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The Influence of Insect Noise on Human Language

Project Description

1 State of the art and preliminary work

The proposed study is a first empirical investigation of the hypothesis that insect noise can influence the sound systems of human languages.

Environmental factors and the sound systems of human languages

The shape and size of the sound system of a language are determined by many different factors and possibly even by stochastic events (for a good overview see [65]). One group of factors concerns the physical properties (i.e. climatic, geographic, biological) of the environment in which a community of speakers resides and is thus referred to as 'environmental factors'. In [12] it is argued that the influence of environmental factors on language diversity is an indirect one: the environment has a selective pressure on groups of speakers, thus separating them from each other, and thus leading to language diversity. On the other hand, according to the Acoustic Adaptation Hypothesis (AAH) ([17]; for a recent overview see [13]; also cited by Maddieson in [14]) the acoustical environment can have a direct influence on a language's sound system. More specifically, the AAH states that the acoustical environment can directly inhibit the perception of certain sounds and can, as a result, shape the development of sound systems over time. The AAH in its original form ([17]) argues that different acoustic transmission conditions in different environments partially explain some of the spectral and temporal differences of acoustic communication systems between and within species, predominantly found in bird's song ([13,15,17]), but also in the communication systems of anurals and mammals. However, as Greenhill ([19]) states: "While there has been some work by anthropologists (e.g. Ember and Ember 2007; Fought et al. 2004), linguistics has, to date, seen little value in looking for environmental effects on language."
A number of existing studies have investigated the relationship between climate and language structure, but have not considered sound systems in particular; see [19] for a good overview. Specific to sound systems, existing studies have tested the influence of specific environmental factors, namely *atmospheric pressure* (caused by varying geographical altitude, [29]), *temperature* ([14,18]), *humidity or precipitation* ([16]) and the *presence/absence of foliage* ([16]).
In [14] 100 languages were investigated regarding their sonority statistics (based on recorded speech samples) and then correlated with the average *temperature*, *foliage* and *humidity* of the environment in which the languages are spoken. The study proposed that these environmental factors should cause a dampened acoustic transmission, especially in higher frequencies, thus inhibiting the perception of obstruent vs. sonorant sounds, since the transmission of the former requires a broader bandwidth in higher frequencies. Results showed a strong correlation between higher average environmental temperature and the percentage of sonority in recorded speech samples; in other words, higher environmental temperature is a good predictor for diminished usage of obstruent sounds. Neither average humidity nor foliage was significantly correlated with sonority statistics, although in an earlier study based on structural factors rather than actual speech signals ([16]) Madiesson & Coupé reported both of these environmental factors to be correlated with the number of consonants and the complexity of syllable onsets and codas in a language's sound system. To date, no existing study has included controlled experiments to directly test the influence of temperature, humidity or dampening materials like foliage on the perception of sonorants vs. obstruent sounds.

In [29] a significant positive correlation was reported between *geographical altitude* and the probability of ejectives in the sound system of a language. As an explanation, the study argued that lower air pressure as found in high altitudes "reduces the physiological effort required for the compression of air in the pharyngeal cavity" for the production of ejectives, thus favoring their usage. However, no controlled experimental test was performed to test this hypothesis. Indeed, no existing investigation into the influence of environmental factors on sound systems has directly tested the link between the two.

While correlation analyses of typological data provide valuable insights, understanding the influence of environmental factors on sound systems requires direct experimental testing to determine whether the environmental factor in question measurably influences human listeners' perception of speech sounds. The proposed project will include correlation analyses of typological data and will complement this established methodology with direct experimental tests. The proposed project concentrates on the environmental factor of *insect noise* because it has been the subject of especially little linguistic attention to date.

Insect noise and the perception of speech sounds

Maddieson, [14] p. 2 states: "... the presence of any competing sounds in the environment can affect a hearer’s perception of the properties of a signal. Sound is generated by wind, rainfall, flowing water, birds, insects and other creatures, among other sources. Environmental sounds of this kind can selectively mask some characteristics of an acoustic signal in natural settings." Nonetheless, the potential influence of insect noise on human listeners' speech perception and on the long-term shape of linguistic sound systems has to our knowledge not been investigated before. It is worth mentioning here that although Maddieson only writes about perception, for an actual sound change not only the changed perception is of relevance but even more the fact that there is a carry-over to the production of speakers. As Beddor (2012) points out “perceptual grammars only contribute to sound change […] if they are publicly manifested” ([57], p. 51).

The distinction between sibilants requires the undisturbed perception of a broader frequency range primarily above 2000Hz than the distinction between most other sounds (e.g. [7]).

The perception of sibilants under the influence of cicada noise, in particular, was chosen as the test case for this study, because cicadas produce a very loud broadband noise in high frequency ranges. One contemporary case in which the hypothesized influence of cicada noise may have led to a reduced number of sibilants is Modern Greek.

