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AUDITORY AFTER-IMAGES
PRODUCED BY COMPLEX TONES WITH A SPECTRAL GAP

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INTRODUCTION

About 20 years ago, Zwicker (1964) discovered the phenomenon that after switching off a band-stop noise, a faint tone may be heard. The effect was confirmed for band-rejected noise and pulse trains by Neelen (1967) as well as Lummis and Guttman (1972), who proposed to name the phenomenon a "Zwicker-tone". Despite the fact that a Zwicker-tone is the negative after-image elicited by a notched noise, its pitch strength or tonal quality is virtually identical to the pitch strength of a pure tone (Fastl and Stoll, 1979).

Since only relatively few data on Zwicker-tones have been published, we explored with 52 subjects the existence of a Zwicker-tone for a bandstop-noise at 4 kHz, presented at various levels. The main issue of this paper, however, is to show that complex tones with a spectral gap also may elicit a Zwicker-tone. The dependence of the Zwicker-tone's pitch and loudness on relevant stimulus parameters will be discussed.

METHOD

All subjects participating in the experiments had normal hearing; their age was between 20 and 65 years. Only one subject had experienced the phenomenon of the Zwicker-tone before the start of the measurements. Sounds were presented monaurally in a sound isolated chamber via an electrodynamic earphone (Beyer DT 48) with a freefield equalizer (Zwicker and Feldtkeller, 1967). At the subjects disposal was a switch with three positions: in position 1 the bandstop noise or complex tone with spectral gap was presented, in position 2 this sound was switched off, and in position 3 a pure tone could be heard. The levelof that tone could be controlled by an attenuator and the frequency of the tone was controlled via a helix-potentiometer by which the voltage to a VCO was varied, yielding frequencies beetween 200 Hz and 8 kHz. The level and frequency of the pure tone heard by the subject in position 3 of the switch could be measured by the experimenter outside the booth. Bandstop noise was produced by a filter cutting out of white noise a notch centered at 4 kHz with 1150 Hz bandwidth and steep filter slopes of 0.4 dB/Hz. Complex tones with a spectral gap and fundamental frequencies of f_b=20 Hz or 200 Hz were used. They were generated by adding up pure tones of equal amplitude but random phase with frequencies of $n \cdot f_b$ (n=1,2,3...) up to a maximal frequency of 10 kHz. In order to produce spectral gaps in the complex tones, some pure tones within the sequence $n \cdot f_b$ were omitted. The sum of the added pure tones was stored in a memory of a desk-top computer. For the experiments, the content of the memory was cyclically read out and D/A converted by a 12 bit converter.

EXPERIMENTS

Survey

The first experiment was intended as a survey with respect to the question: "How common is the Zwicker-tone phenomenon?" 52 naive subjects were presented white noise with a notch of 1150 Hz at 4 kHz, a bandwidth of 20 kHz and 43 dB overall SPL. The notched noise could be heard in position 1 of the switchand was switched off in position 2. The subjects were not informed about the signals presented in different switch positions, but were asked: "What do you hear, when switching from position 1 to position 2 of the switch?" 26 subjects (50%) answered sponaneously that they hear a faint, decaying pure tone. 10 subjects (19%) reported a Zwicker-tone after being informed "you may hear something which is soft" and 13 subjects (25%) reported a Zwicker-tone after the hint "you may hear something which is short". The remaining three subjects (6%), however, could not hear a Zwicker-tone even after an explanation of the stimuli and the expected phenomenon. Summarizing the results of our survey it can be stated that 94% of our naive listeners could hear a Zwicker-tone without information about the phenomenon.

With the same 52 subjects we explored, at which levels of the bandstop noise at 4 kHz, a Zwicker-tone can be produced. The overall SPL of the bandstop noise was varied in 5 dB steps between 23 dB and 83 dB and the question was: "Can you hear a Zwicker-tone?" We got 75% positive answers for levels between 38 dB and 53 dB, and 25% positive answers for levels between 28 dB and 73 dB. Thus, in line with data from the literature (Zwicker, 1964; Lummis and Guttman, 1972) we found that in a large number of subjects bandstop noises with levels around 43 dB overall level (about 0 dB spectrum level) produce a Zwicker-tone.

Complex tones with spectral gap

It is known from the literature (Zwicker, 1964; Neelen, 1967; Lummis and Guttman, 1972) that line spectra produced by pulse trains, from which several lines are removed by filtering or cancelling, may elicit a Zwicker-tone. While the temporal envelope of these line spectra shows high peaks, we synthesized complex tones with a spectral gap, showing much less peaked temporal envelopes because of random phase relations between the sinusoidal components. With 9 subjects we measured the pitch and loudness of Zwicker-tones elicited by complex tones with fundamental frequencies of 20 Hz and 200 Hz, and a spectral gap of 1200 Hz at 4 kHz for 40 dB overall SPL.

