

Effects of pain on vowel production – Towards a new way of pain-level estimation based on acoustic speech-signal analyses

M. Salinas Ranneberg¹, O. Niebuhr², M. Kunz³, S. Lautenbacher¹, & P. Barbosa⁴

¹*Physiological Psychology, University of Bamberg, Germany*

²*Mads Clausen Institute, Technology Entrepreneurship and Innovation, University of Southern Denmark*

³*Faculty of Medical Sciences, University of Groningen, The Netherlands*

⁴*Instituto de Estudos da Linguagem/Unicamp, Campinas University, Brazil*

Abstract

The estimation of pain levels of patients requiring medical treatment is critical to successful pain management interventions, the dosing of drugs, and the selection of appropriate therapeutic measures. Current estimation methods are based on given sets of words like WILDA or stepped rating scales like the Wong-Baker faces. It is debatable whether such methods are targeted and fine-grained enough, and whether they can be consistently applied by patients, particularly across the different cultures and languages of a modern globalized society. Addressing these issues, we present an initial step into a line of research whose long-term goal is to automatically detect and measure – at a new level of detail and with ubiquitous technical devices – a patient's pain level from changes in the acoustic source and filter characteristics of the speech signal. Our first study focused on prosodic source characteristics and was based on 50 German speakers who immersed their hands in water tanks with temperatures from 41° to 47 °C. A multi-parametric acoustic analysis of sustained vowel productions showed an increase of mean F0 and mean acoustic-energy level for the painful 47 °C condition, particularly in those vowels that are associated with stereotypical pain groaning. Moreover, inspections of the acoustic data beyond the measured parameters suggest that the scope of our analysis is worth being extended in future studies to include voice-quality and formant parameters. Our research has the potential to create new opportunities in electrical engineering and provides a basis for developing various applications in healthcare and welfare technology.

Introduction

Vocalization is a regular accompaniment of pain; with utterances like screaming, mumbling, moaning, groaning and crying being believed to be pain-indicative. Such non-verbal utterances are in the focus of clinical interest when so-called non-verbal individuals (e.g., infants or patients with dementia or delirium) are under study [1,3,4,5,16]. However, these non-verbal utterances are yet merely subjectively rated on observer scales but not phonetically analyzed. Thus, no objective acoustic-phonetic characteristics like loudness and pitch have been tested whether they qualify for detecting and grading pain in adults. This is surprising, considering the recent interest to find objective “pain signatures” on the basis of physiological parameters obtained by clinically less applicable methods like brain imaging or advanced EEG, cf. [2]. This neglect of phonetic characterizations of pain vocalizations is even more surprising given the promising approaches to phonetically characterized utter-

ances of emotions and stress [6,10,11,17,18]. Primarily based on the two fundamental phonetic parameters loudness and pitch, some emotional states as well as stress types have been found to be accompanied by characteristic vocalization patterns. Therefore, one might expect similar state-indicative patterns to show up in the realm of pain as well.

The aim of the present study was to investigate the phonetic characteristics of vocalizations during pain in adults. Whereas previous studies focused on pain vocalizations in newborns (e.g., [8]), we focused on adult vocalizations because our clinical background was the study of pain in non-verbal seniors (e.g., with dementia). The relationship between vocalization, pain sensitivity and underlying noxious agents due to injury or disease often remains unclear. Such ambiguities can be prevented by experimental methods. However, in order to reliably trigger spontaneous pain-related vocalizations, very strong pain intensities would be necessary, which are unethical to create and apply in a lab experiment. Thus, for a first attempt to investigate the phonetic effects of pain, we trained individuals to reliably produce sustained vowels on command. The vowels were selected such that they either do or do not represent approximations to stereotypical forms of moaning and groaning. The vowels were analyzed for phonetic changes in pitch and loudness caused by experimental pain.

Methods

Subjects and design

Vocalizations of 50 students at the University of Bamberg (50% female; mean age: 22.5 years, SD 3.0 years, all German native speakers), were tested for changes in the sustained production of isolated vowels. Four different German vowel phonemes were used, i.e. /a/, /u/, /i/, and /ə/ (central "schwa" vowel, i.e. a darker "e" as in hesitations like "er", and "ehm"), and realized by the 50 experimental participants in individually randomized orders while their hands were immersed in water tanks for 20 seconds with temperatures ranging in 4 ascending steps from 41 to 47°C. The temperature range was chosen with reference to previous empirical pain studies to lead from clearly non-painful to noticeably (but still only moderately) painful sensations. Ethical approval was given by the local committee; participants gave written informed consent.