Ancient (attic) Greek is assumed to have had only two phonemic fricatives /s/ and /h/. The former was probably produced as a coronal ([45]). Greek has undergone many complex sound changes from Attic Greek to Modern Greek, the most relevant for this study being the change of aspirated and voiced stops into voiceless and voiced fricatives, respectively, (called 'spirantization', a form of lenition, [45] pp. 23-26) during the period of Koine Greek.

Modern Greek has eight phonemic fricatives corresponding to Greek letters: /f v θ ð s z x ɣ/ ([41]). These are expressed in a rich set of fricative phones: [f v θ ð s̠ z̠ ç̠ ʝ̠ x ɣ] ([42]), but notably the alveolars [s z] and post-alveolars [ʃ ʒ], contrasting in many other Indo-Germanic languages, are not to be found in Modern Greek. Instead, there is a pair of retracted alveolars [s̠ z̠], articulated somewhere between the classic alveolar and post-alveolar position: "/s/ and /z/ are somewhat retracted ([s̠, z̠]); they are produced in between English alveolars /s, z/ and postalveolars /ʃ, ʒ/. /s/ is variably fronted or further retracted depending on environment, and, in some cases, it may be better described as an advanced postalveolar ([ʃ̟])" ([41], p. 12).

Further, modern Greek "has two phonetically affricate clusters, [t͡s] and [d͡z]" whose phonemic status is disputed ([42], p. 20, 23) but no distinction between alveolar and post-alveolar affricates.

The question is why Modern Greek has not developed an aveolar vs. post-alveolar contrast for sibilants (given an otherwise rich fricative inventory), whether the same may be true for other languages and whether the absence of an alveolar vs. post-alveolar contrast for sibilants is correlated with the presence of cicadas in the environment.

In the following we will describe known facts about cicada noise and the physiological/pychoacoustical effects of such a noise on the perception of speech sounds by humans.

Cicadas' song

"The cicadas (/sɪˈkɑːdə/ or /sɪˈkeɪdə/) are a superfamily, the Cicadoidea, of insects in the order Hemiptera (true bugs). They are in the suborder Auchenorrhyncha, along with smaller jumping bugs such as leafhoppers and froghoppers." ([21]) Although more than 1.500 species exist, only very few can be found in Southern Europe ([22], p. 455).

About the cicadas' song Burton & Burton, 2002 writes: "Adult cicadas spend much of their time sitting ... singing intermittendly ... Male cicadas produce a louder song than any other insect and can be heard up to 1/4 mile (400m) away ... The purpose ... is to attract mates." ([22], p. 455)

And about the mechanism of sound production: "The singing apparatus of cicadas consists of a pair of membranes at the base of the abdomen, each surrounded and held by a stiff elastic ring. Each membrane is convex when relaxed, but an attached muscle can pull it down and then allow it to pop back, rather as a distorted tin lid can be popped in and out ... the membranes ... oscillate at a rate from over 100 to nearly 500 times per second ... The entire singing apparatus is enclosed in a pair of air sacks, which act as resonating chambers to amplify the sound ... each species of cicadas produces its own unique signature tune." ([22], p. 456)

Sources differ about the daily and yearly periods in which cicada songs take place. From Schiel's own experience, most greek cicadas start and end their song with sun rise and sun set, sometimes a few hours earlier than sun rise depending on the temperature; greek cicadas are to be heard mainly in the warmer months when the lymphs change into the imago form, probably at least April until October.

At least two sources ([23],[24]) report of measured near-distance 120db (SPL) sound pressure which is enough to cause permanent hearing loss in humans, if endured for even a short period of time. According to [25], p. 52 the following cicada species have recently been found on Σκόπελος (Skopelos), an island in the same archipelago as Σκιάθος (Skiathos, the place of the planned field studies): *Lyristes plebejus, Cicada orni, Cicadatra atra, Tibicina haematodes* and *Dimissalna dimissa*. No sources report about cicadas in Skiathos, but since the two islands, Skopelos and Skiathos, are only a few hundred meters apart, we can assume that the same five cicada species are also to be found in Skiathos.

All authors about cicada sound are agreed that the song is specific for the species and can in most cases distinguished by trained human listeners (there are a few cicadas that sing in ultra sound but not in Europe). Schiel collected some recordings of at least two audible different species of cicadas on Skiathos 2019 ([26]), most likely *Lyristes plebejus* and *Cicada orni,* This corroborates [25] that there are only very few species to be found on Skopelos.

The spectrum of cicadas' song is characterized by a very strong, sometimes rhythmically shifting fundamental frequency with strong complete harmonics, since the source pitch period basically consists of a very loud and hard click which has strong harmonics. This leads to widely spread energy in the spectrum, which has relatively to other sound sources more energy in the higher frequency range (caused by the strong harmonics of the click). No sources could be found about a more concise acoustical analysis of cicadas' song; this will therefore be a part of the planned study.

Physiological/psycho-acoustical effects caused by noise

Broadband noise can inhibit the perception of sounds and thus the comprehension of language, and can therefore be hypothesized to influence the development of sound systems.

