DEMONSTRATIONS

OF

DICHOTIC PITCH

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INTRODUCTION

What is dichotic pitch?

A dichotic[1] pitch can be perceived when white noise is presented binaurally by headphones to a listener, provided that a particular interaural phase relationship exists between the left-ear and right-ear signals. In other words, the information at either ear independently is only able to evoke a sensation of white noise, but the stimulation of both ears together produces the sensation of pitch[2]. Generally, a dichotic pitch is perceived somewhere in the head amidst the noisy sound filling the binaural space; roughly, its image is "lateralized" along the imaginary axis connecting the left and right ear.

In summary, each dichotic pitch phenomenon is characterized by three perceptual properties depending on the specific interaural parameter, viz. pitch value, timbre, and in-head position (lateralization) of the pitch image.

With analogue noise as a basic signal, two types of interaural phase relationships have been reported in the literature, namely sharp 2π (or π) phase transition(s) in limited frequency range(s), or relatively large (> 3 ms) interaural time delays. Such interaural phase relations do not occur in daily life; they are non-ecological, as they are the result of signal generation in the laboratory. Such

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[1] "Dichotic" means that the ears receive different signals. "Monotic" means that only one ear is stimulated. "Diotic" implies equal signals to both ears (In old Greek language: ωτιον: ear, διχα: different, μονοσ: single, δι: two).

[2] A parallel exists in vision with random-dot stereograms. When monocularly viewed, the left- and right-eye patterns appear as formless random textures. But, when stereoscopically fused, an object might be perceived separate from the background (Julesz, 1971).

signals are the more non-ecological as the amplitude spectra of both the left- and right-ear channels are always made flat to avoid monaural pitch information.

Why does the study of dichotic pitch make sense?

The above immediately might raise the question whether phenomena evoked by non-ecological signals should be considered seriously. As will be repeatedly shown by the sound examples on the present CD and the theory in this booklet, dichotic pitch phenomena have perceptual properties (pitch and timbre) that are very similar to those of daily-life signals. This implies that the human central pitch processor seems to deal with pitch information always similarly, independently from the place in the auditory system where the information originates, be it in the outer ear or in the auditory brainstem.

Pitch information, apparently, can be either monaural (monotic or diotic), or binaural (dichotic) in origin. Thus, the system is thought to be parsimonious and unique in its pitch processing strategy. Moreover, one cannot think of any reason for the human brain to have developed a separate pitch processor for non-ecological signals. Therefore, dichotic pitch phenomena are generally considered to be *natural byproducts (epiphenomena) of the binaural system*, and thus they can be used to study this system as well as the central pitch processor (see also Stern and Trahiotis, 1995).

In addition to the localization of sound sources, one of the most important and intriguing capabilities of the binaural system is its ability to single out a wanted sound (e.g. a communicating human voice) from disturbing noises that are present at the same time in the acoustic environment. Only little is known of the underlying neural processes of this so-called cocktail-party phenomenon. In view of the apparent analogy (the dichotic pitch being singled out from the disturbing head-filled noisy sound), it seems obvious to exploit dichotic pitch phenomena for the study of localization and the cocktail-party phenomenon together with the underlying binaural-interaction system.

How to use the CD together with the booklet?

On the CD different dichotic pitch phenomena have been programmed in historical order mainly. In some places, the historical order is abandoned and strongly related phenomena are dealt with close together for reasons of logic, didactics, and economy. For each dichotic pitch phenomenon the two main perceptual aspects, pitch value and pitch image position (lateralization), are dealt with consecutively. Also the monaural counterpart is always given for comparison of pitch and timbre.

The listener is urgently advised not to listen to all the tracks in one go. This is not a CD with musical sounds for easy listening or with sounds that speak for themselves. Without carefully reading the introductory text parts of the booklet for each dichotic pitch the CD might bring annoyance rather than fun. Furthermore, it is advised to go through the CD in two rounds. First to familiarize and to appreciate the different dichotic pitch phenomena, then for a more in-depth study.

Suggested first round: tracks 1, 2, 3, 4, 5, 6, 10, 18, 19, 28, 34, 42.
Second round: these and remaining tracks.

Also, one might be obliged to repeat a track in order to pick up the particular effect programmed. For reasons that will be explained in the course of this booklet, the one pitch phenomenon is easier to deal with than the other.

Monaural equivalents have been programmed by recording the sum of the left- and right-ear signals. These diotic tracks serve two purposes: to show the similarity of pitch and timbre for the monotic and dichotic cases and to serve as a searching tool to make the listener familiar with the particular sound before listening to the dichotic version. The reader is encouraged, however, to listen (unbiased) to the dichotic track first and take refuge to the diotic track only, if one remains unsuccessful in grasping the dichotic pitch after repeatedly playing the dichotic track.

In order to check the quality of the dichotic signals, one might want to aurally inspect the pure white-noise character of the left- and right-ear signals separately by lifting either transducer. Alternatively, one might sum these acoustically by bringing the left and right transducer close together at one ear. Depending on the signal configuration, this action will result in an audible monaural pitch.

For those readers interested in objective measurements, also 60-sec. duration tracks have been included presenting the dichotic or diotic pitch signal continuously for a single parameter setting. These tracks will not be very interesting to listen to, unless one manipulates the headphones.

Reproduction quality of the signals on the CD

Today, auditory experiments are often performed with computer-generated multi-component stimuli, experiments on dichotic pitch likewise. The signals on this CD, however, were processed based on analogue white gaussian noise. This was done for several reasons. First, historically, the older dichotic pitch phenomena were discovered with signals based on analogue white noise (Huggins Pitch, Fourcin Pitch, and Dichotic Repetition Pitch). Secondly, the use of continuous white gaussian noise made it possible to change, for example, the notes of a scale without interrupting the pleasant sensation of continuous noise at the ears individually. Further, for the long-duration tracks, the distracting sensation of periodicity typically for multi-component stimuli could be avoided. Finally, it is known from literature that with monotic multi-component stimuli, abrupt phase transitions might produce specific components to stand out as audible and disturbing artefacts (Kohlrausch and Houtsma, 1992).

Basically, analogue white gaussian noise was low-pass filtered with a cut-off frequency of 3 kHz and a slope of 36 dB/oct. and digitized with a sample rate of 10 kHz. Proper real-time data processing algorithms were applied in a DSP, after which signals were carefully reconstructed to analogue[3].

As cross talk between the left- and right-ear channel might be fatal for the demonstration of dichotic pitch, utmost care was taken to avoid that during recording. This was checked with a fourier analyzer by measuring the spectra of the left- and right-ear channels separately, and after addition or subtraction. In the added or subtracted signals, always a peak-to-valley distance of at least 30 to 40 dB was measured at those places where, theoretically, an infinite peak-to-valley ratio was expected due to phase dependent cancellation.

Assuming that CD players always have a sufficiently large channel separation, replay of the CD should generally produce a clean signal. One might want to repeat spectral measurements with one's own CD player for verification.

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[3] These algorithms were constructed to represent the signal configurations corresponding to the various dichotic pitches. This was done by using the SPW-CGS (Signal Processing Workstation annex Code Generation System) by Comdisco-Alta to create the proper C-programs. These were compiled and loaded into Motorola 96002 DSP system boards that could be controlled by a PC.

