Harmony Cognition by Neural Transformation

Die Wahrnehmung der Periodizitätstonhöhe in komplexen Harmonien aus EEG-Zeitreihen

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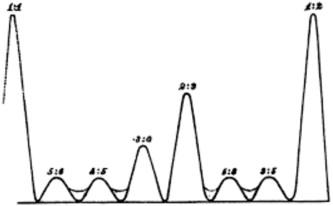
Overview

Carl Stumpf's *Tonpsychologie* (Volume 2)

- Stumpf assumes listeners recognise whether one or more tones are present.
- Perception of musical harmony arises after tonal fusion: sensation of several tones results into a single impression.
- Musical harmony is more than the summation of interval consonance/dissonance (cf. gestalt psychology).
- From introspection and experiments, in particular with musically not trained persons, he deduces the degree of tonal fusion (Stumpf, 1890, p. 176).



Carl Stumpf's *Tonpsychologie* (continued)

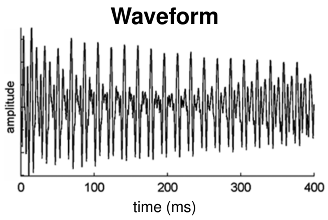
- Rules of Tonal Fusion (Stumpf, 1890, Sect. 19):

1. *Tonal fusion depends on frequency and is independent of the tone region and loudness.*	*Verschmelzung ist dasjenige Verhältnis zweier Inhalte, speziell Empfindungsinhalte, wonach sie nicht eine bloße Summe, sondern ein Ganzes bilden. Die Abhängigkeit der Verschmelzungsstufen von den genannten Schwingungsverhältnissen ist das Hauptgesetz der Tonverschmelzung. Der Verschmelzungsgrad ist unabhängig von der Tonregion. Der Verschmelzungsgrad ist auch unabhängig von der Stärke. Durch Hinzufügung eines beliebigen dritten und weiteren Tones wird der Verschmelzungsgrad zweier gegebener Töne in keiner Weise beeinflusst.*
2. *Small deviations of the frequencies do not produce a noticeable change in tonal fusion.*	*Sehr kleine Abweichungen der Schwingungszahlen von den angegebenen Verhältnissen erzeugen noch keine merkliche Veränderung des Verschmelzungsgrades.*
3. *Tonal fusion remains even if both sounds are not offered to the same ear and even in the mere imagination.*	*Die Verschmelzung bleibt und behält ihren Grad, wenn beide Töne nicht demselben Ohr [. . .] geboten werden. Die Verschmelzung bleibt auch in der bloßen Phantasievorstellung erhalten. Wenn wir über eine Oktave hinausgehen, so kehren dieselben [. . .] Schwingungsverhältnisse wieder.*

- Research in neuroacoustics and music cognition supports this (Langner, 2015; Ebeling, 2007; Stolzenburg, 2015)
  $\leadsto$ harmony perception $\approx$ approximate periodicity detection in the brain

Motivation

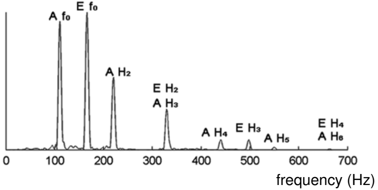
- An acoustic stimulus, e.g. a musical harmony, is transformed highly non-linearly during the hearing process:
  - **ear:** combination tones in inner ear (differences)
  - **brain:** autocorrelation mechanism (Langner, 1997, 2015)
- In brainstem response, periodicity pitch (i.e. missing fundamental) 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)



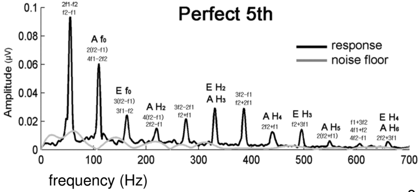
Auditory Brainstem Responses

- 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



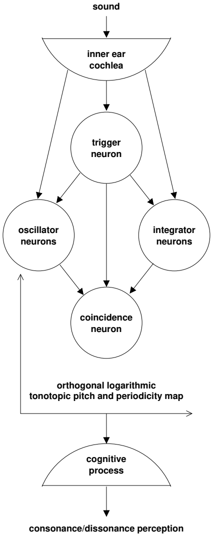
Response



Neuronal Model by Langner (1997, †2016)

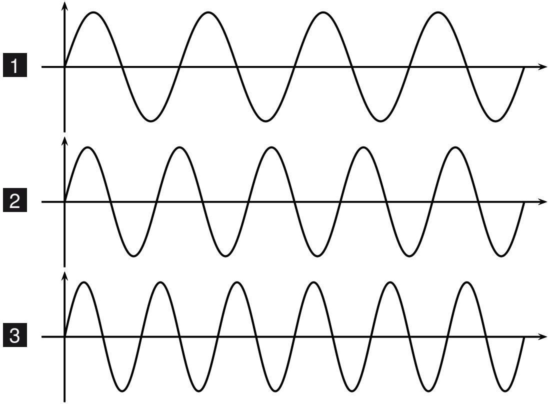
- Trigger neurons in cochlear nucleus transfer signals without significant delay (spike trains).
- Oscillator neurons with intrinsic oscillation $n \cdot T$, base period $T = 0.4\,\text{ms}$, $n \geq 2$.
- Integrator neurons in cochlear nucleus transfer periodic signals with (significant) delay.
- Coincidence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

- Summary: Periodicity can be detected in the brain (by comb-filtering).