To our knowledge no empirical work has been done on the physiological/psychoacoustical effects of the broadband noise produced by cicadas on human speech perception.

However, the physiological/psychoacoustical mechanisms of permanent hearing damage, auditory fatigue and masking or partial masking of pure tones caused by broadband noise are well understood ([31, 32, 33, 34]). The facts regarding these three mechanisms that are of most relevance for this study are reviewed in turn below. It is important to note here that the effects of all three mechanisms on human speech perception can be measured.

Simultaneous masking

Simultaneous masking is of relevance for this study because we can hypothesize that the detection of and distinction between sibilants /s/ and /ʃ/ will be compromised by masking when there is simultaneous cicada noise.

Simultaneous spectral masking is the effect that a noise has on the perception of a near or overlapping pure tone ([31], pp. 56ff): If the so called masking threshold, i.e. the sound pressure level of a pure tone just necessary to be detected by a healthy human ear in the presence of a masking (white) broadband noise, is measured over a wider range of tone frequencies and for a large number of subjects, it forms a horizontal level for the frequency range 0 - 500Hz that is approx. +17dB above the density level of the masking noise. For tone frequencies above 500Hz the masking threshold increases logarithmically with frequency of about +10dB per decade. That means that at a flat absolute background noise density level of for example 50dB (white noise), a pure tone of 5000Hz must have an absolute level of 67dB + 10dB = 77dB to be detected by a healthy human ear. There are two remarkable properties of simultaneous broadband noise masking: first, the difference of +17dB + 10dB/decade is a linear function of frequency (other than most other psychoacoustical laws which follow non-linear functions); second, the masking threshold profile for a given noise level is uniform across listeners, even though the detection threshold in silence can be very different across listeners (depending for instance on age and possible hearing damage).

Since cicada noise is probably not white noise but rather has a certain spectral energy distribution (to be established more precisely in this project), it is also appropriate to consider the simultaneous masking effect of critical bandwidth noise ([31], pp. 59ff) and the increase of simultaneous masking caused by multiple masking noises ([31], pp. 96-97): Zwicker and Fastl show that complex masking sounds cause detection thresholds that are even higher than would be expected by simple intensity addition (+6dB rule for doubling intensity). While a single critical bandwidth masker causes a maximum threshold (at the mid frequency of the masker) of approx 3-5dB below the masker level (in stark contrast to white noise where the threshold level is at least +17dB above the density level of the masker), noise that is broader than a critical band is expected to increase threshold levels significantly above the noise density level. And like with narrowband maskers, steep threshold flanks are expected beneath and above the lowest/highest noise frequency edges. (The masking effects of pure tones and short temporal masking are not addressed here, since it is unlikely that these apply to cicada noise.)

For the proposed study this means in short that for instance, if a typical cicada noise is established to be approximated by a rectagular broadband noise with a density level of 95dB in the frequency range between 1000 - 15000Hz, then the masking threshold for pure tones would start to rise approximately half a critical band below 1000Hz (which equals approx. 820Hz), be at least higher than the masking level within the masking noise frequency range (probably 15-17dB higher), and phase out for another half critical band above 15kHz (appox. 18kHz) until reaching the silence threshold.

Permanent hearing damage

The case of permanent hearing damage (Permanent Threshold Shift, PTS) is of relevance for this study because we can hypothesize that listeners that are exposed to cicada noise over longer periods of time will acquire PTS in the spectral regions of cicada noise and therefore have a diminished ability to detect and distinguish between speech sounds in this spectral region, namely the sibilants /s/ and /ʃ/.

The cause of PTS can be either a traumatic or constant noise exposure over a longer period. It is frequency-dependent, can be measured as a raised hearing threshold in the audiogram, and is often accompanied by tinnitus. Sound levels below 70dBA are considered safe even for a long exposure period; sound levels of 85dBA and higher may cause permanent hearing damage ([32]).

Auditory Fatigue

Auditory fatigue is of relevance for this study because we can hypothesize that, as with PTS, the perceptual detection and distinction between sibilants /s/ and /ʃ/ will be compromised by auditory fatigue caused by exposure to the noise of cicadas. Schiel experienced this auditory handicap many times after long (several hours') exposure to cicada noise in Greece; the TTS affects the auditory feedback loop of the listener in such a way that the listener perceives a dramatic change in his/her own sibilants.

Auditory fatigue or Temporary Threshold Shift (TTS) is a temporary effect of long-term exposure to (broadband) noise on auditory perception (not to be confused with non-simultaneous temporal masking ([31], p.72)). Measurable effects of TTS disappear a few hours after the exposure ends, but can last up to 48 hours. Auditory fatigue can lead to permanent hearing damage (PTS) if the recovery time is not long enough. ([33,34]). There are two known types of auditory fatigue ([33,34]):

- short-term auditory fatigue
    - . full recovery can be achieved in approximately two minutes
    - . the TTS is relatively independent of exposure duration
- long-term auditory fatigue
    - . recovery requires a minimum of several minutes but can take up to 48h
    - . effect is dependent on exposure duration and noise level

For both cases the TTS is maximal at the exposure frequency of the noise. Currently it is not known how to estimate the required recovery time after the end of the noise exposure; [36] reports that the recovery time is related to the sound pressure level of the TTS, for example a noise of 95dBA requires about 120min total recovery time, but most of the recovery takes places within the first 15 minutes after exposure ([35]).