Finally, but most importantly, the headphones have to be first quality, with equal amplitude and phase responses. Also, they should preferably not be acoustically transparent as to avoid leakage and cross talk through the air.

CD tracks

1. Check of correctness of headphones phase
Bring the left and right headphones close together at one ear and listen monaurally. If headphones phase is correct, one should perceive a five-times repeated pitch interval, followed by just noise (*Use is made of a 200/220-Hz MPSP interval in the + condition, followed by the – condition).*

2. Check of correctness of headphones right-left
A white-noise signal is presented with a stepwise changing ITD. If headphones are correctly placed on the head, a noise is perceived moving from the right ear towards the left ear.

3. Adjustment of the sensation level at about 50 dB
White noise is presented at a relative level of 0 dB during 1.5 sec., followed by –50 dB during 15 sec., and again 0 dB during 1.5 sec. During the 15-sec. interval the sensation level should be adjusted such that the noise is barely audible. The adjustment is not critical, but in the following demonstrations high uncomfortable levels should be avoided; they are not necessary to perceive the effects.

4. "Frères Jacques" melody, note range: G2 (98 Hz) – A3 (220 Hz)
A well-known melody is played with the MPSP signal. The duration of the notes is chosen equal as to exclude rhythmic information, which might have been helpful in recognizing the melody. Repeat the track and try to lift one of the headphones (while avoiding acoustic

cross talk) as to experience that dichotic pitch needs both the left and right ear stimulated simultaneously.

5. “Frères Jacques” melody, note range: G3 (196 Hz) – A4 (440 Hz)
The same melody in a different note range. (The tuning of the MPSP signal might possibly be experienced as not always perfect, especially at the higher notes. This is due to the relatively low sampling frequency of 10 kHz used during signal generation for all demonstrations.)

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DESCRIPTION OF SIGNALS AND PITCH WITH CS THEORY

Central Activity Pattern (CAP) and Central Spectrum (CS)

A successful theoretical concept to explain dichotic pitch is the Central Spectrum (CS) theory (Bilsen, 1977; Raatgever and Bilsen, 1986). Based on cochlear frequency analysis and Jeffress' binaural cross correlation network (Jeffress, 1948; Colburn, 1973), it calculates a *"Central Activity Pattern (CAP)"* as a function of frequency and internal delay (see Fig. 1). The central pitch processor scans this CAP for familiar spectral patterns. For example, a sharp isolated peak will give rise to a pure-tone-like pitch. A well-modulated periodic spectral pattern at a particular internal delay will give rise to a "low" pitch comparable to repetition pitch or periodicity pitch (residue pitch, virtual pitch). In general, the pattern selected, the *"Central Spectrum (CS)",* is claimed to predict the value of the pitch; the internal delay where the pattern is found, determines the perceived lateral position of the pitch image.

The CS theory was devised for qualitative understanding rather than for exact quantitative prediction of central spectra. Detailed physiological and psychophysical knowledge of the peripheral hearing organ is not built in, although peripheral filtering is included formally in the original formulation of the model. Its elegance still is its mathematical simplicity, providing insight with a minimum of calculus. Because of its success in the past, and also for didactical reasons, the calculations below are confined to the idealized case of infinitely sharp frequency analysis. Also temporal jitter in the cross correlation process is not included.

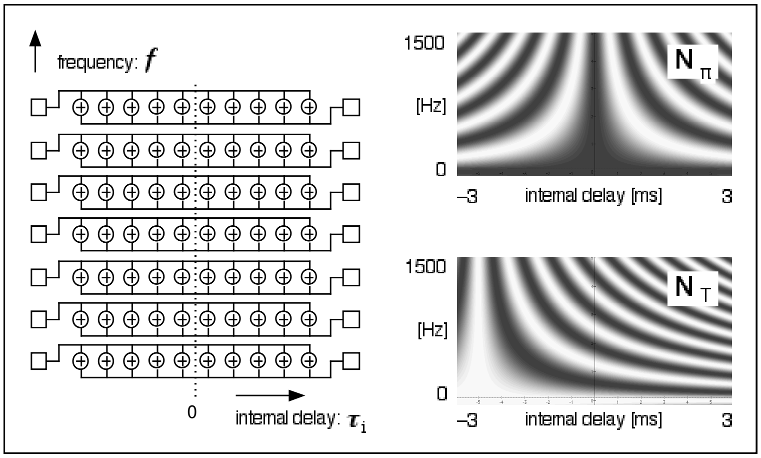

Fig. 1. Schematics of the Central Spectrum theory. On the left, a binaural interaction network is shown composed of a series of left-ear and right-ear auditory filters. Corresponding filters are connected by tapped delay lines and adders which include a squaring function. The (power) output of all these units together constitutes the Central Activity Pattern (CAP). Examples of CAPs are shown on the right for out-of-phase noise (N_π) and noise with interaural delay (N_T). The relevant frequency span (0 to 1500 Hz) and internal delay (–3 to 3 ms) are indicated. No weighting (in time or frequency) is applied.

The selection mechanism for a Central Spectrum to be a serious candidate as predictor of pitch was not mathematically specified in the original formulation of the model (Raatgever and Bilsen, 1986). Instead, the following *selection criteria* for the scanning process as described above were assumed:

(1) resemblance with familiar (monaural) spectral patterns, for example, a single isolated spectral peak, or a series of equidistant peaks,
(2) common internal delay ("straightness") for a series of spectral peaks, or near-straightness for dominant harmonics (Bilsen and Raatgever, 1973),
(3) maximum modulation depth in the spectrum selected. In the idealized formulation, this requirement will simply be fulfilled by claiming an *infinite peak-to-valley ratio*.

Assuming *idealized* frequency analysis the (normalized) Central Activity Pattern (CAP) can be expressed in three alternative ways (see Raatgever and Bilsen, 1986) by

$$\mathrm{CAP}(f,\tau_i) = [H(f) + \exp j2\pi f\tau_i]^2 , \quad (1a)$$
$$= 1 + \mathrm{Re}\{S_{rl}(f)\exp j2\pi f\tau_i\} , \quad (1b)$$
$$= 1 + \cos\{\phi(f) + 2\pi f\tau_i\} , \quad (1c)$$

with *f* frequency and τ_i internal delay. $H(f)$ represents the complex interaural transfer function with $|H(f)|^2 = 1$ for white noise as input, $S_{rl}(f)$ the cross-power spectral density, and $\phi(f)$ the interaural phase relationship. Either variant of Eq. (1) is used below in the calculation of the CAP of a particular dichotic pitch phenomenon. Only the resulting equation will be shown for each case.

Some demonstrations are devoted to the notion that dichotic pitch images behave like *"time images"* (Bilsen et al., 1978; see also Hafter and Jeffress, 1968), as they show hardly any sensitivity to interaural intensity differences (IIDs) (e.g. Raatgever and Bilsen, 1986). The CS theory is in agreement with this experimental fact, because IIDs only appear to affect the modulation depth of central spectra resulting in a decrease of the salience of the pitch, not its value nor its intracranial position (compare Eq. 1). In contrast, the image(s) belonging to the noise percepts itself are notably affected by an IID.

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HUGGINS PITCH (HP)

The first binaural pitch phenomenon found in the literature is the Huggins Pitch (HP) (Cramer and Huggins, 1958). It is created by dichotic broad-band noise having a transition frequency region over which the interaural phase changes by 2π radians. Such a phase shift can be accomplished by an all-pass filter consisting of a bypassed 2^{nd}-order system (see Fig. 2, left panels).

