Scaling the perceived fluctuation strength of frequency-modulated tones

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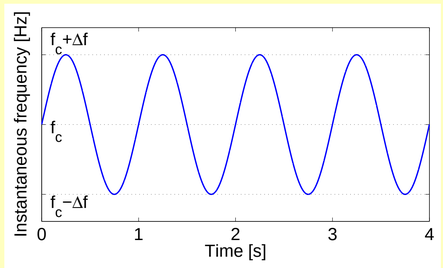
Introduction

Fluctuation strength (Terhardt, 1968; Fastl, 1983) is described as a supra-threshold sensation due to slow modulations (≤ 20 Hz) of amplitude or frequency.

- Fluctuation strength is one of only a handful of elementary auditory attributes (like loudness, pitch, sharpness, roughness, etc.).
- It has been modeled (Zwicker & Fastl, 1999), and is readily available as an instrumental psychoacoustic metric in various software packages for sound quality analysis.

Among other physical parameters, the modulation frequency f_m and the modulation depth Δf have been identified as predictors of the fluctuation strength of frequency-modulated sounds.

Instantaneous frequency as a function of modulation frequency and modulation depth



The instantaneous frequency (f_i) of a sinusoidally frequency modulated pure tone with a carrier frequency f_c is defined as

$$f_i = f_c + \Delta f \sin(2\pi f_m t).$$

Experiment I – A full-factorial design

In the first experiment modulation frequency and modulation depth were varied in a factorial design, in order to assess the interaction of these two parameters.

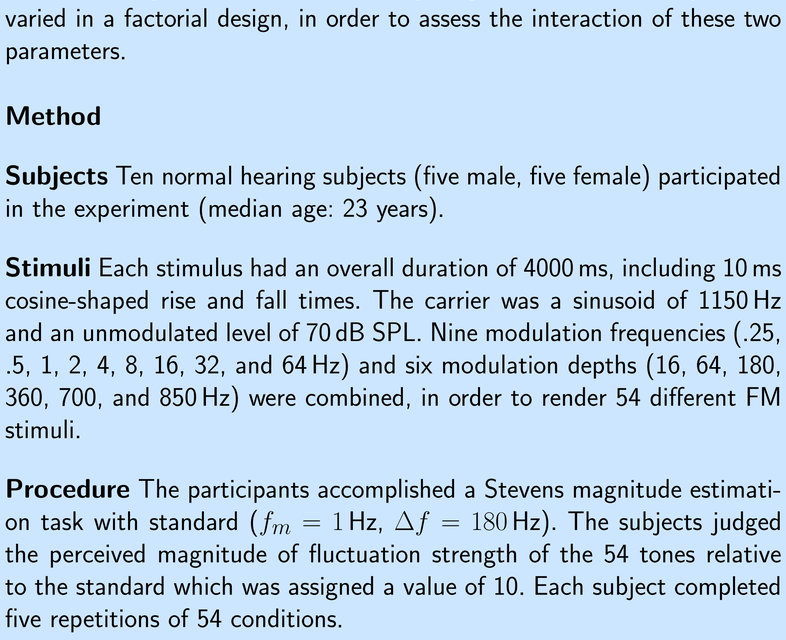
Method

Subjects Ten normal hearing subjects (five male, five female) participated in the experiment (median age: 23 years).

Stimuli Each stimulus had an overall duration of 4000 ms, including 10 ms cosine-shaped rise and fall times. The carrier was a sinusoid of 1150 Hz and an unmodulated level of 70 dB SPL. Nine modulation frequencies (.25, .5, 1, 2, 4, 8, 16, 32, and 64 Hz) and six modulation depths (16, 64, 180, 360, 700, and 850 Hz) were combined, in order to render 54 different FM stimuli.

Procedure The participants accomplished a Stevens magnitude estimation task with standard ($f_m = 1$ Hz, $\Delta f = 180$ Hz). The subjects judged the perceived magnitude of fluctuation strength of the 54 tones relative to the standard which was assigned a value of 10. Each subject completed five repetitions of 54 conditions.