Related previous work of the PI

Schiel has worked on the agent-based modelling of sound change ([5,6,7,10]) and on the fPCA-based analysis of a New Zealand sound change ([9]), as well as most recently on the analysis and agent-based modelling of sound change in an isolated group in Antarctica ([8]). In his work (together with Harrington and Stevens) for the first time real acoustic data (contours of formants or of spectral energy weight) were used in a simulation in which artificial agents stochastically produced acoustic data (based on statistical models derived from stored exemplars in memory), and perceived and memorized these in simulated speech exchange ([5]). Schiel and colleagues could show that in such simulations based on real acoustic data asymmetrical distributions of memorized exemplars in the feature space can be the cause for asymmetrical sound changes ([5,6,7]).

Schiel has further directed several large German speech data collections (PhonDat, Verbmobil, SmartKom, SmartWeb; all funded by the German Ministry of Education and Science, BMB+F) and is therefore experienced in the logistics and techniques of speech data recordings.

Schiel has also worked extensively on one other influencing factor on speech production, namely intoxication ([1,2,3,4]), and is therefore an expert in the analysis of speech influencing factors as well as related perception experiments.

Regarding psychoacoustical effects Schiel has studied Psychoacoustics in his major under Prof. Dr. E. Zwicker and Prof. H. Fastl of the Technical University of Munich (TUM), both leading authorities in psychoacoustics ([31]).

Schiel speaks Modern Greek (A1) and is well connected to local residents, Greek and British, in the planned region of the field studies (Skiathos island), and will therefore conduct the field studies in person.

1.1 Project-related publications

1.1.1 Articles published by outlets with scientific quality assurance, book publications, and works accepted for publication but not yet published.

[1] Baumeister B, Heinrich Chr, Schiel F (2012): The influence of alcoholic intoxication on the fundamental frequency of female and male speakers. J. Acoust. Soc. Am. Volume 132, Issue 1, pp. 442-451, DOI: 10.1121/1.4726017.

[2] Schuller B, Steidl S, Batliner A, Schiel F, Krajevski J, Weninger F, Eyben F (2014): Medium-term speaker states—A review on intoxication, sleepiness and the first challenge. In: Computer, Speech and Language, Vol. 28, Issue 2, March 2014, DOI: 10.1016/j.csl.2012.12.002, pp. 346-374.
[3] Heinrich Chr, Schiel F (2014): The influence of alcoholic intoxication on the short-time energy function of speech. J. Acoust. Soc. Am. Volume 135, Issue 5, pp. 2942-2951, DOI: 10.1121/1.4859820.
[4] Schiel F, Heinrich Chr (2015): Disfluencies in the speech of intoxicated speakers. International Journal of Speech, L57anguage and the Law, Volume 22.1, pp. 19-33, ISSN: 1748-8885, DOI: 10.1558/ijsll.v22i1.24767.
[5] Harrington J, Schiel F (2017): /u/-fronting and agent-based modelling - The relationship between the origin and spread of sound change. Language, Vol 93, No 2 (2017), pp. 414-445, doi:10.1353/lan.2017.0019.
[6] Harrington J, Kleber F, Reubold U, Schiel F & Stevens M (2018): Linking cognitive and social aspects of sound change using agent-based modeling. Topics in Cognitive Science, 1-21, ISSN:1756-8757 print / 1756-8765 online DOI: http://doi.org/10.1111/tops.12329.
[7] Stevens M, Harrington J & Schiel F (2019): Associating the origin and spread of sound change using agent-based modelling applied to /s/-retraction in English. Glossa: A Journal of General Linguistics, 4(1), 8. DOI: http://doi.org/10.5334/gjgl.620.
[8] Harrington J, Gubian M, Stevens M & Schiel F (2019): Phonetic change in an Antarctic winter. The Journal of the Acoustical Society of America 146, 3327 (2019); https://doi.org/10.1121/1.5130709.
[9] Gubian M, Harrington J, Stevens M, Schiel F, Warren P (2019): Tracking the New Zealand English NEAR/SQUARE Merger Using Functional Principal Components Analysis. In: Proc. of the Interspeech 2019, Graz Austria:ISCA, pp. 296-300.
[10] Harrington J, Kleber F, Reubold U, Schiel F, Stevens M (2019). The phonetic basis of the origin and spread of sound change. In: Katz W, Assmann P (eds.): The Routledge Handbook of Phonetics. Routledge, London and New York, pp. 401-426, ISBN: 978-1-138-64833-3.