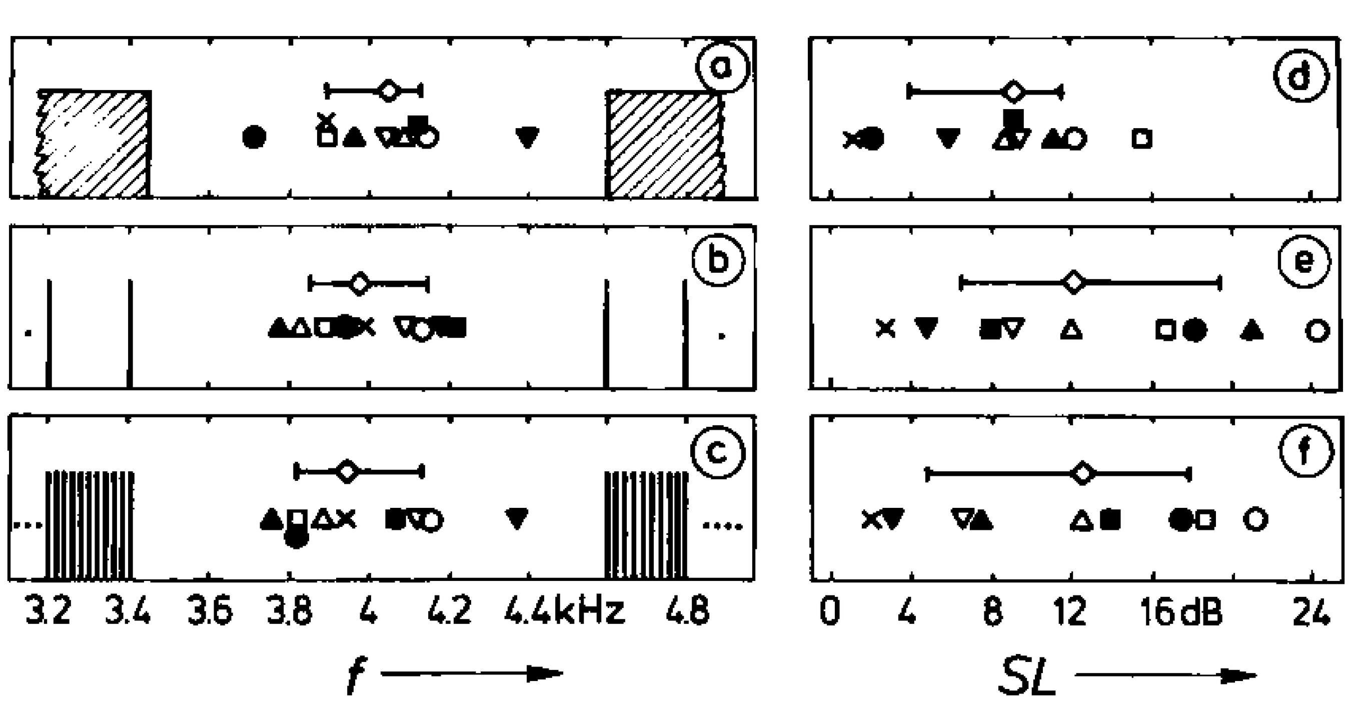

Fig. 1: Zwicker-tones elicited by bandstop noise and complex tones with a spectral gap. Frequency f and sensation level SL of pure tones which produce the same pitch and loudness as the corresponding Zwicker-tones.
(a) and (d) Bandstop noise with 43 dB overall level and a gap of 1150 Hz at 4 kHz.
(b) and (e) Complex tone with 200 Hz fundamental frequency and 40 dB SPL; gap at 4 kHz is 1200 Hz wide.
(c)and (f) Complex tone with 20 Hz fundamental frequency, 40 dB SPL and 1200 Hz-gap at 4 kHz.