The dichotic pitch resembles a fluctuating pure tone as if it were generated by a narrow band of noise. It exists for center frequencies in the range 200-1000 Hz. It is optimally salient for about 600 Hz and for a transition bandwidth (π range) of about 6% of the transition-center frequency (Cramer and Huggins, 1958; Guttman, 1962).

The CAP of this HP^+ case is also visualized in Fig. 2, bottom right panel. Inspection reveals that a clear CS candidate is to be selected at the center as indicated by the windowed arrow. It is a single peak (Fig. 2, upper right). This explains both the pure tone character and the perceived position of the HP image.

If an additional π-phase shift is added to one of the ears (HP^- case), the pitch image jumps to the left or right ear depending on one's attention or "side dominance". Indeed, the CAP now displays a dip instead of a peak at the center. Instead, a distinct peak is now to be seen at an internal delay equal to half the period of the transition frequency.

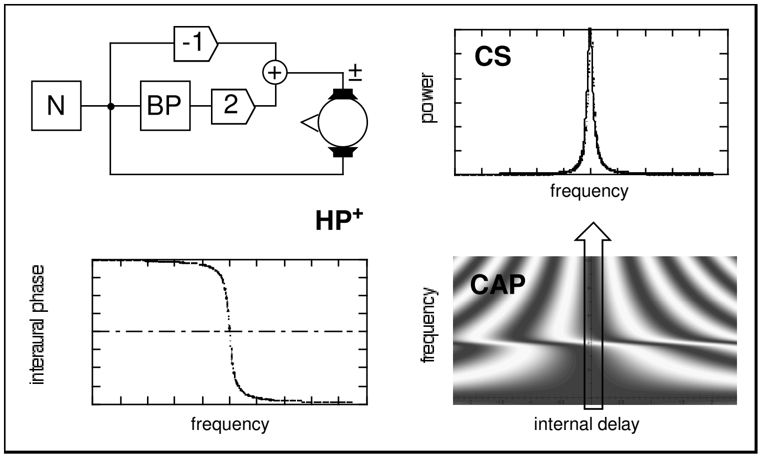

Fig. 2. Schematics of the Huggins Pitch (HP) configuration. Central Activity Pattern (CAP) and selected Central Spectrum (CS) for the case of HP^+ (see interaural phase pattern, bottom left) are shown. Following the CS shape and its position in the CAP, the pitch and timbre are predicted to resemble a warbling pure tone (narrow band of noise), positioned in the middle of the head amidst the stimulus noise.

CD tracks

6. HP^+, 2-octave scale up/down: C4 (262 Hz) ⇔ C6 (1047 Hz)
CS theory predicts this pitch to be perceivable as a fluctuating pure tone in the center of the head. Note that the notes between 400 and 700 Hz have highest pitch strength.

7. HP^+ versus HP^- with 600/660-Hz tone interval
An extra phase shift of π radians in alternation with 0 radians is introduced. CS theory predicts the pitch interval to be shifted back and forth between the center of the head and a lateralized position towards the left or right ear.

8. HP^+ versus HP^- with 250/275-Hz tone interval
Similar as 7 but for a lower pitch. Note that the pitch is weaker, but the lateralization span is wider.

9. HP^-, 2-octave scale up/down: C4 (262 Hz) ⇔ C6 (1047 Hz)
Following 6 and 7, the scale is lateralized towards the left or right ear. Try to estimate the lateralized position of each note.

10. "Diotic HP^+", 2-octave scale: C4 (262 Hz) ⇔ C6 (1047 Hz)
The left- and right-ear signals have been added. This results in the well-known sound of a narrow band of noise. It is expected to resemble the sound in the center of the CAP, i.e. the Huggins Pitch.

11. "Diotic HP^+ versus HP^- " with 600/660-Hz interval
Following 7 and 10, the alternation of a pitch interval and just white noise is expected.

12. Lateralization of HP^+ with ITD from –0.8 to 0.8 ms in 0.4-ms steps

A 600/660-Hz HP interval is presented five times at each of five different ITDs. The pitch interval should be perceived moving stepwise from right to left.

13. "Diotic Central Spectra" for τ_i from –0.8 to 0.8 ms in 0.4-ms steps

This track is intended to demonstrate how, for a 600/660-Hz HP interval, CS theory expects hypothetical central spectra at five different internal delays in the CAP to sound. Therefore, the left- and right-ear signals were added after the inclusion of an extra delay at the right-ear channel. Note that the pitch strength is low to very low for these spectra, except for internal delay 0, which represents the perceived HP.

14. Lateralization of HP^+ with IID range of –6 dB to +12 dB

CS theory predicts that the perceived lateralized position of a dichotic pitch image is hardly dependent on IIDs. Only pitch strength is expected to change with IID. To demonstrate this "time image" behaviour, a five-times repeated 600/660-Hz HP interval is presented for three different Δ*Ls at the right-ear signal, in succession: 0, +6, 0, -6, 0, -12, and 0 dB.*

15. HP^+, 600 Hz, continuous for measuring purposes

16. HP^-, 600 Hz, continuous for measuring purposes

17. "Diotic HP^+", 600 Hz, continuous for measuring purposes

Remarks

- The lateralization of dichotic pitches was originally observed with MPSP (see below). Both for HP^+ and HP^- it was investigated that the addition of an extra interaural delay caused a pitch-image shift that could be matched with a white noise pointer, and that showed hardly any sensitivity to IIDs (Raatgever, 1980, Raatgever and Bilsen, 1986).

- Using Eq. (1a) and the expression for $H(f)$ as given by Cramer and Huggins (1958) the (idealized) CAP for the case of HP^{+} is calculated as

$$\mathrm{CAP}(f,\tau_i) = [\frac{(\omega_c^2-\omega^2)^2-4\mu^2\omega^2}{(\omega_c^2-\omega^2)^2+4\mu^2\omega^2} - \cos\omega\tau_i\,]^2 + \\ +[\frac{4\mu\omega(\omega_c^2-\omega^2)}{(\omega_c^2-\omega^2)^2+4\mu^2\omega^2} + \sin\omega\tau_i\,]^2, \qquad (2)$$

  where $\omega = 2\pi f$, $\omega_c = 2\pi f_c$, with f_c the transition-center frequency and μ half the transition bandwidth. Putting $\tau_i = 0$ gives the expression for CS.

- Culling et al. (1998a) showed that if one incorporates realistic peripheral auditory functions and an automatic CS-selection process, the (enriched) CS model essentially predicts the same pitch values. Additionally, the enriched model is able to predict the disappearance of the pitch if the transition bandwidth becomes too small. This is easily explained by the limitations imposed by the auditory filter bandwidth.

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MULTIPLE PHASE SHIFT PITCH (MPSP)

Using an all-pass-filter concept designed originally for artificial reverberation (Schroeder, 1962), Bilsen (1976) found that it was possible to create a dichotic stimulus with which untrained subjects could easily recognize a dichotic pitch melody. Block schematics of this stimulus are given in Fig. 3. On purpose, its interaural phase function shows a series of equidistant Huggins-type phase shifts.