Results



Displayed are the median ratings for each subject, the median over subjects, and the fluctuation strength as predicted by Zwicker & Fastl's (1999) model (using Brüel & Kjær Sound Quality software; bottom rightmost panel).

The subjects showed large individual differences in their ratings of the fluctuation strength and strong deviations from the model predictions. Only for one subject (we) the pattern of ratings roughly corresponds to the predicted pattern (having a peak at a modulation frequency of 4 Hz).

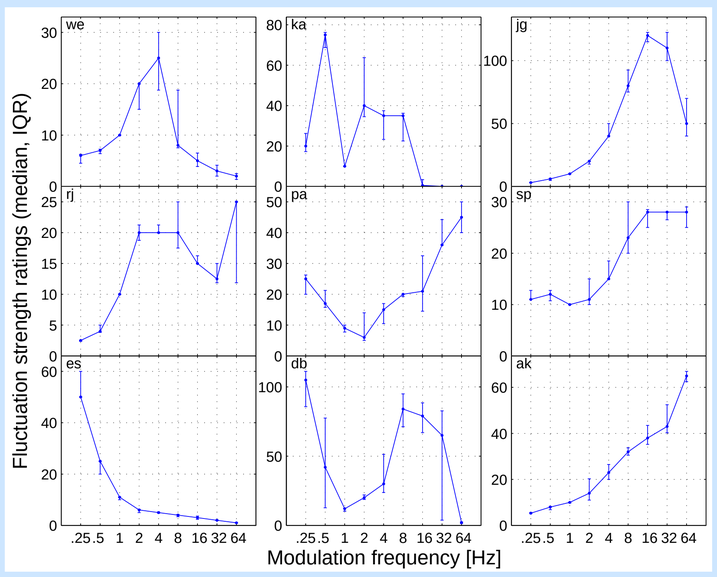
Experiment II – Disentangling the factors

Research questions: Can the heterogeneity in the results of the first experiment be attributed to the simultaneous variation of f_m and Δf? Which of the two factors is responsible for the large individual differences?

Results

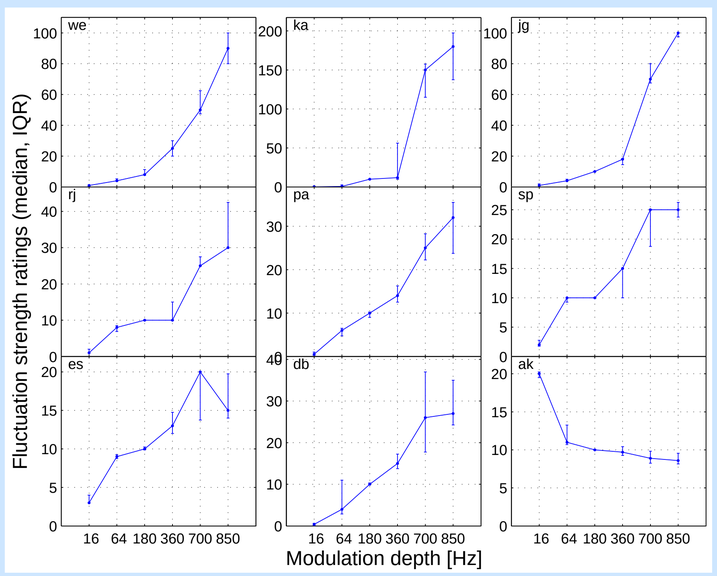
Influence of modulation frequency on fluctuation strength

All stimuli had a constant Δf of 700 Hz.
The standard had a modulation frequency of 1 Hz.



Influence of modulation depth on fluctuation strength

All stimuli had a constant f_m of 4 Hz.
The standard had a modulation depth of 180 Hz.



Displayed are the median fluctuation strength ratings per subject, the error bars indicate the interquartile range (IQR).

No general response pattern for the impact of the modulation frequency could be detected. The effect of the modulation depth, however, was reflected in a general response pattern. Eight of the nine participants showed increasing ratings with increasing modulation depth.

Discussion of Experiment I and II

Subjects do not agree on the contribution of the modulation frequency on their fluctuation strength ratings. The heterogeneity in the results cannot be attributed to the simultaneous variation of f_m and Δf.

