Harmony Perception, Periodicity Detection, and Neural Transformation

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Overview

Motivation

- **Question:** What happens when one listens to music, in particular musical harmonies?
- **Claim:** Periodicity detection helps understand this. There is empirical and neurophysiological evidence.

Outline

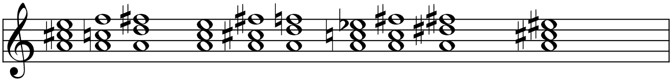
A. Harmony Perception by Periodicity Detection

B. Periodicity Detection by Neural Transformation

C. Ongoing Activities

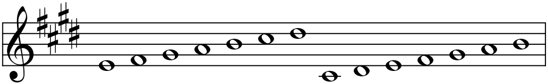
Motivation

- What are underlying principles of music perception?
- How can perceived consonance/dissonance of musical chords and scales be explained?
- Empirical analyses (by psychologists) reveal preference ordering wrt. pleasantness.
  - intervals: octave $\prec$ perfect fifth $\prec$ major third $\prec$ tritone
  - triads: major $\prec$ minor $\prec$ diminished $\prec$ augmented



(a) major (b) minor (c) diminished (d) augmented

  - (Western music) scales: major (Ionian) $\prec$ minor (Aeolian)



(a) major (Ionian) (b) minor (Aeolian)

♫ happy birthday – major version ♫ ♫ happy birthday – minor version ♫

Main Contribution

- Periodicity-based approach: apply consistently recent results from psychophysics and neuroacoustics:
  1. Just noticeable difference (JND) between two pitches for humans is about 1% for musically important low frequency range $\rightsquigarrow$ use respective tunings and frequency ratios.
  2. Periodicities of complex chords can be detected by the human (and animal) brain $\rightsquigarrow$ determine periodicity pitch.
- Aims and goal:
  - Fully mathematical model for musical harmoniousness.
  - Applicable to harmonies in broad sense (chords, scales).
  - High correlation with empirical studies.
  - Regard results from psychophysics and neuroacoustics.

Related Works

- Theories of harmony perception (not complete):
  - Overtones ♫ overtones of guitar string ♫, frequency ratios, gradus suavitatis (Euler, 1739) $\rightsquigarrow$ purely mathematical models
  - Dissonance, roughness, and instability (Cook and Fujisawa, 2006): Harmony should be more than the summation of interval consonance (frequency domain).
  - Periodicity-based approaches and neuronal models (Langner, 1997; Ebeling, 2007, time domain)
  - Cognitive theories for chords (mainly triads) and scales (Johnson-Laird et al., 2012; Temperley and Tan, 2013)
- Existing explanations for harmony perception
  - do not correlate too well with empirical rankings (overtones, dissonance curves, roughness, etc.), or
  - have restricted explanatory power (cognitive models assume principles of tonal music, e.g. existence of diatonic scales or common use of the major triad).

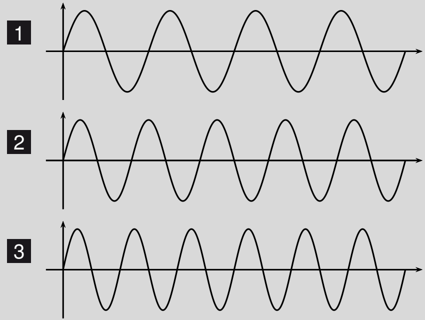
♫ chromatic and diatonic scale, major triad ♫

Overview

Computing Periodicity

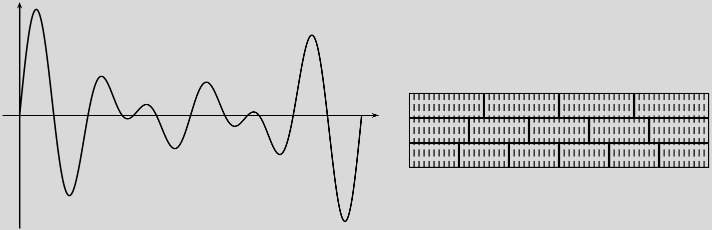
- Example: major triad (e.g. A–C#–E)
  - semitones $\{0, 4, 7\}$, frequency ratios $\{\frac{1}{1}, \frac{5}{4}, \frac{3}{2}\}$, $f_i \sim 4:5:6$
  - $\sin(\omega_1 t) + \sin(\omega_2 t) + \sin(\omega_3 t) \qquad \omega_i = 2\pi f_i$

Sinusoids of Major Triad



Computing Periodicity (Continued)

Superposition and Periodic Structure of Sinusoids



- Relative periodicity h = approximated ratio of the period length of the chord relative to the period length of its lowest tone component:
  - corresponds to least common multiple of denominators, here: $h = \text{lcm}(1, 4, 2) = 4$, and
  - does not change if harmonic overtones are present.
- Hypothesis: Perceived consonance of harmony decreases as relative (logarithmic) periodicity h increases.