The strong dichotic pitch evoked by this stimulus for delay times *T* in the range of 3 to 10 ms and a feedback factor *g* of about 0.7 (g=0.7 was actually used for the present CD), was correspondingly called Multiple Phase Shift Pitch (MPSP). It has a "low" (residue, periodicity, virtual) pitch character, very similar to that of comb-filtered white noise (Bilsen and Raatgever, 1983; Raatgever and Bilsen, 1986).

By visual inspection of the CAP of Fig. 3 (the case of MPSP^{+}) and applying the general CS-selection rules, the obvious CS follows for internal delay zero as indicated by the windowed arrow. This predicts the pitch to be a low pitch indeed, perceived in the middle of the head.

For the MPSP^{-} case (having an extra interaural phase shift of π radians) the CAP provides dips instead of peaks at $\tau_i = 0$. However, the (nearly-straight) harmonics in the dominant frequency region around 0.6 kHz (Bilsen and Raatgever, 1973), thus at $\tau_i = \pm 0.8$ $(= 0.5 * 1/0.6)$ ms on the average, provide two pitch candidates being ambiguous in lateralized place.

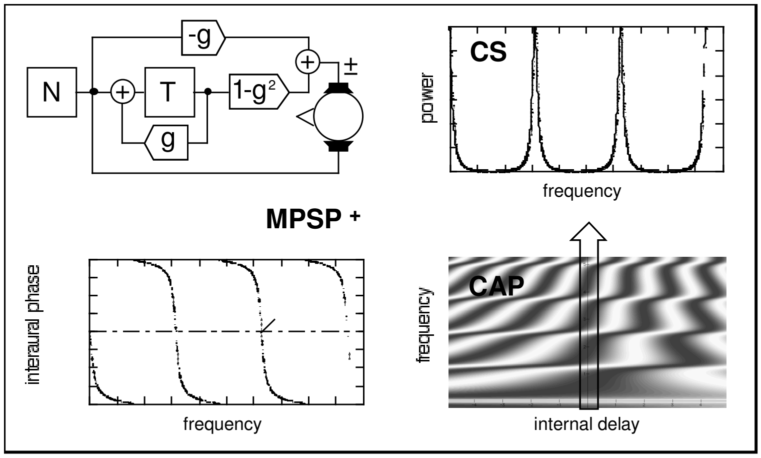

Fig. 3. Schematics of the Multiple Phase Shift Pitch (MPSP) configuration. Central Activity Pattern (CAP) and selected Central Spectrum (CS) for the case of MPSP$^+$ (see interaural phase pattern, bottom left) are shown. Following the CS shape and its position in the CAP, the pitch and timbre are predicted to resemble a "low" (periodicity, residue, virtual) pitch, positioned in the middle of the head amidst the stimulus noise.

CD tracks

18. MPSP^+, 2-octave scale up/down: G2 (98 Hz) ⇔ G4 (392 Hz)
CS theory predicts this pitch to resemble a low pitch based on higher harmonics (synonymously: periodicity pitch, virtual pitch, residue pitch). Therefore, the range of the scale had to be chosen differently from HP (compare track 6). The position of the pitch image is expected to be perceived in the very center of the head.

19. "Diotic MPSP^+", 2-octave scale: G2 (98 Hz) ⇔ G4 (392 Hz)
The left and right ear signals have been added (compare track 10). The resulting (diotic) signal has an harmonic comb spectrum and produces a very strong pitch.

20. MPSP^+ versus MPSP^- with 200/220-Hz interval
Similarly to track 7 and 8, an extra phase shift of π radians in alternation with 0 radians is introduced. CS predicts the pitch interval to be shifted back and forth between the center of the head and a lateralized position towards the left or right ear.

21. MPSP^-, 2-octave scale up/down: G2 (98 Hz) ⇔ G4 (392 Hz)
Similarly to track 9, the pitch scale is perceived away from the center of the head. Try to estimate the lateralized position of each note.

22. Lateralization of MPSP^+ with ITD from –0.8 to 0.8 ms in 0.4-ms steps
Similarly to track 12, a 200/220-Hz MPSP interval is presented five times at each of five different ITDs: 0.8, 0.4, 0, -0.4, and -0.8 ms. The perceived pitch interval is expected to move stepwise from right to left.

23. "Diotic Central Spectra" for τ_i from –0.8 to 0.8 ms in 0.2-ms steps
Similarly to track 13, this track is intended to demonstrate how, for a 200/220-Hz MPSP interval, CS theory expects hypothetical central spectra at nine different internal delays in

the CAP to sound. Therefore, the left- and righ-ear signals were added after the inclusion of an extra delay at the right-ear signal. Note that the pitch strength is low to very low for these spectra, except for internal delay equal to zero.

24. Lateralization of MPSP^{+} with IID range of –6 dB to 12 dB
CS theory predicts that the perceived lateralized position of a dichotic pitch image is hardly dependent on IIDs. Only pitch strength is expected to change with IID. To demonstrate this, a five-times repeated 200/220-Hz MPSP interval is presented for three different ΔLs at the right-ear signal, in succession: 0, +6, 0, -6, 0, -12, and 0 dB (Compare track 14).

25. MPSP^{+}, 200 Hz, continuous for measuring purposes

26. MPSP^{-}, 200 Hz, continuous for measuring purposes

27. "Diotic MPSP^{+}", 200 Hz, continuous for measuring purposes

Remarks

- Using a BMLD paradigm with a centralized probe tone of varying frequency, a masking pattern resembling the central spectrum could be measured. Also, by applying an extra interaural delay to the stimulus the lateralization of MPSP could be established (Raatgever and Bilsen, 1977, 1986; Raatgever, 1980).

- Measurements with "scattered harmonics" showed that straightness (equal τ_i for central spectral peaks) should not be considered a severe restrictive criterion for MPSP to arise (Bilsen et al., 1998).

• Using Eq. (1b) the CAP for the case of MPSP^{+} is calculated as

$$\mathrm{CAP}(f,\tau_i)=1+\frac{\cos 2\pi f(T-\tau_i)+g^2\cos 2\pi f(T+\tau_i)-2g\cos 2\pi f\tau_i}{1+g^2-2g\cos 2\pi fT}\,, \qquad (3)$$

with feedback factor *g* and delay time *T*. The CS follows by putting $\tau_i = 0$.

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ASYMMETRIC FOURCIN PITCH (AFP)

Speculating about a possible explanation of the Huggins Pitch in terms of its cross correlation function (compare Licklider, 1959), Fourcin (1962) searched for a stimulus producing two well-defined lateralization peaks. A stimulus synthesized from the binaural presentation of two independent noises, which individually ought to be pitch-free, provided such a two-peak cross correlation function. The simplest configuration he could think of consisted of a single interaurally delayed noise together with a second independent (uncorrelated) in-phase or out-of-phase noise.

In general, if two independent noises with interaural delays T_1 (in the range of 3-10 ms) and T_2 (< 2 ms) respectively are presented simultaneously, a clear sensation of dichotic pitch is observed. Its pitch value (Fourcin, 1962, 1964, 1970; Bilsen and Goldstein, 1974; Bilsen and Wesdorp, 1974; Bilsen, 1977) and pitch image position (Raatgever and Bilsen, 1977; Bilsen and Raatgever, 2000) depend on T_1, T_2, and the interaural polarities. Pitch and timbre resemble Monotic Repetition Pitch, thus being a low (residue, periodicity, virtual) pitch. Because of the asymmetry of the cross correlation function (generally $T_1 >> T_2$) this pitch is called asymmetric Fourcin Pitch (aFP).