Phonetic preparation and recording

Participants were trained before testing to evenly produce and hold the target vowel qualities for a 10-second duration. The training was conducted based on videos developed by the experimenter (1st author, a licensed speech therapist) and

served to reduce intra- and inter-individual variability and, thus, decrease error variance. The participants' vocalizations were recorded digitally by a pressure zone microphone (Bayerdynamik, model MPC 50) and transmitted via a USB interface to a PC for storage. The signal resolution was 48 kHz, 24-bit.

Regarding the subsequent acoustic analysis of the recorded signals, phonetic parametrizations were accomplished by means of the signal-processing software ProsodyPro [19] and included loudness (Root Mean Square amplitude, RMS in dB), pitch (mean F0, in Hz) and phonatory fluctuations (F0 range in semitones, st). Within the phonetic community, ProsodyPro is an established and reliable tool that allows for manual outlier checks of F0 measurements. The phonetic parameters obtained during stimulation conditions were baseline corrected through difference scores between stimulation and baseline conditions. A total of 1,381 vowels were analyzed, 686 vowels of male and 695 vowels of female speakers (a few tokens had to be excluded from analysis due to incorrectly produced vowels or corrupted sound files).

Thermal stimulation

After a first baseline condition (vowel production without thermal stimulation), four stimulation conditions followed (41, 43, 45 and 47°C) in which participants had to produce the sustained target vowels while simultaneously immersing one hand into hot water. At the end, a second baseline condition followed (see Figure 1). We used two identical tanks with circulating water (Witeg, model wcb-11) for left and right hand. Participants rested the non-stimulated hand on a towel. The body side of first immersion was balanced (50% starting left); thereafter, body sides alternated. After 10 seconds of immersion, participants were asked to produce the vowels during the other 10 seconds of immersion. After each thermal stimulation, subjects had to first rate whether the stimulation was painful or non-painful. Then, they rated additionally the sensation intensity on Numerical Rating Scales (NRS) separately for heat (-10 no sensation to 0 very strong heat) and pain (1 mild pain to 10 very strong pain) sensations.

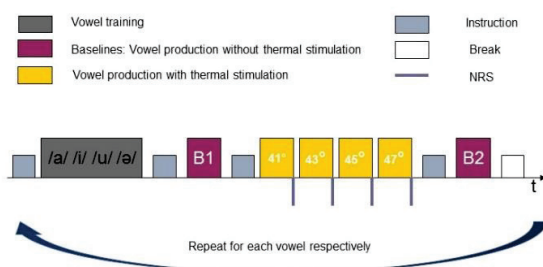


Figure 1: Timeline of experimental design

Results

Effects of thermal stimulation and vowels

Inferential statistics on the acoustic measurements were based on repeated-measures ANOVAs (two within-subject factors: “thermal stimulation“ and “vowel”). Since the effects of “thermal stimulation” on phonetic characteristics were of interest, only main effects and interactions for the

factor “thermal stimulation” are reported here: “Thermal stimulation” had a significant effect on pitch ($F[3,147]=3.53$, $p=0.007$, $\eta^2=0.067$; see Figure 2). In addition, we found a significant interaction of “thermal stimulation” and “vowel” for the loudness parameter ($F[9,441]=1.93$, $p=0.047$, $\eta^2=0.038$; see Figure 3).

Post-hoc analyses conducted separately for each vowel yielded significant effects of “thermal stimulation” on /u/ and /ə/ for pitch (/u/: $F=5.01$, $p=0.002$, $\eta^2=.093$; /ə/: $F=4.35$, $p=0.006$, $\eta^2=.082$) as well as on /ə/ alone for loudness ($F=4.22$, $p=0.008$, $\eta^2=.079$). The effects of “thermal stimulation” were due to significant increases of the two phonetic parameters at 47 °C (see Figures 2 and 3). According to the NRS ratings, only 47°C was perceived as painful (mean NRS: 2.3, SD 1.9), whereas 41° C (mean NRS: -7.2, SD 4.6), 43° C (mean NRS: -6.3, SD 2.1) and 45°C (mean NRS: -3.4, SD 3.9) were rated as non-painful. Thus, in summary, pitch and loudness only increased for painful stimulation and only for /ə/ and /u/, with effect sizes (η^2) pointing to moderate effects. The range F0 was not pain-indicative (Figure 4).