The subjects first listened to the complex tone with spectral gap, switched it off to hear the Zwicker-tone, and then adjusted a pure tone in frequency and level in such a way that the pure tone produced the same pitch and loudness as the Zwicker-tone. Results of this experiment are given in Fig.1 together with data for bandstop noise. The left panels show the frequency f and the right panels the sensation level SL of the pure tone matched to the respective Zwicker-tone. The symbols represent individual medians, each calculated from eight adjustments which coincided within about 2% on the average; the rhombs with bars indicate the corresponding global medians with interquartiles. The data depicted in Fig. 1 show quite similar results for bandstop noise (a) and complex tones with a fundamental frequency of 200 Hz (b) or 20 Hz (c). Despite some individual differences, results plotted in the left panels of Fig. 1 indicate that, on the average, the pitch of the Zwicker-tone corresponds closely to the centerfrequency of the spectral gap. Data plotted in the right panels of Fig. 1 also show pronounced individual differences in the sensation level of pure tones producing the same loudness as Zwicker-tones. On the average, for bandstop noise, a sensation level of about 10 dB is reached (d) while for complex tones with spectral gap(e) and (f), a sensation level of about 12 dB shows up. This larger sensation level corresponds to a larger loudness of the respective Zwicker-tones and would seem to confirm the reports of the subjects that the Zwicker-tone is more distinct and stable for complex tones with a spectral gap than for bandstop noise.

Since the existence of Zwicker-tones for complex tones with a spectral gap was established, we explored with 5 subjects the minimal width of the gap necessary to produce a Zwicker-tone. At 2 kHz centerfrequency, we found 400 Hz minimal gap width forcomplextones with 200Hz fundamental frequency and a 240 Hz gap for 20 Hz fundamental frequency. At 4 kHz centerfrequency, the minimum gapwidth is 800 Hz for 200 Hz fundamental frequency and 400 Hz for 20 Hz fundamental frequency.Thus, the minimal gapwidth necessary to produce a Zwicker-tone with complex tones depends both on the centerfrequency of the gap and the fundamental frequency of the complex tone, i.e. the spacing between the spectral lines. For complex tones with line spacings of 200 Hz, the spectral gap has to exceed one critical band to elicit a Zwicker-tone, while for complex tones with 20 Hz line spacing spectral gaps only half a critical band wide can produce a Zwicker-tone.

In the last experiment we discuss here, we used complex tones with 20 Hz fundamental frequency, 10 kHz bandwidth and 40 dB overall SPL, and introduced spectral gaps of different widths. Fig. 2 shows results for gaps around 4 kHz in the upper part and for gaps around 2 kHz in the lower part. The symbols indicate individual medians of four subjects, each derived from four pitch matchings. Again, the reproducibility of the pitch matches was good, the average deviations amount to only 1%. From the data displayed in Fig. 2 it becomes clear that for small spectral gaps, the pitch of the Zwicker-tone corresponds to the centerfrequency of the gap, while for larger gaps the pitch of the Zwicker-tone drifts awayfrom the center towards the low-frequency edge of the gap. For constant width of the gap, this effect depends on the centerfrequency of the spectral gap: For an 800 Hz gap at 4 kHz (first line in Fig. 2) the pitch of the Zwicker-tone corresponds to the center, whereas for an 800 Hz gap at 2 kHz (sixth line in Fig. 2) the Zwicker-tone occurs at lower frequencies closer to the low-frequency edge of the gap.