Rational Tunings

- Periodicity detection requires (small) integer ratios for the frequencies (employ Stern-Brocot tree for computation).
- Equal temperament: $f_k = \sqrt[12]{2}^{\,k}$ (k-th semitone) all keys sound equal $\leadsto$ reference system.
- Rational tunings apply JND $\approx$ 1% (#1), 1.1% (#2), others not, e.g. Pythagorean, Kirnberger III.

Table of Relative Frequencies

Interval	k	Equal temperament	Pythagorean	Rational tuning #1	Rational tuning #2
Unison	0	1.000	1/1 (0.00%)	1/1 (0.00%)	1/1 (0.00%)
Minor second	1	1.059	256/243 (-0.56%)	16/15 (0.68%)	16/15 (0.68%)
Major second	2	1.122	9/8 (0.23%)	9/8 (0.23%)	9/8 (0.23%)
Minor third	3	1.189	32/27 (-0.34%)	6/5 (0.91%)	6/5 (0.91%)
Major third	4	1.260	81/64 (0.45%)	5/4 (-0.79%)	5/4 (-0.79%)
Perfect fourth	5	1.335	4/3 (-0.11%)	4/3 (-0.11%)	4/3 (-0.11%)
Tritone	6	1.414	729/512 (0.68%)	17/12 (0.17%)	7/5 (-1.01%)
Perfect fifth	7	1.498	3/2 (0.11%)	3/2 (0.11%)	3/2 (0.11%)
Minor sixth	8	1.587	128/81 (-0.45%)	8/5 (0.79%)	8/5 (0.79%)
Major sixth	9	1.682	27/16 (0.34%)	5/3 (-0.90%)	5/3 (-0.90%)
Minor seventh	10	1.782	16/9 (-0.23%)	16/9 (-0.23%)	9/5 (1.02%)
Major seventh	11	1.888	243/128 (0.57%)	15/8 (-0.68%)	15/8 (-0.68%)
Octave	12	2.000	2/1 (0.00%)	2/1 (0.00%)	2/1 (0.00%)

Formal Definitions

1. Assume that $H = \{f_1, \ldots, f_k\}$ is a rational harmony, f is the minimum of H, and $f_i/f = a_i/b_i$ for $1 \leq i \leq k$ and coprime positive integers a_i and b_i. Then $h = \mathrm{lcm}(b_1, \ldots, b_k)$ is called relative periodicity.
2. Logarithmic periodicity $= \log_2(h)$
   Rationales (cf. Langner, 1997):
   - logarithmic organisation of neuronal periodicity map (brain)
   - octave has frequency ratio 2 $\rightsquigarrow$ base-2 logarithm
3. Let $\mathcal{T}'$ be a tuning (ratio function), $S = \{s_1, \ldots, s_n\}$ a set of n semitones, and $\mathcal{H}$ a measure of harmoniousness. Then, the value of $\mathcal{H}$ may be smoothed, by averaging over the shifted semitone sets of S:

$$\overline{\mathcal{H}}(S) = \frac{1}{n} \sum_{i \in S} \mathcal{H}(\mathcal{T}'(S_i))$$

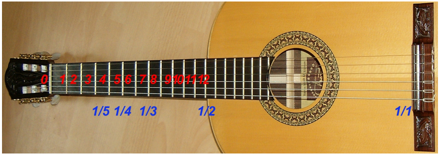
Reference: Stolzenburg, F. (2015). Harmony perception by periodicity detection. *Journal of Mathematics and Music*.

Approaches and Discussion

- Properties of Periodicity:
  - Harmonic overtones do not change periodicity.
  - Smoothing improves results.
  - Logarithmic periodicity for whole chromatic scale (12-TET):

$$\overline{\log_2(h)} \approx 7.4 < 8$$

= #octaves representable in neuronal periodicity map.



