SPECIAL FITTING PROBLEMS AND OPEN-CANAL SOLUTIONS

Mead C. Killion

ETYMŌTIC RESEARCH
61 Martin Lane
Elk Grove Village, IL 60007
USA

Almost anything can now be accomplished electronically in a hearing aid, but there are several unusual losses whose very rarity makes it economically unattractive to design a special hearing aid just for them. Many of these cases are characterized by normal or near-normal hearing over a substantial range of frequencies, where the best thing the hearing aid can do is nothing (neither stand in the way of the normal hearing nor provide amplification that is not needed). As described some 13 years ago in several papers at the Seventh Danavox Symposium, the open-canal or no-mold fitting is ideally suited to this task. With the help of special-purpose acoustic filters built into oversized earhooks, we have been able to extend the advantages of the open-canal fitting to some suprising audiometric configurations.

In the two sections of this paper, I will first give a semi-historical review of the solutions we have evolved to the following cases:

1. "Reverse audiograms" with normal high frequency hearing;
2. Very-high-frequency loss with normal hearing thru 2 or 3 kHz;
3. "Cookie bite" audiograms with normal hearing at low and high frequencies;
4. "Reverse Cookie Bite" audiograms with normal hearing only for the middle frequencies; and
5. Spike of normal hearing at 2 kHz (a closed mold fitting in this and the next case),
6. "Corner audiogram" feedback (whistling) problems.

In the second section, I will describe some surprising findings about feedback in open-canal fittings:

1. Compared to the gain obtainable with a shallow eartube placement, some 10 to 15 dB greater <u>low</u>-frequency gain can be obtained before oscillatory feedback occurs if the sound tube is inserted as deeply (close to the eardrum) as possible;
2. Compared to the gain obtainable with a deep eartube placement, some 10 to 15 dB greater <u>high</u>-frequency gain can be obtained before oscillatory feedback occurs if the sound tube is inserted only about 8 mm into the earcanal.

K-BASS FITTING

Six years ago Charles I. Berlin called me with the vexing problem of a six year old boy who was having trouble in school.

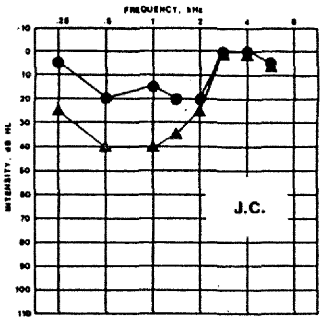


FIG. 1 *Sound field audiogram for patient J.C.—(▲) unaided and (●) aided.*

(FROM KILLION, BERLIN, AND HOOD; 1984)

JC's audiogram is shown in Figure 1. Chuck said he had very little success fitting such cases with closed-mold fittings, he thought because the hearing aid blocked off the normal hearing in a frequency range where pinna cues were extremely important to localization and rejecting sounds from unwanted directions. We both laughed when he asked if there weren't some way to provide bass amplification in an open-canal fitting, because we knew only too well that the effect of an open-canal fitting was to roll off the lows: By some 30 dB at 300 Hz. But then a light dawned: Losing 30 dB wouldn't be a problem if you had 30 dB excess output to begin with. The new Knowles CI-series receiver designed by Stuart Ewens was finding its way into powerful BTE hearing aids with extended low frequency response designed for "corner audiograms". At 300 Hz these aids had 50 to 60 dB of gain and could develop an undistorted SPL in excess of 130 dB in a closed earcanal, so losing 30 dB would not be so bad.

The design and open-canal fitting results for a hearing aid we somewhat whimsically called the "K-BASS" (Killion-Berlin Bass Amplified unobStructed Sound) hearing aid were described in some detail elsewhere (Killion, Berlin & Hood 1984).