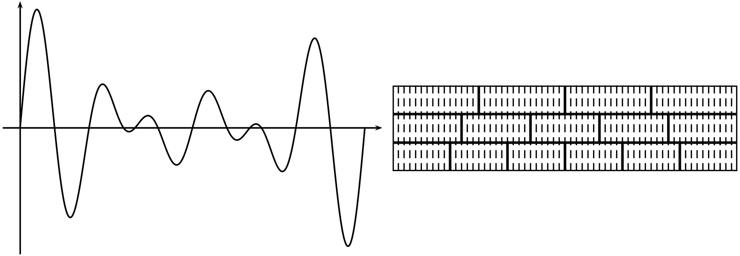
Determine Periodicity

- Example: major triad in root position (e.g. A–C#–E):
  - harmonic-series presentation: 4:5:6 $\sim f_i$
  - $\sin(\omega_1 t) + \sin(\omega_2 t) + \sin(\omega_3 t) \qquad \omega_i = 2\pi f_i$
- **Sinusoids of Major Triad:**



Determine 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 minimum of harmonic-series presentation
  - does not change if harmonic overtones are present
- Claim: Perceived consonance of a harmony decreases as periodicity increases (Stolzenburg, 2015).

Rational Tunings

- Periodicity detection requires (small) integer ratios for the frequencies (employ Stern-Brocot tree for computation).
- 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%)

Consonance Rankings: Triads

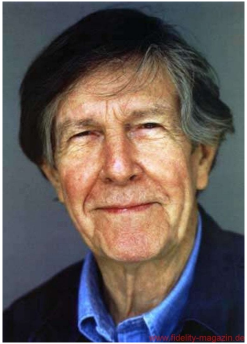
Common Triads

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.

John Cage Organ Project Halberstadt

- John Cage (1912–1992) Organ Project Halberstadt at Burchadi Abbey
- ORGAN^2/ASLSP: As SLow aS Possible – one of the slowest concerts



John Cage Organ Project Halberstadt (Continued)

Actual Organ Chord – 6 tones in tonal fusion

C2	D♭2	D♯3	E3	A♯4	E5	— international notation
16	17	31	32	50	56	— semitones on standard piano keyboard
0	1	15	16	34	40	— normalized to ground tone as reference
0	1	3	4	10	4	— applying octave equivalence

- relative periodicity = 180 (raw), 161.4 (smoothed), 7.2 (logarithmic)
- 8 octaves of tone pitch and periodicity pitch are noticeable
  but: both are completely different dimensions in human brain
- **Question:** Can periodicity pitch frequency be observed in the brain?

Research Questions

- **Research questions**
  1. Can the periodicity pitch, which does not physically exist in the presented stimulus of a triad, be perceived in the human brain?
  2. The right hemisphere is known to be more suitable when it comes to music perception. Can this theory be proved by the frequency following responses?
  3. Does a training or adaptation effect occur with multiple repetition?

Recording Brainstem Activities with EEG

- Experimental design
  - Investigation of the intensity of human perception while hearing randomly arranged variants of 7 stimuli
  - Timbre: synthesized tuba sound
    - G major, G minor, G diminished and G suspended in root position
    - G suspended in first inversion
    - G major and G suspended in second inversion

♫ example sequence ♫

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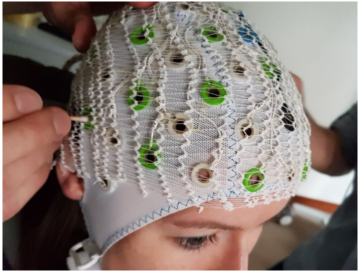
Recording Brainstem Activities with EEG (Continued)