Fig. 4 presents an example of aFP_{-}^{+} with $T_2 \approx 0$. The CAP follows as the superposition of the CAPs of N_T and N_π (compare Fig. 1). The windowed arrow indicating the CS candidate coincides with the N_π trough.

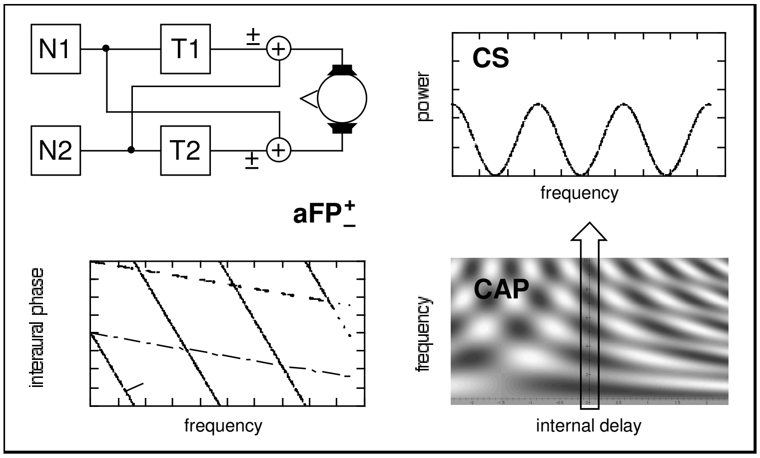

Fig. 4. Schematics of the asymmetric Fourcin Pitch (aFP) configuration with typically $T_1 >> T_2$ for the case of aFP$^{+}_{-}$ (see interaural phase pattern, bottom left). Central Activity Pattern (CAP) and selected Central Spectrum (CS) are shown on the right. Following the CS shape and its position in the CAP, the pitch and timbre are predicted to resemble a Repetition Pitch (compare low, periodicity, residue, virtual pitch), positioned in the middle of the head amidst the stimulus noise.

CD tracks

28. aFP_{-}^{+}, $T_2 = 0$, 2-octave scale up/down: G2 (10.20 ms) ⇔ G4 (2.55 ms)

CS theory predicts this pitch to resemble a low pitch based on higher harmonics. Therefore, the range of the scale had to be chosen similar as for MPSP. The position of the pitch image is expected to be in the center of the head.

29. aFP_{-}^{+} versus aFP_{+}^{+}, for $T_1 = 5$ ms and $T_2 = 0$ ms

Starting and ending with the +– stimulus, the ++ stimulus is presented five times in alternation with the former. CS theory predicts the ++ stimulus to be perceived as an ambiguous pitch, the lower lateralized towards the left and the higher towards the right ear.

30. aFP_{+}^{+}, $T_2 = 0$, 2-octave scale up/down with T_1: 10.20 ms ⇔ 2.55 ms

As this stimulus is predicted to evoke an ambiguous pitch, ambiguously lateralized to the left or to the right (compare track 29), a scale is probably perceived with tonal and positional randomness of individual notes. Try to concentrate on one of the possibilities.

31. Lateralization of aFP_{-}^{+}, T_1 = 5-4.5 ms, $0.8 > T_2 > -0.8$ in 0.4-ms steps

CS theory predicts that changes in the smaller interaural delay alter the position of the perceived pitch image. Simultaneously, notwithstanding the fixed 5-4.5-ms interval in the larger delay (presented five times for each position), the perceived interval changes in pitch with its lateralized position going from right to left.

32. aFP_{-}^{+}, $T_1 = 5$ ms, $T_2 = 0$ ms, continuous for measuring purposes

33. aFP_{+}^{+}, $T_1 = 5$ ms, $T_2 = 0$ ms, continuous for measuring purposes

Remarks

- An expression for the CAP of aFP_{-}^{+} is readily obtained from Eq. (1c) as the (power) sum of two (uncorrelated) CAPs with $\phi(f) = 2\pi f T_{1,2}$ respectively, thus

$$\mathrm{CAP}(f, \tau_i) = [1 + \cos\{2\pi f(T_1 + \tau_i)\}] + [1 - \cos\{2\pi f(T_2 + \tau_i)\}]. \qquad (4)$$

  This predicts a CS resembling a cosinusoidal power spectrum, which gives rise to a pitch equal to $1/(T_1 - T_2)$ at $\tau_i = -T_2$ (compare Fig. 4, where T_2 is chosen close to zero). Note that the modulation depth of the CS is equal to infinity, although a higher output is found at other places in the CAP.

- Predictions by the enriched CS theory show generally comparable results (Culling et al., 1998b; see also Bilsen and Raatgever, 2000).

- In accordance with CS theory, pitch values and their lateralizations can already be prognosed from the interaural phase patterns (see figures 2 to 7, bottom left) by inspecting the intersections with dash-dotted lines. These lines being straight and going through the origin (0 phase, 0 frequency) symbolize an internal delay τ_i similar to an interaural delay *T*.

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SYMMETRIC FOURCIN PITCH (SFP)

Recently, Bilsen and Raatgever (2000) reported a novel pitch, which they choose to be considered a special case of Fourcin Pitch. Instead of a relatively small together with a relatively large interaural delay, they exploited two nearly-equal but opposite delays, i.e. with one noise interaurally delayed in one ear and the second (independent) noise interaurally delayed by about the same amount in the contralateral ear (compare Fig. 5). For this particular near-symmetric configuration the pitch (to be called: "symmetric" Fourcin Pitch, or abbreviated sFP) and timbre resemble the classical Fourcin Pitch (aFP) but its pitch image is more compact and well-defined (lateralized).

Results of informal listening by 14 subjects for a "pitched quality" in a strictly symmetric configuration, with continuously variable delays between 1 and 4 ms, were reported by Fourcin (1962). However, sFP appeared to manifest itself most clearly for delays between 4 and 10 ms (Bilsen and Raatgever, 2000). Their experiments were organized such that subjects had to determine, in consecutive order for each parameter setting, both the pitch value by matching with a diotic pitch and the lateralized position of the pitch image by adjusting an ITD pointer.

Fig. 5 presents an example of sFP^{++} with $T_1 \approx T_2$. The CAP can be understood as the superposition of two mirrored N_T-type CAPs (compare Fig. 1). An obvious CS candidate is found for an internal delay of about zero, which again is able to predict the pitch value and the position of the pitch image for this case.