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2. Objectives and work programme

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2.2 Objectives

Main hypothesis
In this study we want to investigate the hypothesis that insects' noise as an environmental factor can have a causal influence on the development of a language's sound system.
The rationale behind this hypothesis is that in some environments omni-present cicadas (or possible other insects) produce a strong noise that could have an impact on the perception and - caused by this - on the production of sibilants, thus causing the speakers to adapt their communication accordingly, which ultimately could result in a sound system that is acoustically robust against cicada noise, as it seems to be the case in Modern Greek.

General remarks about the applied methodology
One of the many factors that are hypothesized to influence the development of the sounds of a language is the environment in which the community of speakers resides ([14,16,17,18,19]). But to deliver scientific proof of such an influence faces an epistemologic problem: sound change within a language community is always oberserved post-hoc, i.e. after the fact. It is not possible to repeatedly run an in vito experiment on sound change with the appropriate control group to proof the causal connection between an environmental factor and the development of a language's

sounds[1]. That is why investigations into the influence of environmental factors so far exclusively look into typological properties of languages and correlate these to the presence of the environmental factor ([14,16,29], but see [11] for some general problems regarding such 'nomothetic studies').

For example, Butcher ([51]) when investigating Australian Aboriginal languages found some peculiar common features in their sound system although the languages are otherwise very diverse: the phonologies show a great variety in place of articulation (up to 7) while voicing contrasts and manner (friction) is under-represented compared to other languages of the world. Butcher then gives a possible explanation, namely the fact that about 80% of Aboriginal children suffer middle ear infections and thus "consequently have a significant conductive hearing loss". This causes low and very high frequencies harder to hear, which in turn makes the distinction of voiced vs. voiceless and friction difficult to perceive, and this could be a reason that the Aboriginal sound systems developped into the present state. The environmental factor here would be the introduction of pathogens to Australia that - possible in combination with climatic and social factors - cause middle ear infection in infants. Butcher wisely states though: "By this point we are well into the realm of speculation...", probably because he is well aware about the epistemologic problem outlined above.

As we see it this leaves us with three possible scientific approaches regarding the influence of environmental factors on the development of sound systems:

1. The (traditional) correlation approach

We look at a large group of different languages that can be divided in languages that are under the influence of the hypothesized environmental factor and a group of languages that are not. If the properties of sound systems hypothetically caused by this factor correlate significantly with the (quantisized) environmental factor, we can at least say that the hypothesis holds for the synchroneously observable reality of languages. This approach has been applied several times as outlined in section 1. Although this approach can be seen as a falsification of the hypothesis (if no significant correlation can be found, it is unlikely that the main hypothesis of insects' noise as an environmental factor holds), it still has some inherent problems:

The first problem with this approach is that it is basically a 'black-box' view of the process of sound change: we just look at the resulting language properties without considering the underlying processes of speaker interaction, production and perception, that cause these properties.

Secondly, sound change is most likely not a deterministic process but rather a stochastic one of a very complex nature. Influences of the environment could easily be masked by other factors; in the correlation approach it is therefore not possible to isolate the influence on a single environmental factor.

Third, it could well be that the observed correlation between environmental factor and language property is caused by a third (hidden) factor (see also [11] for the more general problem of spurious correlations in large datasets).

Fourth, on the other hand, it could be the case that other factors that influence the development of a language mask the hypothesized effect of insects' noise in the statistics.

It follows that we need other approaches which are missing in earlier studies regarding environmental factors: the direct experimentation which effects the possible environmental factor has on speech perception and production.

2. Test for possible prerequisites for the hypothesized influence on sound systems

The second possible scientific approach is to deduct the possible fundamental prerequisites of which at least one must be met so that the environmental factor can possibly have a causal influence on the perception of speakers, and thus on the development of the language's sound system.

In the example of Butcher (2008) above such a prerequisite would be the fact that middle ear infection typically causes a conductive hearing loss in low and high frequencies. If we therefore can proof in a series of experiments that there is no possible causal influence of the factor insects' noise on the perception of speakers, we can dismiss the hypothesis that the same factor has an

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[1] It is, however, possible to simulate repeatedly a sound change or certain aspects of it in an agent based model, but this not an objective of the proposed study.

influence on the development of sounds over time. On the other hand, if we show the existence of at least one prerequisite condition, we can still hold the main hypothesis (until proved otherwise). Methodologically, this approach is more powerful than the first, since it is logically impossible to prove a causal connection solely based on the outcome of correlation analysis ([50]).
However, these possible prerequisites (in form of a compromized perception of sibilants) are only one half of the medal; if the development, for example, of the Modern Greek sound system has happened in the hypothesized way, there are implications regarding the production of speakers ([57]). This leads us to the third possible approach:

3. Test for changes in production caused by the environmental factor

If listeners' perception of sibilants is compromised by one or more ways as outlined above, and if this is not just a temporary change but rather the cause of the hypothesized influence of cicada noise on the sound system, we expect to see this also in the production of affected speakers (following the argument of Beddor [57] as outlined in section 1). A third testable approach is therefore to analyse the productions of speakers that live with and without exposure to cicada noise, whether there is any significant change in articulation.

