4.3, 0.7]
cries with subharmonics	**3.0 [1.6, 4.3]**	**3.6 [1.8, 5.4]**	**2.3 [0.6, 4.1]**	1.3 [−1.1, 3.7]
cries with vibrato	0.6 [−0.8, 2.0]	**2.0 [0.1, 3.9]**	−0.7 [−2.5, 1.1]	**2.7 [0.3, 5.1]**
cries with vocal fry	−0.7 [−2.3, 1.0]	−0.5 [−2.6, 1.7]	−0.8 [−2.9, 1.2]	0.4 [−2.3, 3.1]

Table 3. Comparison between pain levels estimated by adult listeners listening to synthetic cries without nonlinear phenomena and synthetic cries with nonlinear phenomena. Results are summarized by the median of the posterior distributions and their 95% credible interval. Values in bold correspond to comparisons for which more than 97.5% of the posteriors are positive and indicate a credible difference.

comparison with synthetic cries without nonlinear phenomena	rating by all participants	rating by parents	rating by non-parents	difference between parents and non-parents
synthetic cries with amplitude modulation	**5.8 [4.0, 7.5]**	**7.7 [5.3, 10.3]**	**3.7 [1.0, 6.5]**	**4.0 [0.7, 7.2]**
synthetic cries with chaos	**10.9 [8.9, 12.9]**	**12.9 [10.1, 15.5]**	**9.0 [6.5, 11.5]**	**3.8 [0.5, 7.2]**
synthetic cries with frequency jump	**2.6 [1.0, 4.3]**	**4.6 [2.4, 7.1]**	0.5 [−1.6, 2.7]	**4.1 [0.9, 7.4]**
synthetic cries with subharmonics	**6.0 [3.9, 8.2]**	**8.3 [5.3, 11.4]**	**3.8 [1.6, 6.1]**	**4.6 [0.6, 8.6]**
synthetic cries with vibrato	**5.6 [3.6, 7.7]**	**8.3 [5.4, 11.5]**	**2.9 [0.1, 5.7]**	**5.4 [1.4, 9.6]**

acoustic properties, such as the f_o of cries or their duration. Indeed, as these parameters are controlled in synthetic cries and do not vary among variants (cries with versus without nonlinear phenomena), this may explain why synthetic cries are less likely to evoke pain for non-parents compared with natural cries. Future work could systematically test this hypothesis by replicating our experiment using synthetic cries in which the cry's f_o or duration vary, as these two acoustic features have also been demonstrated to affect perceived distress [33,47].

Furthermore, the cries of acute pain considered here were recorded during a simple vaccination and therefore probably do not correspond to the maximum pain that a baby can feel. They therefore represent only a subspace of the 'acoustic space of pain' that can be expressed by babies' cries [5,48]. We can hypothesize that the expression of extreme pain by a baby's cry may combine several acoustic features, such as nonlinear phenomena, strong modulations of f_o, and the duration of the cry syllables.

In humans, nonlinear phenomena are also present in nonverbal vocalizations of adults. More specifically, their presence is common in sounds emitted in negative contexts with high arousal, like screams [32,49]. Recent studies have also demonstrated that nonlinear phenomena affect pain perception in volitional nonverbal vocalizations expressing different levels of pain produced by actors [50] or in vocalizations emitted during the different phases of epidural-free childbirth [34]. While nonlinear phenomena are key features for the communication of distress and pain in human babies and adults, these features are also common in the distress calls of non-human infant mammals ([14–16,51]. Yet, whether the function of nonlinear phenomena in communicating distress is potentially shared across mammals remains to be clarified as only few studies have so far systematically tested the effect of nonlinear phenomena on distress perception in the vocalizations of non-human animals. For example, Massenet and colleagues [17] showed that nonlinear phenomena, and particularly chaos, characterize the whines of domestic dog puppies, and that experimentally adding chaos to synthetic whines increases perceived distress as judged by both experienced and non-experienced human listeners in puppy caregiving (such as breeders or veterinarians) [33]. Note that here too, experience counts: only experienced listeners were sensitive to whines in which authors added amplitude modulation and subharmonics [33]. Finally, the interspecific function of nonlinear phenomena for distress vocal communication may extend even to taxa that are phylogenetically distant from mammals. A recent study has shown experimentally that adult Nile crocodiles are attracted by the cries of baby hominids (bonobo, chimpanzee and human), and that the intensity of the crocodiles' response depends mainly on nonlinear phenomena, in particular chaos [52].

By demonstrating the importance of various nonlinear phenomena as markers of pain in the cries of human babies, the present study makes an important contribution to our understanding of this communication signal. Various avenues of investigation now lie ahead. A first objective will be to gain a more global understanding of the acoustic space of pain encoded by infant cries, by considering more critical situations than a simple vaccination session, such as when babies have to receive care known to be painful at the hospital. Indeed, accurate assessment of pain in newborns, both premature and full-term, remains a challenge even today [53]. A second objective will be to continue exploring the variability of pain expression between different babies. In recent work, we have shown that the idiosyncratic characteristics of cries (the 'vocal signature' specific to each baby) are less prominent in pain cries than in discomfort cries [9]. This result indicates that intense pain causes the cries of different babies to converge in a constricted acoustic space. This convergence of cries owing to pain could open up possibilities for the implementation of automated pain detection systems in hospital settings. A third objective will be to characterize the ontogeny of pain coding in the first weeks of life. How do changes in the vocal apparatus accompanying infant growth translate into the production of nonlinear acoustic phenomena? We know that vocal signatures drift predictively with age [4], but are nonlinear phenomena reliable indicators of pain in babies of all ages? While this may be the case, longitudinal investigations on this topic are still lacking. A final objective relates more specifically to listeners. Although we have considered various nonlinear phenomena in the present study, we have only tested a small number of experimental signals. Among other possibilities, it would be interesting, for example, to test how adult listeners react to different combinations of nonlinear phenomena. It is indeed possible that some of these phenomena have a potentiating effect on others (e.g. the presence of vibrato, which is not very effective on its own, perhaps reinforces the perception of pain in a cry with chaos). In this respect, modern methods for analysing and synthesizing sound signals, such as those used in the present study, will be indispensable tools for exploring the coding of pain information in babies' cries, as well as for exploring the decoding of this information by caregivers.

5. Conclusions

Here, we tested whether nonlinear phenomena encode pain in babies' cries, and found that baby cries expressing acute pain are characterized by a pronounced presence of nonlinear phenomena, and that these nonlinear phenomena drive pain evaluation by adult listeners. While adult listeners rated all cries presenting any of nonlinear phenomena as expressing more pain, they were particularly sensitive to the presence of chaos. Our results thus show that nonlinear phenomena, especially chaos, encode pain information in baby cries and may be critically helpful for the development of vocal-based tools for monitoring babies' needs in the context of paediatric care.

Ethics. The local ethics committee approved the experiment (October 2019 Comite d'Ethique du CHU de Saint-Etienne, Institutional Review Board: IORG0007394), and informed consent was obtained from all participants.

Data accessibility. The natural and synthetic cries, the R codes to create the synthetic cries, the acoustic and playback datasets and the R code for analyzing data can be downloaded from https://osf.io/4yexz/

Supplementary material is available online [54]

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. S.C.: conceptualization, data curation, formal analysis, investigation, methodology, writing—original draft; M.M.: conceptualization, investigation, methodology, writing—original draft; A.H.: investigation, methodology; H.P.: funding acquisition, resources; R.P.: funding acquisition; C.F.: conceptualization, funding acquisition, methodology, writing—review and editing; N.M.: conceptualization, funding acquisition, methodology, project administration, writing—original draft.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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