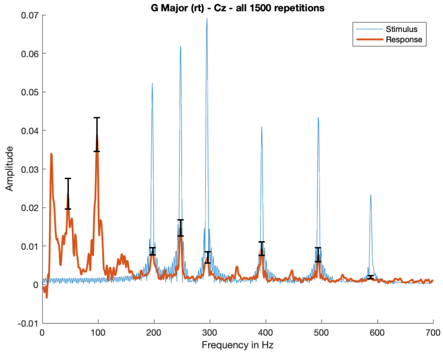
- Experimental design
  - Sampling rate: 10 kHz
  - Stimulus duration: 300 ms
  - Interstimulus interval: 100ms
  - Repetition rate per stimulus: 1500 times
  - Participants: 15 healthy adults (2 males, 13 females with ∅ age: 21.6)
  - Responses were recorded using EEG with 32 active electrodes

Methods and Results

- Analysis
  - Bandpass filter: 15–700 Hz
  - Rejection of trials with a greater activity than $\pm 35\,\mu$V
  - Averaging of the responses
  - Performing an absolute baseline correction and a
  - Fast Fourier Transformation
- Results
  - All responses show clear peaks in the presented stimulus frequencies.
  - The more dissonant the triad the smaller was the deflection.
  - The periodicity pitch occurred in all responses related to a triad in root position, the G suspended (first inversion) and to C major (second inversion).

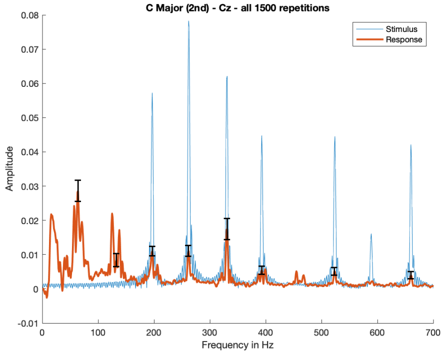
Methods and Results (Continued)

- Results
  - G Major in root position
  - present frequencies: G3 (196 Hz), B3 (248 Hz) and D4 (294 Hz)
  - periodicity pitch: 49 Hz
  - blue = stimulus, red = response



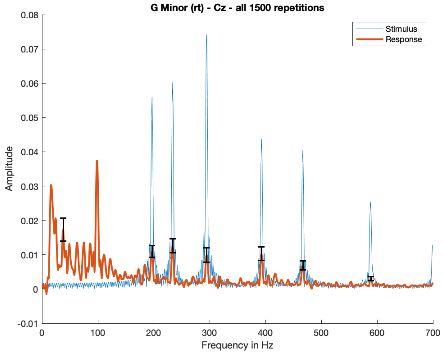
Methods and Results (Continued)

- Results
  - C Major in second inversion
  - present frequencies: G3 (196 Hz), C4 (262 Hz) and E4 (330 Hz)
  - periodicity pitch: 66 Hz
  - blue = stimulus, red = response



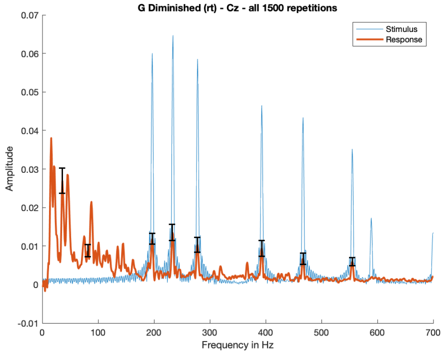
Methods and Results (Continued)

- **Results**
  - G Minor in root position
  - present frequencies: G3 (196 Hz), B♭3 (233 Hz) and D4 (294 Hz)
  - periodicity pitch: 20 Hz
  - blue = stimulus, red = response



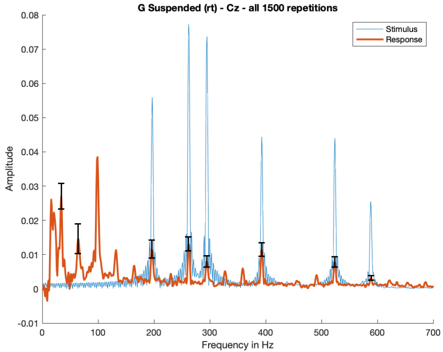
Methods and Results (Continued)

- Results
  - G Diminished in root position
  - present frequencies: G3 (196 Hz), B♭3 (233 Hz) and D♭4 (278 Hz)
  - periodicity pitch: 39 Hz
  - blue = stimulus, red = response



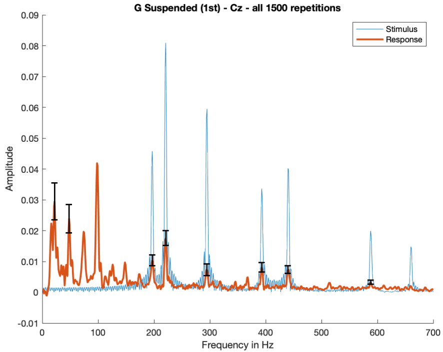
Methods and Results (Continued)