To summarize, the objectives of this study are as follows:
1. Investigate the correlation of typological features on non-existing or diminished sibilant contrast in a language against the presence of cicadas in the language's region (approach 1).
2. Investigate possible causal relations between cicada noise and non-existent or diminished perception of sibilant contrast as possible prerequisites for the hypothesized sound change (approach 2). This can be further broken down into three testable objectives:
2a. Can cicada noise cause permanent hearing damage and thus inhibit the perception of sibilants?
2b. Can cicada noise cause auditory fatigue which temporarily inhibits the perception of sibilants?
2c. Can cicada noise inhibits the perception of sibilants' contrast by simultaneous spectral masking?
3. Investigate possible influence on the production of sibilants in speakers with and without exposure to cicada noise.
All these objectives are testable in experiments/investigations as out-lined in the work program.

2.3 Work programme incl. proposed research methods

Summary

The following work program consists of the following experiments:
Typological study: correlation analysis (WP1)
Analysis of cicada noise (WP2)
Testing the relationship between cicada noise and permanent hearing damage (WP3)
Testing the influence of cicada noise on sibilant perception (WP4-5)
Testing the influence of cicada noise on production (WP6)

Workprogram

The proposed study involves several analyses and experiments that are all designed to test the main hypothesis regarding the influence of insect noise on human language. For practical reasons these are structured into work packages (WP) to facilitate referencing throughout this application and future reporting on progress and results of the study. We applied this structuring in WPs in previous DFG projects and found it most useful. The experiments will be conducted either in the host institution, Institut of Phonetics and Speech Processing (IPS) in Munich or in the planned field area (Skiathos). In the following, each experiment is described in the logical but not necessarily chronological order, list the expected time line, the requirements of resources for each work package, and the expected outcome regarding the objectives of the project.

WP 1 - Sibilant contrasts and the presence of cicadas

We will collect phonological and lexical data (word statistics) from languages spoken in regions with and without cicada noise and perform a statistical correlation analysis. In terms of precisely which linguistic variable, simple binary factors such as the presence or absence of a sibilant phoneme will be complemented where possible with actual usage statistics for sibilants within each spoken language.

The LAPSyD database ([20]) provides information about typological features accross a large number of languages. Building on this resource this work package will build up a dataset that links actual sibilant contrast usage (based on lexical data and word usage statistics) with (numeric) climatic factors that are strongly correlated with the presence of singing cicada species. Numeric climatic factors will be used for the correlation in the absence of reliable data regarding the actual occurence of cicadas word-wide. A simple Pearson correlation will show whether or not the main hypothesis can be supported by this sort of data.

Requirements: this analysis can be conducted without any field work at the IPS in Munich; it is suitable for a graduate student project supervised by Schiel; one student assistant is required (10h/week for 6 months) to synchronize linguistic and climate data from different sources.

Time line: first 6 months of project or adjusted to university deadlines for graduate projects

Expected outcome: there is a statistically significant negative correlation between sibilant contrast usage and the likelihood of cicada noise.

WP 2 - The spectral properties of cicada noise

The spectral properties of cicada noise have to our knowledge not been acoustically investigated. This work package will analyse recordings collected by Schiel in 2018 and 2019 on Skiathos as well as new recordings from field data gathering phase I (see Section 2.1). The first component of this work package will be to establish precisely which cicada species are most common in the field area, ideally with the assistance of experts on cicadas such as Prof. Matija GoGala, director of Ljubljana's Museum of Natural History (retired), Andrej GoGala, entomologist at Ljubljana's Museum of Natural History, or Prof. Chris Simon at the Department of Ecology and Evolutionary Biology at the University of Connecticut. A first auditory comparison of the recordings in the planned field area ([26]) with recordings in [27], which contains a large collection of classified recordings of European cicadas, suggests that *Lyristes plebejus, Cicada orni* and possibly also *Tibicina haematodes* ([28]) were recorded by Schiel in Skiathos. Other, less likely candidates include *Cicadatra atra* and *Dimissalna dimissa* ([25]).

Aside from the spectral properties (long-term spectral average and spectral weight), this work package will also determine the noise level density to which listeners in the planned field area are typically exposed. Since cicadas are very sensitive to approaching humans, the closest possible proximity to a singing cicada can be established easily. Level density measurements in this close proximity can be seen as an upper bound of possible noise level exposure.

Requirements: the recordings and sound level measurements will be necessarily conducted in the planned field area; the analysis will be conducted at the IPS in Munich.

Time line: months 0-3 and 18-21 of project.

Expected outcome: a robust estimate of the main spectral energy distribution and the sound pressure level of the cicada species found in Skiathos will be established. This will allow accurate predictions regarding the psychoacoustic impact of cicada noise on human listeners, which is a critical component of the following work packages.

