Supplemental material for the article "Exploration of a physiologically-inspired hearing aid algorithm using a computer model mimicking impaired hearing"

Details about the brainstem layer in the auditory model

The brainstem layer used in the auditory model of the present study is the same as used in Panda et al. (2014). With respect to the version of this layer thoroughly described in Meddis (2006), a second layer of tonotopically-organised MacGregor (1987) point neuron models was added to the brainstem stage with the aim of improving the performance of the system when acting as decision mechanism. These layers are identified as BS1 and BS2. Each neuron model of layer BS1 accepts input from 10 auditory nerve fibers (all from the same best frequency). Coincidental input triggers spiking activity in these neuron models. The output from 10 of these neuron models of BS1 converges in a single neuron of BS2. This is repeated across all best frequency channels. The units in BS2 were parameterized so that they never fired in the absence of an acoustic signal. As the signal level increased, however, there was an increased probability that a cell would respond. A simple decision mechanism was implemented to distinguish between signal 'heard' and 'not heard'. A signal was designated as 'heard', when at least one neuron in BS2 responded with a spike during the presentation of a probe signal. BS2 was introduced to make the decisions of the model less variable (i.e., steeper psychometric functions). This stage represents the least complicated arrangement of physiological components able to give stable 'yes'/'no' decisions in a psychophysical procedure. It is clearly not a complete model of the physiology of auditory signal detection. Nevertheless, the probabilistic nature of the model has much in common with the theoretical description of auditory thresholds offered elsewhere (Neubauer and Heil, 2008; Meddis and Lecluyse, 2011).

Tab. S1: Hearing aid algorithm parameters used for the hearing impaired listeners and for the impaired computer model. All level values are given as dB SPL input levels to the algorithm.

	Channel center frequency (kHz)	Impaired computer model	IH10	IH05	IH67
Within-channel gain	0.25	45 dB	30 dB	5 dB	0 dB
	0.5	45 dB	30 dB	5 dB	10 dB
	1	45 dB	30 dB	13 dB	2 dB
	1.41	45 dB	32.5 dB	18.5 dB	12 dB
	2	45 dB	40 dB	24 dB	22 dB
	2.82	45 dB	45 dB	25 dB	26 dB
	4	45 dB	45 dB	26 dB	30 dB
	5.66	47.5 dB	50 dB	30.5 dB	-35 dB
	8	50 dB	55 dB	35 dB	-100 dB
Compression threshold	0.25	40 dB	50 dB	90 dB	90 dB
	0.5	40 dB	50 dB	90 dB	80 dB
	1	40 dB	50 dB	82 dB	88 dB
	1.41	40 dB	47.5 dB	75 dB	75.5 dB
	2	40 dB	45 dB	70 dB	63 dB
	2.82	40 dB	40 dB	69 dB	59 dB
	4	40 dB	40 dB	68 dB	55 dB
	5.66	37.5 dB	35 dB	60 dB	71.5 dB
	8	35 dB	30 dB	55 dB	88 dB
DFAC threshold	All channels	10 dB	10 dB	10 dB	20 dB
DFAC factor	All channels	0.85	0.85	0.85	0.5

Quantification of hearing profile characteristics of the impaired model and three hearing-impaired listeners

TMC slopes, IFMC depths, and absolute threshold values at all frequencies tested in unaided and aided condition are shown for the impaired computer model (Table S2) and the listener IH10, IH05, and IH67 (Table S3-S5).

Table S2: Statistics of unaided and aided profiles of the impaired computer model

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	mean
TMC slope (dB/100ms)							
unaided normal model	110	105	90	65	41	52	77
unaided impaired model	21	18	18	18	17	11	17
aided impaired model gain-only	21	19	25	33	20	15	22
aided impaired model gain-compression	n.a.	126	145	102	63	64	100
aided impaired model gain-DFAC	46	41	49	41	38	41	43
aided impaired model gain-compression-DFAC	57	66	70	59	52	74	63
IFMC depth (dB)							
unaided normal model	4	28	49	59	51	55	41
unaided impaired model	2	5	4	3	2	0	3
aided impaired model gain-only	1	4	2	2	0	19	5
aided impaired model gain-compression	n.a.	12	12	15	12	-25	5
aided impaired model gain-DFAC	10	8	13	17	15	25	15
aided impaired model gain-compression-DFAC	3	8	13	17	17	30	15
absolute thresholds (dB SPL)							
unaided normal model	7	4	3	6	13	19	9
unaided impaired model	65	59	59	63	69	73	65
aided impaired model gain-only	20	13	12	14	20	24	17
aided impaired model gain-compression	19	13	12	14	20	25	17
aided impaired model gain-DFAC	21	14	13	15	21	26	18
aided impaired model gain-compression-DFAC	21	14	12	15	22	27	18

Table S3: Statistics of unaided and aided profiles of listener IH10

IH10	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	mean
TMC slope (dB/100ms)							
unaided listener		71	61	49	34		54
aided listener		72	74	77	76		75

IFMC depth (dB)							
unaided listener		13	14	3	1		8
aided listener		14	17	27	32		23
absolute thresholds (dB SPL)							
unaided listener	52	49	45	54	68	>102	62
aided listener	19	14	14	19	22	65	25

Table S4: Statistics of unaided and aided profiles of the listener IH05

IH05	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	mean
TMC slope (dB/100ms)							
unaided listener		30	35	39	25		32
aided listener		33	39	46	46		41
IFMC depth (dB)							
unaided listener		4	11	2	5		5
aided listener		3	8	10	8		7
absolute thresholds (dB SPL)							
unaided listener	20	22	33	38	47	56	36
aided listener	16	15	18	20	22	24	19