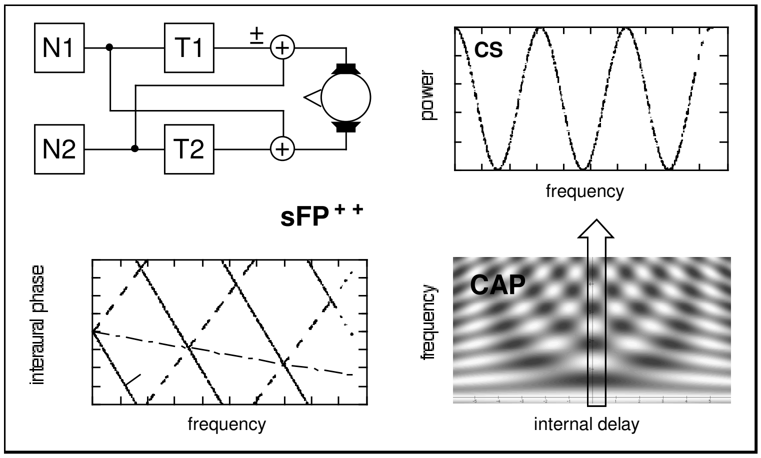

Fig. 5. Schematics of the symmetric Fourcin Pitch (sFP) configuration with typically $T_1 \approx -T_2$*. Central Activity Pattern (CAP) and selected Central Spectrum (CS) for the case of* sFP^{++} *(see interaural phase pattern, bottom left) are shown. Following the CS shape and its position in the CAP, the pitch and timbre are predicted to resemble a Repetition Pitch (compare low, periodicity, residue, virtual pitch), positioned close to the middle of the head amidst the stimulus noise.*

CD tracks

34. sFP^{++}, 2-octave scale up/down: G2 (10.20 ms) ⇔ G4 (2.55 ms)
For this track, both delays were chosen equal to T (perfect symmetry). Here CS theory predicts that, contrary to aFP, the sFP stimulus evokes an unambiguous pitch, equal to the reciprocal value of T, positioned in the very center of the head.

35. sFP^{++} versus sFP^{+-} for $T = T_1 = T_2 = 7$ ms
Starting and ending with the ++ stimulus, the +– stimulus is presented four times in alternation with the former. CS theory predicts the +– stimulus to be perceived as an ambiguous (lower or higher) pitch lateralized left or right from the center of the head.

36. sFP^{+-}, 2-octave scale up/down with T: 10.20 ms ⇔ 2.55 ms
As this stimulus is predicted to evoke an ambiguous pitch, ambiguously lateralized to the left or to the right (compare track 35), a scale is probably perceived with tonal and positional randomness of individual notes. Try to concentrate on one out of four possibilities.

37. Lateralization of sFP^{++}, T = 7–6.3 ms, $-0.4 < \Delta T < 0.4$ in 0.2-ms steps
A ++ stimulus interval is presented five times for each value of ΔT (see text with Eq. (5)). CS theory predicts that with changing ΔT the lateralized position of the pitch image changes but not the value of the pitch interval itself. The position should shift from 0.4 ms right from the center towards 0.4 ms left from the center, in five 0.2-ms steps.

38. Lateralization of sFP^{++}, T = 7–6.3 ms, –6 dB < IID < 12 dB
CS theory predicts that the perceived lateralized position of a dichotic pitch image is hardly dependent on IIDs. Only pitch strength is expected to change with IID. To demonstrate this "time image" behaviour, a five-times repeated 7–6.3-ms interval is

presented for three different ΔLs at the right-ear signal, in succession: 0, +6, 0, –6, 0, –12, and 0 dB.

39. sFP^{++}, $T_1 = T_2 = 7$ ms, continuous for measuring purposes

40. sFP^{+-}, $T_1 = T_2 = 7$ ms, continuous for measuring purposes

Remark

- Like for aFP, the CAP for the case of sFP^{++} follows from Eq. (1c) with $\phi_1(f) = 2\pi f T_1$ and $\phi_2(f) = -2\pi f T_2$ as

$$\mathrm{CAP}(f, \tau_i) = 2 + \cos 2\pi f(T_1 + \tau_i) + \cos 2\pi f(-T_2 + \tau_i) \,. \qquad (5)$$

This predicts a CS corresponding to a cosinusoidal power spectrum with a pitch equal to $2/(|T_1| + |T_2|)$ at a lateralized position equal to $\tau_i = -\Delta T$ with $\Delta T = (|T_1| - |T_2|)/2$. Fig. 5, lower right panel, shows the CAP for $T_1 \approx T_2$. Similarly, for the case of sFP^{+-} an ambiguous pitch, ambiguously lateralized towards the left or the right, is predicted. A survey of different possibilities is given by Bilsen and Raatgever (2000).

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DICHOTIC REPETITION PITCH (DRP)

In contrast with the conditions for the Fourcin Pitch, also a dichotic pitch can be perceived with stimuli consisting of only a single interaurally delayed white noise. Reports came from Bilsen (1972, 1995), Bilsen and Goldstein (1974), Warren et al. (1981), and Culling (1996). It was not reported by Blodgett et al. (1956) though they studied the sidedness of interaurally delayed noise with relatively large interaural delays. Further, its existence was denied by Fourcin (1962, 1970), disputed but finally confirmed by Hartmann (1996, 2001).

Typically, this so called Dichotic Repetition Pitch (DRP) is generally perceived in the middle of the head and its pitch and timbre resemble Monotic Repetition Pitch, thus being a low (residue, periodicity, virtual) pitch. Delays reported are in the range of 4 to 20 ms.

The CAP for the case of DRP^+ is presented in Fig. 6. Note that for each value of the internal delay a well-modulated cosinusoidal function of frequency can be found waxing and waning between 0 and 1, thus with a peak-to-valley ratio equal to infinity. This implies that no pitch at all might be expected due to mutual competition of an infinite number of candidate spectra. The historical reports of a single faint pitch in the center of the head are reconciled with the CS model only if strong prevalence for the central position would be assumed. However, other data on dichotic pitch but also data on lateralization with conventional stimuli plead against such an assumption.

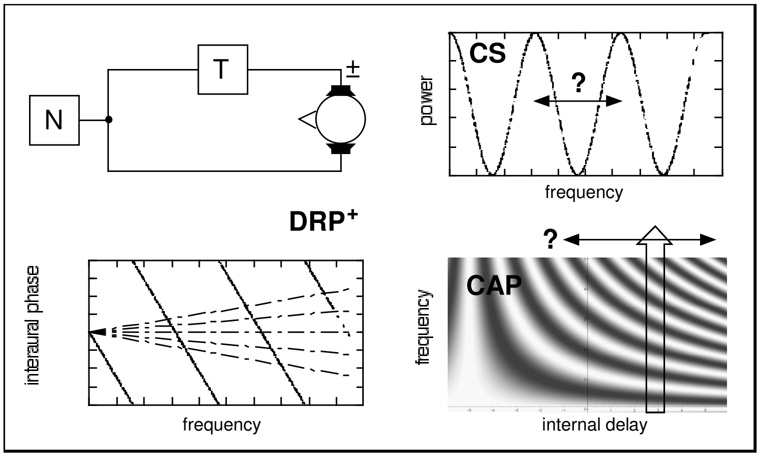

Fig. 6. Schematics of the Dichotic Repetition Pitch (DRP) configuration. Central Activity Pattern (CAP) and selected Central Spectrum (CS) for the case of DRP^{+} (see interaural phase pattern, bottom left) are shown. Following the CS shape, pitch and timbre are predicted to resemble a Repetition Pitch (compare low, periodicity, residue, virtual pitch). Theoretically, an infinite number of combinations of pitch value and pitch image position is offered. Usually, one perceives only the pitch in the middle of the head.

CD tracks

41. DRP^+, 2-octave scale up/down: G2 (10.20 ms) ⇔ G4 (2.55 ms)
CS theory predicts an infinite number of possible pitches (scales), each with its own particular lateralized position of the pitch image. Usually, one only perceives the pitch in the center of the head corresponding to 1/T. Try to concentrate on other positions also.