- Limitations:
  - Empirical ratings take average over all participants $\leadsto$ individual differences (culture, familiarity, training, etc.) are neglected.
  - Harmony is taken out of context (musical piece, history).
  - Studies focus on Western scales (twelve-tone system).

Consonance Rankings: Dyads

Dyads

Interval		Emp. rank	Roughness		Sonance factor		Similarity		Rel. periodicity	
Unison	{0, 0}	1	2	(0.0019)	1-2	(1.000)	1-2	(100.00%)	1-2	(1.0)
Octave	{0, 12}	2	1	(0.0014)	1-2	(1.000)	1-2	(100.00%)	1-2	(1.0)
Perfect fifth	{0, 7}	3	3	(0.0221)	3	(0.737)	3	(66.67%)	3	(2.0)
Perfect fourth	{0, 5}	4	4	(0.0451)	4	(0.701)	4	(50.00%)	4-5	(3.0)
Major third	{0, 4}	5	6	(0.0551)	5	(0.570)	6	(40.00%)	6	(4.0)
Major sixth	{0, 9}	6	5	(0.0477)	6	(0.526)	5	(46.67%)	4-5	(3.0)
Minor sixth	{0, 8}	7	7	(0.0843)	7	(0.520)	9	(30.00%)	7-8	(5.0)
Minor third	{0, 3}	8	10	(0.1109)	8	(0.495)	7	(33.33%)	7-8	(5.0)
Tritone	{0, 6}	9	8	(0.0930)	11	(0.327)	8	(31.43%)	9	(6.0)
Minor seventh	{0, 10}	10	9	(0.0998)	9	(0.449)	10	(28.89%)	10	(7.0)
Major second	{0, 2}	11	12	(0.2690)	10	(0.393)	11	(22.22%)	12	(8.5)
Major seventh	{0, 11}	12	11	(0.2312)	12	(0.242)	12	(18.33%)	11	(8.0)
Minor second	{0, 1}	13	13	(0.4886)	13	(0.183)	13	(12.50%)	13	(15.0)
Correlation r			.967		.982		.977		.982	

- Empirical ranks: Malmberg (1918); Schwartz et al. (2003)
- High correlation with empirical results $\rightsquigarrow$ $r > .9$.
- Many approaches yield good correl. results for intervals:
  - sonance factor: Hofmann-Engl (2004)
  - percentage spectral similarity: Gill and Purves (2009)
  - roughness: Hutchinson and Knopoff (1978)

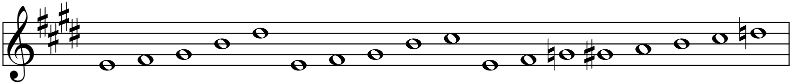
Consonance Rankings: Triads

Common Triads

Chord class		Emp. rank	Roughness	Instability	Similarity	Rel. periodicity
Major	{0, 4, 7}	1 (1.667)	3 (0.1390)	1 (0.624)	1-2 (46.67%)	2 (4.0)
	{0, 3, 8}	5 (2.889)	9 (0.1873)	5 (0.814)	8-9 (37.78%)	3 (5.0)
	{0, 5, 9}	3 (2.741)	1 (0.1190)	4 (0.780)	5-6 (45.56%)	1 (3.0)
Minor	{0, 3, 7}	2 (2.407)	4 (0.1479)	2 (0.744)	1-2 (46.67%)	4 (10.0)
	{0, 4, 9}	10 (3.593)	2 (0.1254)	3 (0.756)	5-6 (45.56%)	7 (12.0)
	{0, 5, 8}	8 (3.481)	7 (0.1712)	6 (0.838)	8-9 (37.78%)	10 (15.0)
Susp.	{0, 5, 7}	7 (3.148)	11 (0.2280)	8 (1.175)	3-4 (46.30%)	5 (10.7)
	{0, 2, 7}	6 (3.111)	13 (0.2490)	11 (1.219)	3-4 (46.30%)	9 (14.3)
	{0, 5, 10}	4 (2.852)	6 (0.1549)	9 (1.190)	7 (42.96%)	6 (11.0)
Dim.	{0, 3, 6}	12 (3.889)	12 (0.2303)	12 (1.431)	13 (32.70%)	12 (17.0)
	{0, 3, 9}	9 (3.519)	10 (0.2024)	7 (1.114)	10-11 (37.14%)	11 (15.3)
	{0, 6, 9}	11 (3.667)	8 (0.1834)	10 (1.196)	10-11 (37.14%)	8 (13.3)
Augm.	{0, 4, 8}	13 (5.259)	5 (0.1490)	13 (1.998)	12 (36.67%)	13 (20.3)
Correlation r			.352	.698	.802	.846

- Empirical ranks: Johnson-Laird et al. (2012)
- Highest correlation with empirical results in contrast to others including instability (Cook and Fujisawa, 2006).
- Logarithmic periodicity even correlates well to ordinal ratings ∼ logarithmic periodicity map in the brain.