Table S5: Statistics of unaided and aided profiles of the listener IH67

IH67	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	mean
TMC slope (dB/100ms)							
unaided listener		35	62	44	41		45
aided listener		42	66	67	76		63
IFMC depth (dB)							
unaided listener		16	20	21	15		18
aided listener		18	15	41	28		26
absolute thresholds (dB SPL)							
unaided listener	13	15	10	21	46	68	34
aided listener	9	3	3	-5	13	77	17

Output of BioAid to psychoacoustic stimuli used for assessment of hearing profiles

In order to understand, why the DFAC-processing restores TMC slopes (compression estimates) and IFMC depths to close-to-normal values, it is instructive to observe the output waveforms of the hearing aid simulation BioAid in response to the forward masking stimuli used.

Each panel of Fig. S1 shows the algorithm's output waveform of a 4kHz, 10 ms target tone following a 100 ms masker at 40 dB SPL (left column) and 80 dB SPL (right column). The parameters used in BioAid here are those of the impaired computer model (cf. Table S1). Note that the scaling of the y-axis is the same across one column, so direct amplitude comparisons can be made within a column, but not between right and left panels. The (algorithm input) level of the target tone is always 34 dB SPL throughout every panel, which corresponds to 10 dB SL for the aided impaired computer model at 4 kHz. Differences in amplitude across panels within one column are thus due to the processing of the algorithm. The DFAC-processing is a relatively slow time-dependent processing. All other components of the algorithm (gain and compression) act instantaneously, i.e., they do not depend on previous samples and thus would have the same effect on the target tone in every panel.

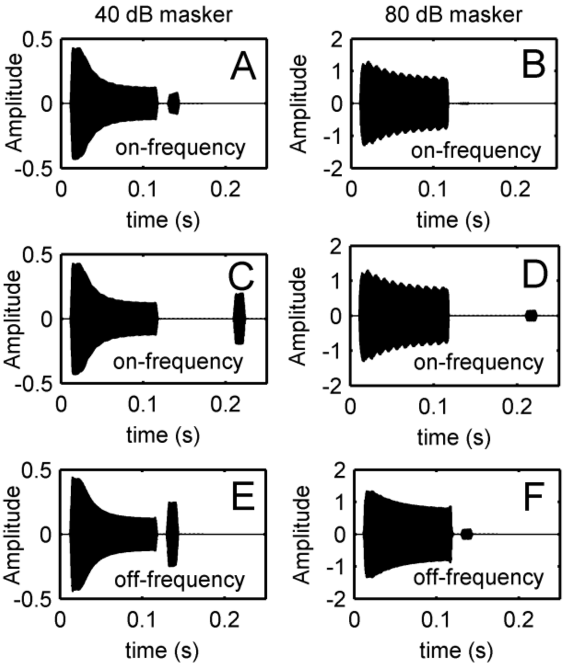

Fig. S1. Output of BioAid to forward masking stimuli for a 34 dB target tone following a 40 dB masker tone (left column) or an 80 dB masker tone (right column) in either on-frequency conditions (top four panels) or off-frequency conditions (bottom two panels).

The different rows in Fig. S1 refer to different variations of the forward masking stimuli used for assessing TMCs and IFMCs. Throughout all panels, the masker experiences an effect by the DFAC-processing, which is hardly any attenuation just after the masker onset and a larger attenuation close to the masker offset. In the following, the focus is set on the effect of the DFAC-processing on the target tone, because the detectability of the target tone after the masker governs the masker threshold obtained.

When comparing the target tone's amplitude in panel A with panel C (on-frequency masker and short vs. long temporal gap) and panel B with panel D (on-frequency masker and short vs. long temporal gaps as varied in TMCs), the DFAC-processing reduces the amplitude of the target tone only for short temporal gaps but not for long temporal gaps. This is due to the DFAC-processing's limited time constant of 50 ms, which means that a 90 ms gap is long enough such that the target tone is virtually not attenuated. Due to the amplitude reduction of both the masker and the probe at short temporal gaps, comparatively low masker levels will already be sufficient to mask the target. Due to the sole effect on the masker for long temporal gaps, much higher masker levels can be tolerated until the target tone is masked. Thus, the DFAC-processing helps in providing a greater tolerance for higher masker levels at large temporal gaps, producing steeper TMCs.

Frequency selectivity is the ability to tolerate a tone with one frequency with respect to a tone at another frequency. Panels E and F in Fig. S1 show BioAid's output waveform of a (off-frequency) 2 kHz masker at 40 and 80 dB SPL preceding the target tone. These signals are typically used for off-frequency data points of a PTC, whereas the signals in panel A and B are used for the on-frequency data point (as well as for the left-most short-gap data point of a TMC). When comparing panel A with panel E (on- vs. off-frequency), the DFAC-processing reduces the amplitude of the target tone considerably more in the on-frequency than in the off-frequency condition. This means that off-frequency maskers can be higher in level than on-frequency maskers until they mask the signal. The effect originates in the within-channel processing of the DFAC-processing: An off-frequency masker does not produce an attenuation in the on-frequency channel, the DFAC-processing is thus not triggered within the on-frequency channel, which would be the prerequisite of attenuating the target tone. Thus, much higher off-frequency masker levels can be tolerated until they mask the target tone. The same is true for an 80 dB SPL masker (compare panel B with panel F). In summary, this produces one tail of the v-shaped characteristics of the IFMC found, e.g., in Fig. 3F.

Additional references

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