42. "Diotic DRP^+" (= MRP^+) scale: G2 (10.20 ms) ⇔ G4 (2.55 ms)
By adding the left and right-ear signals the well-known MRP stimulus is obtained. Its power spectrum is a cosinusoidal function of frequency. Its pitch is less strong than the pitch of a comb spectrum (compare track 19).

43. DRP^+ versus DRP^- for $T = 5$ ms
A – stimulus is alternating with a + stimulus (In fact the polarity in one ear is changed alternatingly), five times. Try to experience the ambiguity of the – stimulus: its pitch might be higher or lower.

44. DRP^-, 2-octave scale up/down with T: 10.20 ms ⇔ 2.55 ms
Due to the ambiguity of each single note (compare track 43) and its multi-valence (see 41) this pitch scale might be hard to follow.

45. MRP^+ lateralization, $T = 5$–4.5 ms, $-0.8 < ITD < 0.8$ in 0.2-ms steps
This stimulus has been included in the CD to serve as a training stimulus for experiencing the lateralization of a pitch interval (Compare track 2).

46. DRP^+, $T = 5$ ms, continuous for measuring purposes

47. DRP^-, $T = 5$ ms, continuous for measuring purposes

48. "Diotic DRP^+" ($=\mathrm{MRP}^+$), T = 5 ms, continuous

Remarks

- With Eq. (1c) the CAP for the case of DRP^+ follows as

$$\mathrm{CAP}\ (f, \tau_i) = 1 + \cos(2\pi fT + 2\pi f \tau_i) \tag{6}$$

  with T the single interaural delay. A cosinusoidal power spectrum and a pitch equal to $1/T$ is correctly predicted for $\tau_i = 0$, but other pitches equal to $1/(T + \tau_i)$ are expected at other possible values of τ_i in the CAP.

- Recent measurements by Bilsen (2001) may be considered as evidence for the perceptual existence of a continuum of possible pitches as predicted above. The listening process of "finding" individual DRP percepts seems best described as trying hard to concentrate on a particular point on the lateralization axis. Sometimes, after some time (order of magnitude 10 sec.), such a pitch percept appeared to "pop out" of the noise filling the head.

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BINAURAL (COHERENCE) EDGE PITCH (BEP, BICEP)

Following the review of the pitch of noise signals (Bilsen, 1977), Klein and Hartmann (1981) devised a dichotic pseudo-noise signal with a gradual interaural phase transition from 0 to π, instead of 0 to 2π as with the HP stimulus. They observed a pitch which they described to be similar in nature to HP and which they called Binaural Edge Pitch (BEP). It was found strongest for edge frequencies in the 350-800 Hz range. Pitch matching experiments revealed that this pitch is about 4% higher or lower than the edge frequency, identically to the shift which was found for the pitch of (monaural) high-pass or low-pass noise bands.

Because of the choice for gaussian-noise stimuli, the BEP signal used on the present CD had to be realized slightly different from its original definition. The block schematic in Fig. 7 shows that a BEP^{+}_{-} stimulus is obtained by the addition of an interaurally out-of-phase low-pass noise and an in-phase high-pass noise from a second (uncorrelated) source. The interaural phase transition from 0 to π (BEP^{-}_{+}) or alternatively from π to 0 (BEP^{+}_{-}) results not as a gradual transition but as a distribution of phase angles randomly varying between 0 and π radians at the edge frequency.

The CAP of BEP^{+}_{-} is plotted in Fig. 7. For different values of the internal delay irregular central spectra can be observed. Only for an internal delay equal to zero as indicated by the windowed arrow, a CS results shaped exactly like a high-pass noise with a steep edge. Secondary (nearly-straight) candidate CSs resembling a low-pass noise instead, appear in the frequency region around the edge frequency at a negative and positive internal delay equal to half the period of the edge frequency.

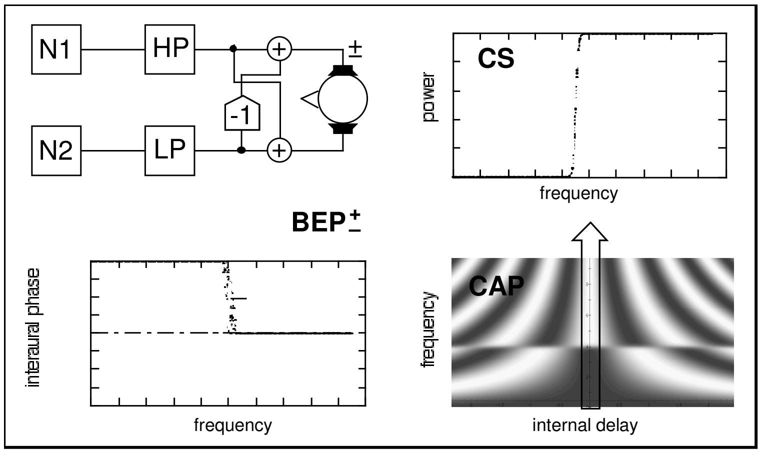

Fig. 7. Schematics of the Binaural Edge Pitch (BEP) configuration. Central Activity Pattern (CAP) and first-candidate Central Spectrum (CS) for the case of BEP^{+}_{-} (see interaural phase pattern, bottom left) are shown. Following the CS shape and its position in the CAP, the pitch and timbre are predicted to resemble the pitch of a high-pass noise, positioned in the middle of the head amidst the stimulus noise.

Following a suggestion by N.I. Durlach, a variant of the BEP stimulus was studied by Hartmann and McMillon (2001). It was recognized that one could possibly avoid the ambiguity in pitch found with BEP by making the noise interaurally incoherent above or below the edge frequency. Thus a pitch sensation similar to BEP was found but with a unimodal instead of a bimodal distribution. It was found to exist for edge frequencies between 300 and 1000 Hz and it was called Binaural Coherence Edge Pitch (BICEP). It is matched by a pure tone that differs from the edge frequency by 5 to 10% and, importantly, lies on the incoherent side of the edge.

The BICEP signal used with the present CD is given in the upper left panel of Fig. 8 for the case of incoherence below and interaural antiphase above the edge frequency (to be indicated by $\mathrm{BICEP}^{-}_{\mathrm{ic}}$). Interaural incoherence is obtained by presenting two uncorrelated gaussian noises to the left and right ear. The coherent part, either in-phase ($\mathrm{BICEP}^{+}_{\mathrm{ic}}$) or out-of-phase ($\mathrm{BICEP}^{-}_{\mathrm{ic}}$), is obtained from a third (uncorrelated) noise source.

The CAP of $\mathrm{BICEP}^{-}_{\mathrm{ic}}$ is shown in the lower right panel of Fig. 8. Only one CS candidate is obvious, i.e. resembling a low-pass spectrum at internal delay zero. Remind that according to CS theory an infinite peak-to-valley ratio is required around the edge frequency. Thus, contrary to BEP, no candidate spectra (high pass) left and right from the middle are selected. This uniquely explains both the unimodal pitch and its shift into the low-pass band.