Consonance Rankings: Chords



(a) pentachord (b) pentatonics (c) blues scale

- consider pentachord Emaj7/9
- standard in jazz music
- classically built from a stack of thirds
- highest ranked harmony with 5 out of 12 tones
- may be understood as the superposition of triads E and B
- tonic-dominant relationship according to classical harmony theory $\rightsquigarrow$ chord progressions
- all shown harmonies rank among the top 5% in their respective tone multiplicity category

Consonance Rankings: Scales

Heptatonic Scales (Church Modes)

Mode	Semitones	Emp. rank		Similarity	Log. periodicity (Rational tuning #1)		Log. periodicity (Rational tuning #2)	
Ionian	{0, 2, 4, 5, 7, 9, 11}	1	(0.83)	3 (39.61%)	1	(6.453)	1	(5.701)
Mixolydian	{0, 2, 4, 5, 7, 9, 10}	2	(0.64)	6 (38.59%)	3	(6.607)	4	(5.998)
Lydian	{0, 2, 4, 6, 7, 9, 11}	3	(0.58)	5 (38.95%)	2	(6.584)	2	(5.830)
Dorian	{0, 2, 3, 5, 7, 9, 10}	4	(0.40)	2 (39.99%)	4	(6.615)	3	(5.863)
Aeolian	{0, 2, 3, 5, 7, 8, 10}	5	(0.34)	4 (39.34%)	5	(6.767)	7	(6.158)
Phrygian	{0, 1, 3, 5, 7, 8, 10}	6	(0.21)	1 (40.39%)	6	(6.778)	5	(6.023)
Locrian	{0, 1, 3, 5, 6, 8, 10}	7		7 (37.68%)	7	(6.790)	6	(6.033)
Correlation r				.036	.964		.786	

- Empirical ranks: Temperley and Tan (2013)
- Periodicity also works for scales, although tones do not sound simultaneously.
- Church modes are in the very front ranks of 462 scales with 7 out of 12 tones (for rational tunings).
- Percentage similarity (Gill and Purves, 2009) does not predict order, but is applicable to arbitrary tone scales.

Summary and Future Work

- Summary:
  - Harmony perception can be explained well by considering the periodic structure of harmonic sounds.
  - Computational model shows highest correlation with empirical results for harmonies in broad sense (dyads, triads, scales).
  - Conclusion: There is a strong neuroacoustical and psychophysical basis for harmony perception including chords and scales.
  - Correlation with neurophysiological data (Lee et al., 2015; Bidelman and Krishnan, 2009).
- Further Information:

  `http://ai-linux.hs-harz.de/fstolzenburg/harmony/`

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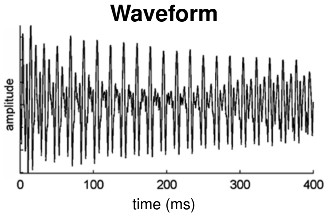
A. Harmony Perception by Periodicity Detection

B. Periodicity Detection by Neural Transformation

C. Ongoing Activities

Motivation

- An acoustic stimulus, e.g. a musical harmony, is transformed highly non-linearly during the hearing process:
  - **ear:** combination tones in inner ear (differences)
  - **brain:** autocorrelation mechanism (Langner, 1997, 2015)
- In brainstem response, periodicity pitch (i.e. missing fundamental) is physically present in frequency spectrum (EEG studies by Lee et al., 2009, 2015).
- Research question: How can this happen?
- **Running example:** perfect fifth (A2–E3, 110 and 166 Hz)