Correlation between phonetic characteristics and subjective self-report

In order to investigate the degree to which phonetic characteristics are indicative of pain, we conducted regression analyses. They tested if and how strongly phonetic characteristics were able to predict the subjective self-reports of our participants. Based on absolute acoustic parameter and rating levels, we found significant correlations between phonetic parameters and heat or pain ratings neither for the non-painful (41°C to 45°C) nor for the painful stimulation (47°C). However, based on relative changes of acoustic parameter and rating levels, the *increases* from non-painful to painful levels in NRS ratings were positively correlated with (and hence significantly predicted) increases in pitch and loudness. That is, the bigger the change from non-painful to painful stimulation (at 47°C) was perceived to be by a participant the larger were the increases in pitch and loudness that s/he produced in the corresponding target vowel. This applies to both /u/ ($r=0.46$, $p=0.012$) and /ə/ ($r=0.41$, $p=0.034$).

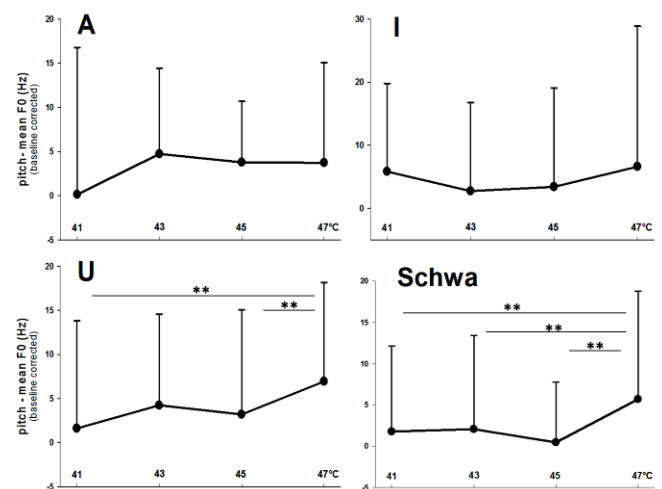


Figure 2: Main effect of thermal stimulation on pitch. Asterisks indicate statistically significant differences. Each datapoint represents between 70 and 80 measurements.

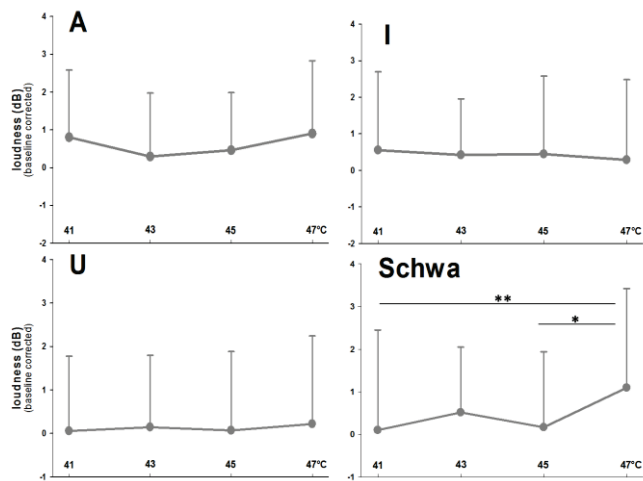


Figure 3: Interaction effect of thermal stimulation on loudness. Asterisks indicate statistically significant differences. Each datapoint represents between 70 and 80 measurements.

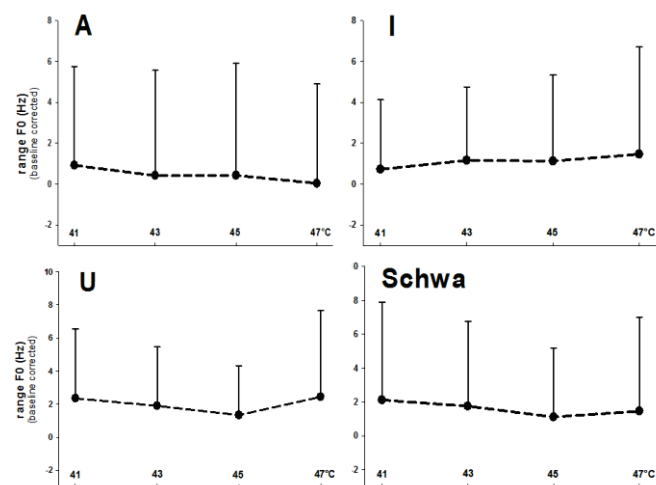


Figure 4: Thermal stimulation did not affect range F0. Asterisks indicate statistically significant differences. Each datapoint represents between 70 and 80 measurements.