WP 3 - Cicada noise and permanent hearing loss

Our hypothesis in this work package is that people who are exposed to cicada noise have significantly higher hearing loss in the parts of the spectrum containing cicada noise than people who are not. This hypothesis will be tested in this work package by comparing audiograms from residents of rural and urban areas of Greece. If significant differences can be found between the two groups, widespread hearing loss can be considered a possible causal factor in the absence of a sibilant contrast in the Modern Greek sound system. If no differences can be found, it follows that

cicada noise does not cause permanent hearing loss and the hypothesis of this work package can be dismissed.
Since it is technically very difficult to perform standardized audiogram tests in the planned field area, we will recruit local ENT doctors (mainly in Athens, Volos and the local island clinics) to provide archived and anonymized audiograms from their patients. Metadata required for each audiogram include place of living for the longest part of life (rural or city), gender and age of the patient at time of audiogram, and ENT doctor. The factors ENT, gender and age are needed to account for unwanted effects in the data.
The collection of audiograms will take place during data gathering phases I and II in the field (see Section 2.1), since it is likely that only personal contact will yield the desired results from local ENT doctors. Also, to cover expenses and as an incentive to cooperate we will offer a moderate compensation to participating ENT doctors.
Requirements: contact via email/telephone (to initiate cooperation) and in person (to collect copies of audiograms) in the planned field area; an incentive of 15€ per collected audiogram; a student assistant is required (15h/week for 6 months) for incorporation of audiograms into a database.
Time line: first 6 months to recruit cooperating ENT practitioners; data gathering phases I and II to collect copies and metadata of audiograms; database construction (ongoing after data gathering phase I).
Expected outcome: a statistically significant stronger hearing loss in the spectral range of cicada noise (as established in WP2) can be shown for greek ENT patients living in rural settings; if no statistical difference in hearing loss in the spectral range of cicada noise can be shown, the hypothesis that cicada noise may cause permanent hearing loss and thus could be a possible prerequisite for sound change, can be dismissed.

The next two work packages describe perception experiments in British English and German that are two examples of languages in which the present phonological system is (according to our main hypothesis) not influenced by cicada noise, and that show the phonological contrast between sibilants /s/ and /ʃ/. We will not investigate perception (and production, see WP6) in Modern Greek because there exists no phonological contrast between sibilants /s/ and /ʃ/ which makes experiments about phonetic distinction difficult.

WP 4 - Cicada noise and simultaneous spectral masking

Another possible reason why cicada noise might influence the stability of sibilant contrasts in human languages is simultaneous masking. This psycho-acoustical effect ([31], p. 59ff) would cause the perception threshold for pure tones to rise considerably in spectral areas that are disturbed by cicada noise (as outlined in section 1); thus the perceptual distinction between sibilants, in particular, would be more difficult.
This hypothesis will be tested in this work package with a perception experiment in which listeners, under exposure to cicada noise (or silence as a test condition), decide between minimal word pairs that are distinguished by an /s/ - /ʃ/ contrast. According to our hypothesis, the perceptual distinction between real minimal pairs will be compromised under exposure to cicada noise due to simultaneous spectral masking.
This perception experiment will be performed in a sound proof room at the IPS in Munich. This allows the dB level of the cicada noise to be held constant across participants (at the level to be established in WP2) and facilitates the recruitment of participants: since Greek has no sibilant contrast (see section 1), German L1 speakers will be recruited who do not report any permanent hearing loss and do not live permanently in an area with insect (or other) noise. The same participants will be tested twice: once under the simultaneous influence of cicada noise and once in a quiet environment (control condition). The order of the two conditions will be randomized to test for possible learning effects. The two tests per participant will not be conducted on the same day to ensure that no long-term effect (auditory fatigue, see next work package) interferes in the second experiment. We aim to test a minimum of 20 participants (10 female + 10 male).
This experiment will be performed on a studio computer fitted with the SpeechRecorder software ([58]) and a pair of high-quality loudspeakers. The sound pressure level of the stimuli (to be

established with pre-testing) will be the same for each participant. The list of stimuli pairs will be designed, recorded and tested by one of the student assistants at the IPS in Munich.
Requirements: German stimuli list; recruitment of participants; experiment supervision (twice per participant); participant remuneration after completion of the second experiment; metadata acquisition; backup procedures to secure collected data.
Time line: months 25 - 36
Expected outcome: listeners' perception of sibilants is compromised during exposure to cicada noise.