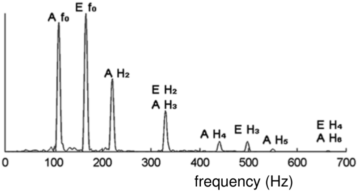


Overview

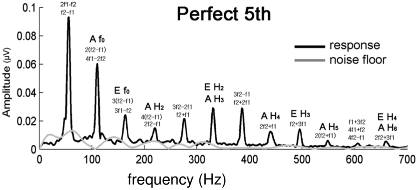
Auditory Brainstem Responses

- Lee et al. (2009, 2015) measure auditory brainstem responses to musical intervals (electric piano sound):
  - **perfect fifth:** A2–E3, 110–166 Hz, frequency ratio 3:2 highest response in brainstem at about 55.3 $\approx 110/2$ Hz
  - **minor seventh:** F#2–E3, 93–166 Hz, frequency ratio 9:5 highest response in brainstem at about 18.5 $\approx 93/5$ Hz
- In both cases, the additionally occurring frequency coincides very well with the periodicity pitch frequency.
- **Frequency Spectra:** (Lee et al., 2015, Fig. 1+5)

Stimulus

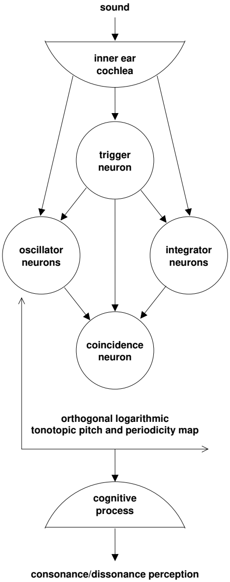


Response



Neuronal Model by Langner (1997, †2016)

- Trigger neurons in cochlear nucleus transfer signals without significant delay (spike trains).
- Oscillator neurons with intrinsic oscillation $n \cdot T$, base period $T = 0.4\,\text{ms}$, $n \geq 2$.
- Integrator neurons in cochlear nucleus transfer periodic signals with (significant) delay.
- Coincidence neurons (auditory midbrain) respond best when delay is compensated by signal period.
- Summary: Periodicity can be detected in the brain (by comb-filtering).

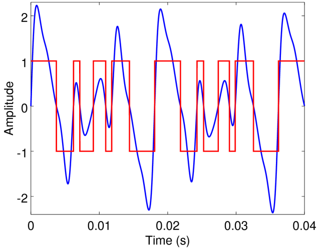


Possible Explanations

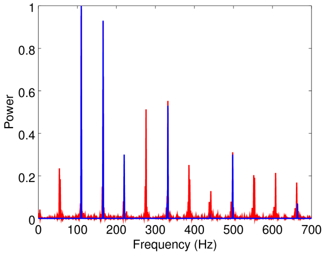
- What are the relevant factors that lead to the occurrence of the periodicity pitch in the response spectrum of a signal?
- Reasons for periodicity detection may be:
  1. **autocorrelation** and phase-locking (Langner, 2015)
  2. **distortion** $\rightsquigarrow$ combination tones (Lee et al., 2015)
     $f_1 - k \cdot (f_2 - f_1)$, given frequencies $f_1 < f_2$ and small k
  3. **spiking:** transformation of input signal into pulse trains
     $\rightsquigarrow$ maximal amplitude is limited by fixed uniform value
- Explanations (except last one) introduce too few or too many combination tones in the frequency spectrum.

Spiking Neuronal Activity

- In the brain, spikes are created when the action potential crosses some threshold.
- This is adopted in theoretical model proposed here: Transform input (blue) as in artificial neural networks.
- A sigmoidal activation function, e.g. the logistic function, the hyperbolic tangent, or simply the sign function, is applied to the input (= signal over time).
- By this, the input signal is transformed into a rectangular pulse train with uniform maximal amplitude (red).



Frequency Spectrum



- Frequency spectra of perfect fifth:
  - original signal (blue)
  - its amplitude-limited response (red)
- Periodicity pitch occurs physically in the real brainstem response (Lee et al., 2015, Figure 5) **and** in frequency spectrum predicted by our model.
- Key point: non-linear, sigmoidal activation
- Complex neural model or analysis (Lerud et al., 2014) is not required.

Results

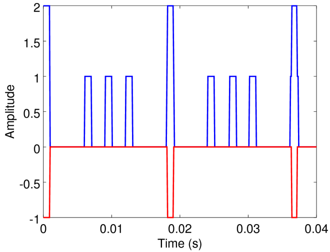
- Stimulus is transformed in the brain, distortion is not heard however, but can be simulated

  ♫ perfect fifth – stimulus ♫ ♫ perfect fifth – distorted ♫

- The response spectra explicitly contain as expected in addition to the original spectrum the periodicity pitch frequency, not arbitrary combination tones.
- The (new) peaks in the response spectrum are sharper the more pulse-like the transformed input is.
- The peaks at the periodicity pitch frequencies are more salient for more consonant harmonies. In this case, the periodicity pitch frequency is comparatively high ($\sim$ relative periodicity low).