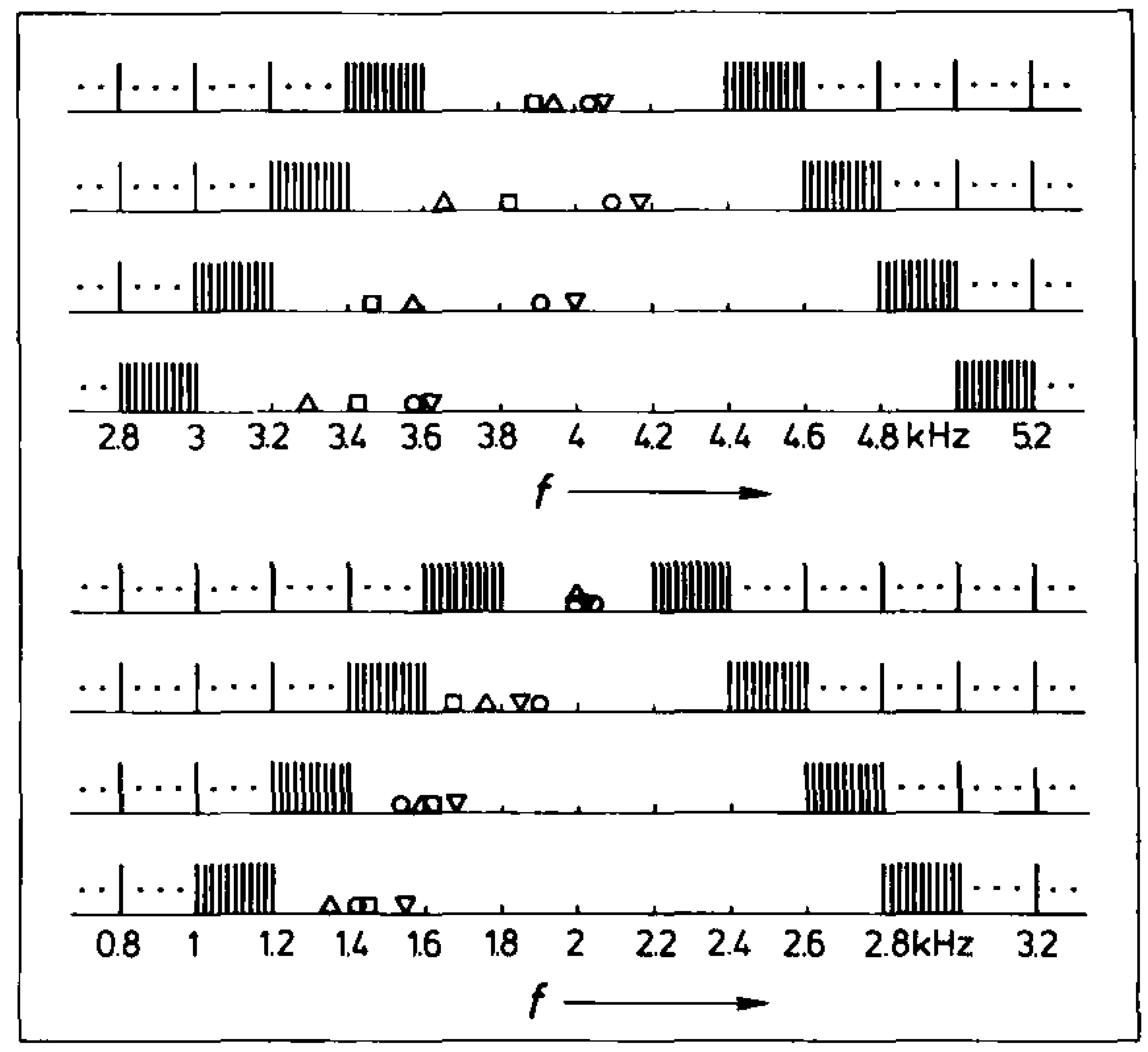

Fig. 2: Zwicker-tones for complex tones with spectral gaps of different width. Frequency f of pure tones producing the same pitch as the corresponding Zwicker-tones. Fundamental frequency 20 Hz, overall level 40 dB, centerfrequency of gaps 4 kHz (upper half) and 2 kHz (lower half). Width of the gaps is indicated by scetches of the spectral lines.

DISCUSSION

In this paper we showed that complex tones with a spectral gap may elicit an auditory after-effect, called Zwicker-tone. Much more work is necessary to explore the behaviour of Zwicker-tones in detail. However, it seems already to be justified to distinguish the Zwicker-tone phenomenon from other after-effects of sound coloration (see e.g. Wilson, 1970; Viemeister, 1980; Terhardt, 1980). The result that with increasing width of the spectral gap, the Zwicker-toneshifts from the center towards the low-frequency edge of the gap would seem to suggest an edge effect for the description of the phenomenon (see Lumis and Guttman, 1972). However, it seems unlikely that an edge effect as observed for the pitch of low-pass noise (Fastl, 1978) may fully account for the Zwicker-tone phenomenon, since we know (Fastl and Stoll, 1979) that the pitch strength of low-pass noise is by a factor of five smaller than the pitch strength of a Zwicker-tone.

References

Fastl, H. (1978), In: Fortschritte der Akustik, DAGA`78, VDE-Verlag, Berlin, 103-111.

Fastl, H. and Stoll, G. (1979), Hearing Research 1, 293-301.

Lummis, R.C. and Guttman, N. (1972), J.Acoust.Soc.Am. 51, 1930-1944.

Neelen, J.J.M. (1967), IPO 2, 37-43.

Terhardt, E. (1980), In: Psychophysical, Physiological and Behavioral Studies in Hearing, Delft University Press, Delft, Netherlands.

Viemeister, N.F. (1980), In: Psychophysical, Physiological and Behavioral Studies in Hearing, Delft University Press, Delft, Netherlands.

Wilson, J.P. (1970), In: Frequency Analysis and Psychophysics of Hearing,, Sijthoff, Leiden, Netherlands.

Zwicker, E. (1964), J.Acoust.Soc.Am. 36, 2413-2415.

Zwicker, E. and Feldtkeller, R. (1967), Das Ohr als Nachrichtenempfänger, Hirzel-Verlag, Stuttgart.