WP 5 - Cicada noise and auditory fatigue

Whereas simultaneous masking (WP4) has no long-term effect on hearing, it is possible that the effects of cicada noise could persist after exposure has ended due to the physiological effect known as *auditory fatigue*, as discussed in Section 1 ([33, 34]). Since auditory fatigue has not been investigated in the same detail as psychoacoustical simultaneous masking, it is difficult to predict the strength or duration of the long-term effects of exposure to cicada noise.
To test for auditory fatigue after exposure to cicada noise, this work package involves a perception experiment in which listeners, after exposure to at least two hours of cicada noise (or silence as a control condition), decide between real word minimal pairs that are distinguished by an /s/ - /ʃ/ contrast. Our hypothesis is that the perceptual distinction between real minimal pairs will be compromised after exposure to cicada noise due to auditory fatigue. If this hypothesis can be supported with the experimental results, this would support the idea of a causal link between cicada noise and instability of sibilant contrasts.
These experiments will be conducted in the planned field area after exposure to real cicada noise in the natural environment because it is difficult to simulate longer exposure phases in the lab (and might pose an ethical problem). The level density of cicada noise in dBA during the exposure phase will be measured to ensure that levels are within the typical range (to be established in WP2).
Since Greek has no /s/ - /ʃ/ sibilant contrast (see section 1), British English L1 speakers will be recruited for this experiment. Participants must not have any permanent hearing loss and must not live permanently in the planned field area. The same subjects will be tested twice: once after the exposure to cicada noise and once without any exposure for the previous 4 hours. We aim to recruit a minimum of 20 participants (10 female + 10 male).
Both conditions (with and without prior exposure to cicada noise) will be tested in the same quiet environment to exclude any simultaneous masking effects; the order of conditions will be randomized to control for possible learning effects. The list of stimuli pairs will be designed, recorded and tested beforehand at the IPS in Munich.
Requirements: English stimuli lists; suitable acoustically-dampened room in the planned field area; recruitment of participants; experiment supervision (twice per participant); participant remuneration after completion of both experiments; metadata collection; remote backup procedures to secure collected data.
Time line: during the data gathering phases I and II.
Expected outcome: listeners' perception of sibilants is compromised after exposure to cicada noise due to auditory fatigue.

WP 6 - Acoustic analysis of British speakers' /s/ - /ʃ/ production

We follow the argument in section 1 that the perceptual effects of exposure to cicada noise should also impact sibilant production, if there is a link between cicada noise and permanent change in the sound system of a language. To test whether this is the case, i.e. whether exposure to cicada noise affects sibilant production, this work package involves recording English words contrasted by /s/ - /ʃ/ spoken by two separate groups of British English L1 speakers. Participants will not be exposed to cicada noise while being recorded. Participants in group A will have lived in the planned field area for at least three years (during which time they will have been exposed to cicada noise); participants in group B will have lived in the United Kingdom (without exposure to cicada noise) and will serve as the control. Since British English has a sibilant contrast, we do not expect the cicada noise to reduce this contrast in production, because this would compromise the existing phonological system. The hypothesis is rather that participants from group A will exhibit a *more* distinct articulation of the sibilants /s/ - /ʃ/ than those from group B due to long-term exposure to cicada noise due to compensation. If we can show that British speakers show such a compensatory behavior, it follows that the compromised perception indeed influences the production and is therefore a possible pre-requisite for a sound change ([57]).

It is important to note here that participants must not experience the effects of simultaneous masking nor auditory fatigue while being recorded. Otherwise it could be that case that they increase the /s/ - /ʃ/ distinction to compensate for the inhibited perception (a kind of Lombard effect) which would mask the targeted group differences. Recruitment for this experiment is therefore more difficult than for the experiments in the previous work packages.

The recordings will be performed in a quiet and sound dampened room in the planned field area using the software SpeechRecorder ([58]), with the same English minimal pairs as in WP5 embedded in carrier sentences. Recordings will be conducted in the early morning hours to avoid any exposure to cicada noise during daylight hours. To measure the acoustic distinction between /s/ - /ʃ/ we will follow an established procedure developed in [7]: the recordings will first be automatically segmented into phone segments using WebMAUS ([59]), then transferred into a EMU-SMDS database for correction and analysis ([60]). The time-contour of the spectral center of gravity over the entire acoustic duration of the sibilant will be calculated and parametrized (smoothed) by the first three parameters of the Discrete Cosine Transform in R ([61]); this effectively reduces the complex contour form to three quasi-morphological parameters: height, tilt and curvature ([64]). If the cicada noise has an influence on production, we expect the averaged parametrised /s/ - /ʃ/ contours of group A to have a greater euclidian distance in the DCT space than those of group B.

Participants will be recruited and recorded in the planned field area, in order to include those who have been exposed to cicada noise for at least three years (group A). It should also be relatively easy to recruit participants for group B since a large number of British tourists spend their holidays in the planned field area. Since this is statistically a 'between groups' test and therefore the speaker identity cannot be used as a random factor, speaker traits should be as similar as possible between the groups. We aim to match speaker pairs across groups A and B as closely as possible; speaker traits that will be considered are gender, age and education level.

Requirements: English prompt lists; suitable acoustically-dampened recording room in the planned field area; recruitment of matching British English L1 speakers for groups A and B; supervision of recordings; remuneration after sucessfully completion of the recording session; metadata collection; remote backup procedures to secure collected data.

Time line: during the data gathering phases I and II.

Expected outcome: speakers' production of English sibilants is more distinct after long-term exposure to cicada noise.

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