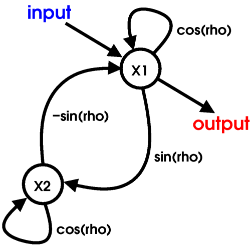
Model Computation

- Assume: input signal = sequence of rectangular pulses, uniform amplitude (cf. Ebeling, 2007, 2008).
- For the perfect fifth, both component signals coincide after an overall period of approximately 18.1 ms (blue).
- The amplitude is not uniform at this point.
- Whenever two pulses of different frequencies coincide, it has to be compensated (red).
- Thus periodicity pitch present in amplitude-limited signal.



Neural Network Model

- Recurrent artificial neural networks can generate periodic waveforms and also explain their perception.
- Artificial neurons may be recursively connected, activation of each neuron changes over time.
- If neurons $x_1, \ldots, x_n$ are connected to neuron y, then:



$$y(t+\tau) = g\big(w_1 x_1(t) + \cdots + w_n x_n(t)\big)$$

  - $w_1, \ldots, w_n$ are weights,
  - τ discrete time constant, and
  - g the activation function.
- Two neurons suffice to generate (co)sine wave: just use 2D rotation matrix (cf. Stolzenburg et al., 2018)

Final Remarks

- Summary: Most important factor during the neural transformation for periodicity detection seems to be the spiking with uniform, limited amplitude.
- That the periodicity pitch appears in the response spectrum and not arbitrary difference tones can be reproduced by Fourier analysis of amplitude-limited pulse trains (Matlab/Octave implementation).
- Reference: Frieder Stolzenburg. Periodicity detection by neural transformation. In Edith Van Dyck, editor, *Proc. ESCOM 2017 – 25th Anniversary Conference of the European Society for the Cognitive Sciences of Music*, pp. 159–162, Ghent, Belgium, 2017. IPEM, Ghent University. `http://www.escom2017.org/wp-content/uploads/2016/06/Stolzenburg-et-al.pdf`.

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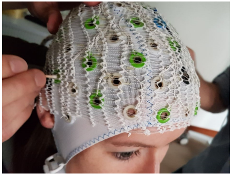
A. Harmony Perception by Periodicity Detection

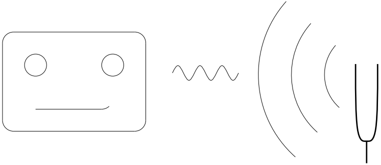
B. Periodicity Detection by Neural Transformation

C. Ongoing Activities

Planned Work

- More extensive studies and comparisons with real brainstem responses have to be done, not only comparison with empirical psychological experiments.
- PhD project HarPer – Harmony Perception (Maria Heinze), joint with Maastricht University, Netherlands, Faculty of Psychology and Neuroscience, since October 2017.
- EEG and fMRI studies about temporal and spatial activity in the brain during harmony perception are planned with complex harmonic sensations ($\geq$ 2 tones in harmony).

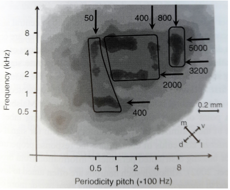




Research Questions

1. Can the results of the EEG experiments for dyads by Lee et al. (2009, 2015) be reproduced?
2. Can the periodicity-based method (Stolzenburg, 2015) be confirmed by EEG experiments for dyads and triads?
3. Where in the brain does harmony perception take place? Are pitch and periodicity orthogonal dimensions in the tonotopic map in the brain?

Orthogonality of tonotopy and periodotopy in the inferior colliculus of the gerbil (mouse) demonstrated using a radiographic (2-deoxyglucose) technique (cf. Langner, 2015, Fig. 10.5).



Research Questions (continued)

Present participants isolated corresponding periodicity pitch frequencies in fMRI experiments.

♫ major triad – stimulus #77 ♫ ♫ periodicity pitches – undertones of D6 ♫

4 How does harmony perception work in general? Can it be modeled by neural network models, e.g. recurrent predictive neural networks (Stolzenburg et al., 2018)?

Thank you very much for your attention!