Discussion

The present study represents the first step into objective, signal-based quantifications of pain levels based on phonetic analyses. Our results reveal pain-associated increases in the loudness (mean RMS) and pitch (mean F0) levels of /u/ and /ə/, i.e. those vowels whose realizations are stereotypically related to painful vocalizations in the form of groaning or moaning. The /i/ was introduced as control vowel that is untypical for pain vocalizations; and indeed, it did not yield the same effects as /u/ and /ə/. We actually also expected these effects to show up for /a/, but this expectation was not met by our data, maybe because /a/ alone is, unlike, for example, the diphthong /au/, not a sufficiently stereotypical pain expression, especially not in combination with a steady-state speech prosody. Another explanation could be that /a/-like pain vocalizations only co-occur with very high pain levels in real-life contexts. In this case, we would be plausible not to find any changes in /a/ realizations unless the pain stimulation exceeds a certain threshold. That is, the moderate pain levels we induced in the 47°C condition of our experiment might simply not have been high enough to

cause changes in the participants /a/ realizations. The implication of this idea is that acoustic-prosodic parameters within vowel realizations are not reliable pain-level indicators in themselves, but need to be measured and interpreted in combination with the vowel qualities on which they are produced. Indeed, the mere fact that not all vowels in our study were equally pain indicative already suggests that the acoustic-prosodic parameter changes are not direct reflections of pain-induced physiological changes. Instead, pain vocalizations in speech seem to be mediated or "filtered" through some kind of linguistic, cultural, and/or cognitive mechanism. Shedding light on this mechanism and "filtering" variables will be a major task of follow-up studies.

The phonetic parameters of loudness and pitch level clearly separated nociceptive sensations from thermoceptive ones, which likely qualifies the two parameters as non-verbal pain indicators. The two parameters have appeared earlier to encode also other forms of distress [7,10,11,13,14,15,17] and might therefore not specifically encode pain but negative states in general. Since only the highest temperature (47°C) in our experiment produced reliable and clear painful sensations whereas the other temperatures (41°C to 45°C) only led to non-painful thermal sensations whose intensity differences are obviously not mirrored by phonetic changes in pitch and loudness. Regression analyses reflecting the association between phonetic characteristics and subjective experience revealed that only the phonetic changes from thermoception to nociception were able to predict changes in the participants' subjective experience.

Oshrat et al.[12] also concluded from their phonetic analysis that distinguishing pain from no pain is easier than differentiating pain levels. Such conclusions fit in with previous findings on the facial expression of pain. Facial expressions help predict the subjective experience of pain, especially when relative changes across different pain intensities are determined [9]. This might mean that nonverbal pain indicators such as vocalizations and facial expressions are better indicators of changes in pain intensity than of absolute levels of pain intensity. In the future, tonic pain models with dynamic variations in pain intensities should be applied to further scrutinize the links between objective phonetic and subjective rating parameters.

Moreover, further acoustic parameters of both source and filter characteristics should be included in the set of analyzed parameters. Figure 5 illustrates some promising candidates based on spectrograms of /ə/ realizations in the non-painful 45°C and the painful 47°C conditions of participant 29 (male speaker). As can be seen, the vowels realized in the two conditions show clear differences that go beyond pitch and loudness. The /ə/ in the painful 47°C condition was realized with a closer and more fronted vowel quality (close to [ɛ]), which caused a decrease in the first formant (F1) and an increase in the second and third formant frequencies (F2 and F3). In addition, the acoustic energy level decreases less strongly from lower to higher spectral frequencies for the 47°C vowel. This shallower "spectral tilt" is indicative of a more pressed voice quality. This also fits in with the higher shimmer level (i.e. cycle-to-cycle micro-variation in signal

amplitude) that is particularly well visible at the lower end of the pain-vowel spectrum. Even though these are all promising further acoustic-phonetic pain indicators, initial inspections of our data show that their manifestations are probably more variable across participants and/or associated with (subjectively) higher-level sensations of pain. Nonetheless, they are worth being taken into account in follow-up studies. As the “schwa” sound /ə/ proved to be the most pain-indicative vowel quality, we think that these more extensive phonetic follow-up studies (as well as initial technological pilot applications derived from our current dataset) should focus on this vowel quality.

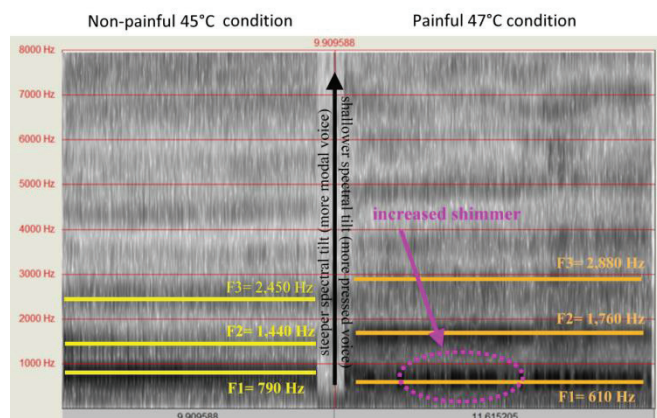


Figure 5: Spectrograms (0-8 kHz) of the two /ə/ realized by the male speaker 29 in the non-painful 45°C condition (left) and the painful 47°C condition (right). Differences in for-mant pattern, spectral tilt and shimmer are marked.