After producing this hearing aid for a little over a year, we realized that of some 68 aids we had supplied on a 60 day trial basis, 52 had been accepted as providing useful hearing assistance. (One of them was the one for JC, whose mother sent me a nice Christmas card the next year to tell me that he was doing much better in school). With a little help from Roy Sullivan, we also realized that we were making these aids the hard way: Opening a ZP-70 hearing aid to replace the receiver, adding one or two resistors, and stuffing in 75 mm of tubing and one damper.

After some 75 computer simulations (see Zuercher, Carlson & Killion 1988, for the tube formulas we used) and a dozen or so prototypes, Don Wilson and I evolved an easier way: We could exactly duplicate the required response without any internal modifications to the hearing aids. The resulting low-pass or "K-

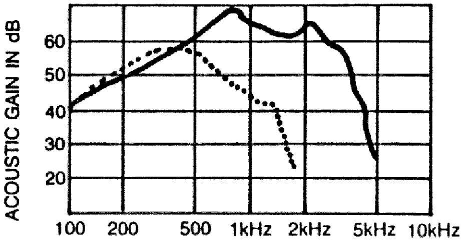
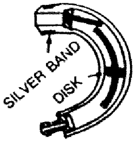
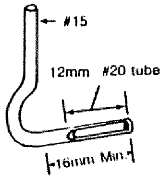


FIG. 2 RESPONSE OF POWER AID WITH:
(—) Standard Earhook
(•••) K-BASS EARHOOK & 1.5LP EARHOLD



ER12-1 LOW PASS



1.5 LP EARTUBE

(KILLION ET AL, 1984)

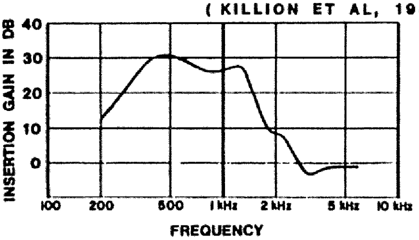
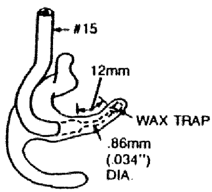


FIG. 3 ***Insertion gain of the hearing aid measured on the KEMAR manikin with the "free field" earmold***



1.5 LP EARMOLD

BASS" earhook contained two acoustic-mass tubes and two compliance chambers in order to produce a second-order acoustic filter that, in combination with a reverse horn earmold, gave some 35 dB/octave rollowff above 1500 Hz. The effect of that filter on the 2cc coupler response of a hearing aid is shown in Figure 2. Note that the coupler response falls at about 12 dB/octave between 300 and 1500 Hz, which almost exactly compensates for the 12 dB/octave rising response imposed by the acoustics of an open-canal fitting. The result, shown in Figure 3, is a nearly flat insertion gain in that frequency range, followed by a rapid drop in output so that above 2000 Hz only normal sound arriving at the earcanal is heard.

HIGH PASS EARHOOK

A year or so later, a pharmacist friend complained to me that he could no longer continue typing out a prescription while answering questions across the counter, but had to stop typing, look up, and watch the face of the talker in order to understand everything said. I tested his hearing and obtained the audiogram in Figure 4.

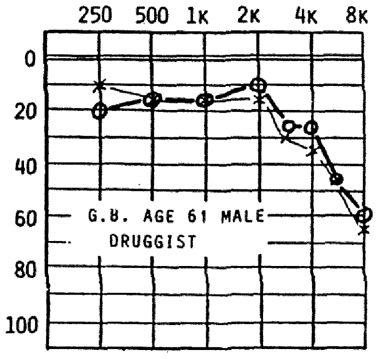


FIG. 4 "NORMAL" HEARING

My normal reaction would have been that he had too mild a loss to worry about ("You don't need a hearing aid yet, Mr. Andersen. Come back in a few years."). Instead, I told him there might be nothing we could do to help, but if he wanted to try hearing aids I would see what could be done to come up with an appropriate fitting. I had in mind Sam Lybarger's two-diameter high-pass eartube shown in Figure 5, whose tiny (.8 mm) internal first diameter "choked off" the mid-frequency sounds by 10 to 15 dB and lowered the first resonance frequency from a troublesome 1000 Hz down to 500 Hz or so (where the output in an open-canal fitting would be well below the natural sound entering the ear), and whose relatively-large-diameter (1.9 mm or 2 mm) final horn-resonator section restored the response at 4 kHz and above. The net result (Lybarger 1980) was to provide a high-pass filter with a 3 kHz cutoff frequency as shown in Figure 6.