- Results
  - G Suspended in root position
  - present frequencies: G3 (196 Hz), C4 (262 Hz) and D4 (294 Hz)
  - periodicity pitch: 33 Hz
  - blue = stimulus, red = response



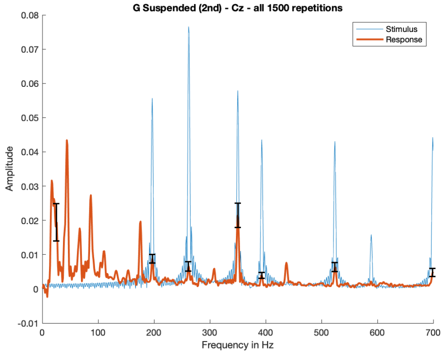
Methods and Results (Continued)

- Results
  - G Suspended in first inversion
  - present frequencies: G3 (196 Hz), A3 (220 Hz) and D4 (294 Hz)
  - periodicity pitch: 25 Hz
  - blue = stimulus, red = response



Methods and Results (Continued)

- Results
  - G Suspended in second inversion
  - present frequencies: G3 (196 Hz), C4 (262 Hz) and F4 (349 Hz)
  - periodicity pitch: 13(26) Hz
  - blue = stimulus, red = response



Methods and Results (Continued)

- The right hemisphere is known to be more suitable when it comes to music perception. Can this theory be proved by the frequency following responses?
  - comparison of the left (-) and the right(+) hemisphere
  - the left brain hemisphere is considered as the average of the electrodes F4, F8, Fc2, Fc6, C4 and T8
  - the right hemisphere consists of F3, F4, Fc1, Fc5, C3 and T7
  - mean values of response peaks concerning individual frequencies show a better perception of the right hemisphere

stimulus interval	pitch	pitch (2x)	1st tone (G3)	2nd tone	3rd tone	1st tone (G4)	2nd tone (2x)	3rd tone (2x)	mean
G maj rt	-0.0010	0.0025	-0.0007	0.0006	0.0013	0.0008	0.0003	0.0003	0.0005
G maj 2nd	0.0006	0.0005*	0.0013	0.0007	0.0008	0.0010*	0.0005	0.0011	0.0008
G min rt	0.0037	0.0033	0.0008	0.0003	0.0008	0.0011	0.0000	-0.0003	0.0012
G dim rt	0.0019*	-0.0019	0.0019	0.0008	0.0014	0.0015	0.0000	0.0007	0.0008
G sus rt	-0.0006	-0.0001	0.0010	0.0019	-0.0009	0.0013	0.0009	0.0000	0.0004
G sus 1st	0.0095*	-0.0002	-0.0003	-0.0005	0.0010	0.0007	0.0001	0.0002	0.0013
G sus 2nd	-0.0010**	0.0002*	-0.0001	0.0011	0.0007	0.0009	0.0008	0.0007	0.0004
mean	0.0018	0.0006	0.0006	0.0007	0.0007	0.0010	0.0004	0.0004	

Methods and Results (Continued)

- Does a training or adaptation effect occur with multiple repetition?
  - three equal runs with 500 repetition per stimulus
  - comparison of the first and third cycle
  - mean values of response peaks concerning individual frequencies show improvements in perception
  - in fact no triad improved its amplitudes in all frequencies at once, but every chord has more amplitude improvements than vice versa

stimulus interval	pitch	pitch (2x)	1st tone (G3)	2nd tone	3rd tone	1st tone (G4)	2nd tone (2x)	3rd tone (2x)	mean
G maj rt	39.22	16.03	3.41	10.87	3.85	-3.57	-6.58	43.48	13.34
G maj 2nd	-8.87	-11.54	40.23	-6.42	34.46	8.93	57.14	8.7	15.33
G min rt	—	2.55	20.79	20.00	-6.19	-13.83	-2.94	20.00	5.77
G dim rt	-17.56	-30.56	3.45	1.48	22.73	1.09	18.46	5.45	0.57
G sus rt	50.91	-6.74	29.9	-3.15	45.00	-18.69	-10.53	73.08	19.97
G sus 1st	-11.04	24.89	-43.04	25.00	27.94	23.88	12.68	48.28	13.57
G sus 2nd	—	-1.34	-25.00	11.11	11.62	36.11	-12.5	0.0	2.86
mean	10.53	-0.96	4.25	8.41	19.78	4.85	7.96	28.43	

Conclusions

- The human brain shows the periodicity pitch frequency of triads.
- The periodicity pitch can be calculated theoretically beforehand by means of the ground tone frequency and the relative periodicity of the harmony.
- The right hemisphere perceives better on average.
- With multiple repetition an adaption effect occurs on Cz.
- The results reveal one step of encoding music perception in the human brain and are in line with Stumpf's theory of tonal fusion.

Thanks for your attention!

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