In summary, the present study showed that phonetic characteristics of vocalization (mainly loudness, pitch) can differentiate pain from non-painful states as well as predict changes in subjective pain experience.

References

- Achterberg WP, Pieper MJ, van Dalen-Kok AH, de Waal MW, Husebo BS, Lautenbacher S, Kunz M, Scherder EJ, Corbett A. Pain management in patients with dementia. *Clin Interv Aging* 2013;8:1471-82.
- Apkarian AV. A brain signature for acute pain. *Trends Cogn Sci* 2013;17:309-10.
- Chanques G, Payen JF, Mercier G, de Lattre S, Viel E, Jung B, Cissé M, Lefrant JY, Jaber S. Assessing pain in non-intubated critically ill patients unable to self-report: an adaptation of the Behavioral Pain Scale. *Intensive Care Med* 2009;35:2060-7.
- Corbett A, Achterberg W, Husebo B, Lobbezoo F, de Vet H, Kunz M, Strand L, Constantinou M, Tudose C, Kappesser J, de Waal M, Lautenbacher S; EU-COST action td 1005 Pain Assessment in Patients with Impaired Cognition, especially Dementia Collaborators: <http://www.cost-td1005.net/>. An international road map to improve pain assessment in people with impaired cognition: the development of the Pain Assessment in Impaired Cognition (PAIC) meta-tool. *BMC Neurol* 2014;14:229.
- Dubois A, Bringuier S, Capdevilla X, Pry R. Vocal and verbal expression of postoperative pain in preschoolers. *Pain Manag Nurs* 2008;9:160-5.
- Guidi A, Schoentgen J, Bertschy G, Gentili C, Landini L, Scilingo EP, Vanello N. Voice quality in patients suffering from bipolar disease. *Conf Proc IEEE Eng Med Biol Soc* 2015;2015:6106-9.
- Hammerschmidt K, Jürgens U. Acoustical correlates of affective prosody. *J Voice* 2007;21:531-40.
- Johnston CC, Sherrard A, Stevens B, Franck L, Stremler R, Jac, A. Do cry features reflect pain intensity in preterm neonates?. *Neonatology* 1999;76:120-124.
- Kunz M, Mylius V, Schepelmann K, Lautenbacher S. On the relationship between self-report and facial expression of pain. *J Pain* 2004;5:368-76.
- Marquard C, Brodersen M, Baasch C, Niebuhr O, Schmidt, G. Speech under Stress. *Conf Proc 43th Annual Meeting of German Acoustical Society, Kiel, Germany* 2017.
- Niebuhr, O. Who wants to be a blabbermouth? - Prosodic cues to correct answers in the WWTBAM quiz show scenario. *Conf Proc 8th Speech Prosody, Boston, USA, 2016: 994-98.*
- Oshrat Y, Bloch A, Lerner A, Cohen A, Avigal M, Zeilig G. Speech Prosody as a Biosignal for Physical Pain Detection. *Conf Proc 8th Speech Prosody, Boston, USA, 2016: 420-24.*
- Pisanski K, Nowak J, Sorokowski P. Individual differences in cortisol stress response predict increases in voice pitch during exam stress. *Physiol Behav* 2016;163:234-8.
- Scherer KR. Expression of emotion in voice and music. *J Voice* 1995;9:235-48.
- Scherer KR. Vocal communication of emotion: A review of research paradigms. *Speech Commun* 2003;40:227-56.
- Solodiuk JC. Parent described pain responses in nonverbal children with intellectual disability. *Int J Nurs Stud* 2013;50:1033-44.
- Sondhi S, Khan M, Vijay R, Salhan AK, Chouhan S. Acoustic analysis of speech under stress. *Int J Bioinform Res Appl* 2015;11:417-32.
- Tolkmitt F, Helfrich H, Standke R, Scherer KR. Vocal indicators of psychiatric treatment effects in depressives and schizophrenics. *J Commun Disord* 1982;15:209-22.
- Xu, Y. (2013). ProsodyPro — A Tool for Large-scale Systematic Prosody Analysis. In *Proceedings of Tools and Resources for the Analysis of Speech Prosody (TRASP 2013)*, Aix-en-Provence, France. 7-10.