Experiment III – Additivity of fluctuation strength

Research question: Is there a simple model representing fluctuation strength as an additive combination of the effects of modulation frequency and modulation depth?

The critical condition for additivity is the so-called Thomsen condition which was tested employing a random conjoint measurement approach (Falmagne, 1976).

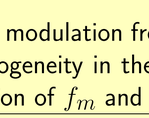
Testing the Thomsen condition

Let a, b, c be three values of f_m (Δf) and x, y, z three values of Δf (f_m). The Thomsen condition holds, iff

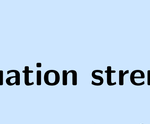
$$ay \sim bz, bx \sim cy \Rightarrow ax \sim c'z.$$

Step 1: Find b such that $ay \sim bz$

Step 2: Find c such that $bx \sim cy$



Step 3: Find c' such that $ax \sim c'z$



The Thomsen condition holds if $c_{med} = c'_{med}$.

Matches ($\sim$) were obtained using 16 repetitions of an adaptive forced-choice procedure (1-up/1-down).

The statistical significance of the difference between c_{med} and c'_{med} was evaluated using a Mann-Whitney U-test. A significant test indicates a violation of the Thomsen condition.

Results

Varying modulation frequency

Fixed components: a=2 Hz f_m; x=180 Hz, y=64 Hz, z=360 Hz Δf
Table entries are modulation frequencies produced for b, c, and c'.

Subject	b_{med}	c_{med}	c'_{med}	$c'_{med} - c_{med}$
jg	0.229	0.386	0.823	0.438*
pa	0.032	0.355	0.122	−0.233
sp	0.311	0.479	0.534	0.055
rj	0.155	0.422	0.325	−0.098*
we	0.279	0.842	0.707	−0.135*
ka	0.152	0.396	0.298	−0.099*
es	0.304	0.479	0.304	−0.175*

Varying modulation depth

Fixed components: a=360 Hz Δf; x=1 Hz, y=0.5 Hz, z=2 Hz f_m.
Table entries are modulation depths produced for b, c, and c'.

Subject	b_{med}	c_{med}	c'_{med}	$c'_{med} - c_{med}$
jg	117.377	244.469	234.104	−10.365
pa	344.772	375.977	353.984	−21.993
sp	124.933	278.446	142.272	−136.174*
rj	254.823	283.722	384.300	100.578
we	138.813	254.584	220.035	−34.550
ka	234.104	302.754	392.623	89.869*

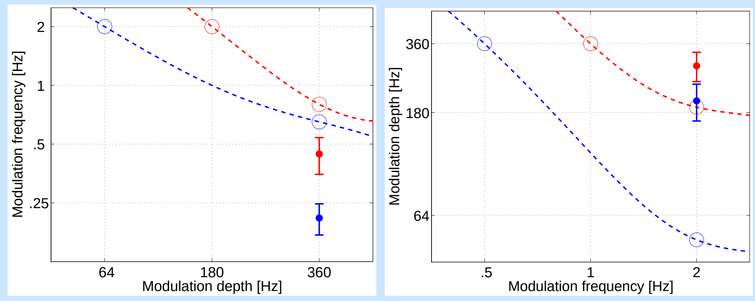
* marks differences between c_{med} and c'_{med} significant on a 10% level.

Thomsen condition: conclusions

For only one out of seven subjects (pa) does the Thomsen condition hold in both experimental conditions. This suggests that listeners are generally not able to integrate modulation frequency and modulation depth additively into a unidimensional percept.

Discussion

Predicted versus observed values of equal fluctuation strength



Contours of equal fluctuation strength as predicted by Zwicker & Fastl's model (open circles) versus observed matches (filled circles). Displayed are the means over subjects ± standard errors.

Concluding remarks

The observed data do not support the prevalent model of fluctuation strength as proposed by Zwicker & Fastl (1999) very well. Further experimental evidence is required in order to clarify whether fluctuation strength deserves the status of a basic auditory attribute.

References

Falmagne, J.-C. (1976). Random conjoint measurement and loudness summation. Psychological Review, **83**, 65-79.

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