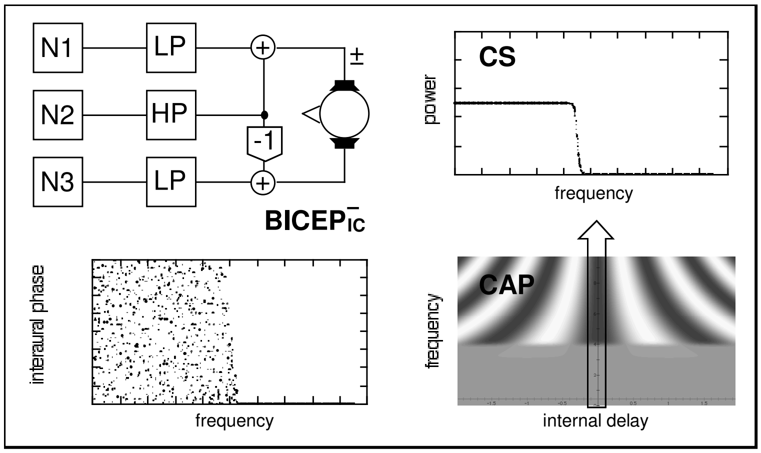

Fig. 8. Schematics of the Binaural Coherence Edge Pitch (BICEP) configuration. Central Activity Pattern (CAP) and selected Central Spectrum (CS) for the case of BICEP$_{ic}^{-}$ (see interaural phase pattern, bottom left) are shown. Following the CS shape and its position in the CAP, the pitch and timbre are predicted to resemble the pitch of a low pass noise, positioned in the middle of the head amidst the stimulus noise.

CD tracks

49. BEP_{+}^{-}, 2-octave scale up/down: C4 (262 Hz) ⇔ C6 (1047 Hz)

CS theory predicts that this signal primarily creates a low-pass noise spectrum in the center of the head. One might observe that the pitch (scale) connected to the edge frequency is heard more easily when it goes up than when it goes down. Alternatively, one might perceive a pitch scale that is connected to a high-pass noise lateralized towards the left or right ear or broadly fused in the center. The latter pitch might be more easily perceivable when falling compared to rising.

50. $BICEP_{ic}^{-}$, 2-octave scale up/down: C4 (262 Hz) ⇔ C6 (1047 Hz)

Following CS theory, this signal creates a pitch connected to a low-pass noise in the center of the head. Contrary to the BEP stimulus of track 49, the alternative possibility of a lateralized high-pass noise is absent here.

51. "Diotic $BEP_{+}^{-}/BICEP_{ic}^{-}$ ", scale: C4 (262 Hz) ⇔ C6 (1047 Hz)

By adding the left- and right-ear signals of the above stimuli a diotic low-pass noise signal is created. As known from literature, this evokes a pitch sensation connected to the cut-off frequency. Note the perceptual analogy of this signal with its dichotic counterparts.

52. BEP_{-}^{+}, 2-octave scale up/down: C4 (262 Hz) ⇔ C6 (1047 Hz)

This stimulus creates a high-pass noise in the center of the head and secondary low-pass noises left and right from the center. The pitch scale connected to the high-pass noise seems easier perceived when it goes down than when it goes up. The opposite is the case with the pitch connected to the lateralized low-pass noises. Rivalry may result if one does not stay concentrated on either one.

53. "Diotic $BEP_{-}^{+}/BICEP_{-}^{ic}$", scale: C4 (262 Hz) ⇔ C6 (1047 Hz)

By adding the left- and right-ear signals of these dichotic stimuli, a high-pass noise is obtained which produces a pitch connected to the cut-off frequency. Is not this pitch stronger when the scale is falling instead of rising?

54. BEP_{+}^{-} versus BEP_{-}^{+}, dichotic-diotic-dichotic, 600 Hz

When switching from low-pass to high-pass noise and vice versa, be it dichotic or diotic, while keeping the edge frequency constant, a small change in pitch might be observable. This would confirm results from the literature showing that the pitch of low- and high-pass noise is shifted into the noise, away from the cut-off (edge) frequency. The demonstration contains three times the dichotic switch, followed by three times the diotic version and dichotic again. An alternative way to perceive the dichotic part of the demonstration is the shift in lateralization of the low (high) pass noise with constant pitch.

55. Lateralization of BEP_{+}^{-} with ITD 0.8 ms for stimulus of track 54

The same signal configuration as in track 54 but with an extra ITD of 0.8 ms. Now the diotic part is clearly lateralized towards the right ear. Try, for the dichotic part, to concentrate on a similar change in pitch with changing low- and high-pass at the same lateralized position. Alternatively, one might predominantly perceive a change in position of the low-pass noise with constant pitch.

56. Lateralization of BEP_{+}^{-} with IID of 12 dB for stimulus of track 54

The same signal configuration as in track 54 but with an attenuation of 12 dB in the left-ear channel. Note that the dichotic pitch hardly shifts its position.

57. BEP_{+}^{-}, 600 Hz, continuous for measuring purposes

58. BEP_{-}^{+}, 600 Hz, continuous for measuring purposes

59. "Diotic $\mathrm{BEP}_{-}^{+}/\mathrm{BICEP}_{-}^{\mathrm{ic}}$", 600 Hz, continuous

60. "Diotic $\mathrm{BEP}_{+}^{-}/\mathrm{BICEP}_{\mathrm{ic}}^{-}$ ", 600 Hz, continuous

61. $\mathrm{BICEP}_{-}^{\mathrm{ic}}$, 600 Hz, continuous for measuring purposes

62. $\mathrm{BICEP}_{\mathrm{ic}}^{-}$, 600 Hz, continuous for measuring purposes

Remarks

- It can be readily seen that by using complementary Butterworth filters of any order n (36^{th} order was actually used) the low- and high-pass spectral band add theoretically flat, thus providing a spectrum indistinguishable from white gaussian noise at either ear. Combining the Butterworth expression with Eq. (1c) the CAP for BEP_{-}^{+} follows as

$$\mathrm{CAP}(f,\tau_i)=\frac{1-\cos 2\pi f\tau_i}{1+(f/f_e)^n}+\frac{(f/f_e)^n(1+\cos 2\pi f\tau_i)}{1+(f/f_e)^n}, \qquad (7)$$

  with f_e the edge frequency and n the order of the Butterworth filters.

- As a beneficial side consequence of its special way of construction, this BEP signal is free from any single peak in the CAP at the edge frequency, which could be kept responsible for a pure-tone-like pitch sensation at this very edge frequency (compare Frijns et al., 1986).

- Again by using complementary Butterworth filters of any order n (36th order was actually used) the low- and high-pass spectral band add theoretically flat at either ear, and the CAP for $\mathrm{BICEP}_{\overline{\mathrm{i}}\mathrm{c}}$ results as

$$\mathrm{CAP}(f,\tau_i) = \frac{1}{1+(f/f_e)^n} + \frac{(f/f_e)^n(1-\cos 2\pi f\tau_i)}{1+(f/f_e)^n}, \qquad (8)$$

  with f_e the edge frequency and n the order of the Butterworth filters. The relevant CS follows by putting $\tau_i = 0$.

- It is interesting to note that contrary to the expectation by Culling et al. (1998a) there seems no need for a single spectral peak in the CAP to explain BEP. As a consequence there is no reason to expect that BEP should disappear when the phase transition would become too steep, as is the case with HP (see above). The perceptual similarity as observed by Klein and Hartmann (1981), and demonstrated on this CD, between the dichotic and diotic cases alone is sufficient to explain BEP in terms of its CS resembling a low-pass or high-pass noise band. Remains only the issue how to explain the pitch extracted from a low-pass or high-pass noise band (see e.g. Hartmann, 1984; Hartmann and McMillon, 2001), but that is a general rather than a specific binaural question.

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