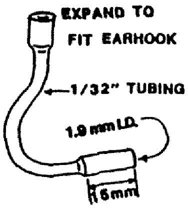
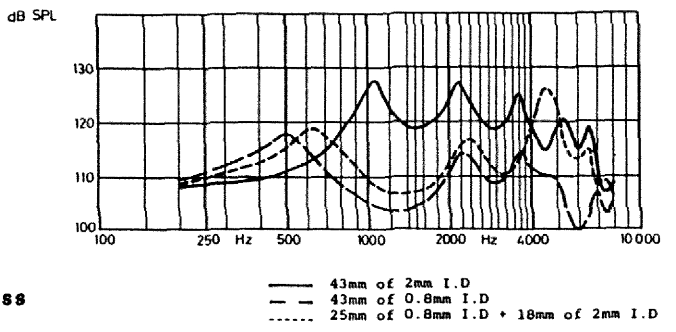


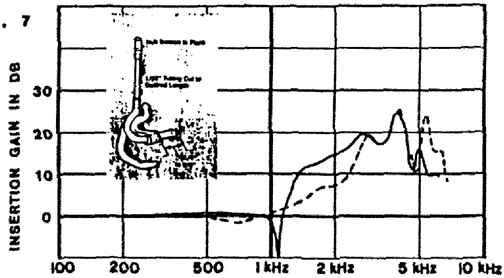
FIG. 5 ONE-PIECE MOLDED VERSION OF LYBARGER'S HIGH PASS EARTUBE

FIG. 6 Effect of Changes in Internal Diameter of the Tubing on the Frequency Response (from Lybarger 1980)



My friend seemed happy with the resulting binaural fitting, which used a pair of directional-microphone hearing aids. I was not completely happy, however, because my probe measurements (Figure 7) indicated he was still receiving too much gain at 2000 Hz, where he had normal thresholds. As a result, we developed a high-pass filter earhook that further reduces the gain at 2000

FIG. 7



OPEN-CANAL FITTING OF HIGH-FREQUENCY-EMPHASIS
OTE AID WITH: (——) 3mm LIBBY HORN
(---) DUAL-DIAMETER LYBARGER EARMOLD

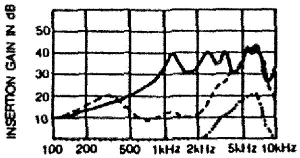


FIG. 8

REAL-EAR RESPONSE OF WIDEBAND HEARING AID USING:
(—) STANDARD EARHOOK WITH CLOSED MOLD
HIGH PASS EARHOOK & LYBARGER EARTUBE WITH:
(- - -) CLOSED EARMOLD
(···) OPEN CANAL FITTING WITH REDUCED GAIN

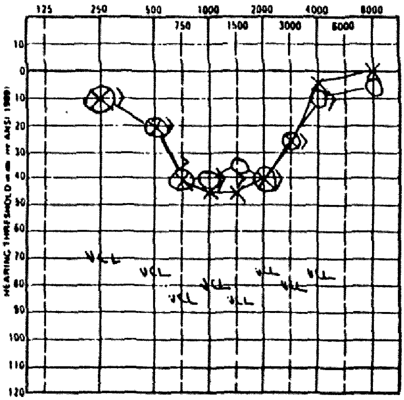
Hz: In combination with the Lybarger eartube, we obtained approximately 20 dB of reduction at 2000 Hz, with virtually no effect on output of a wideband hearing aid in the 4000 to 8000 Hz region (see Figure 8).

Listening tests convinced us that one advantage of this new high-pass fitting approach was that it was never loud or obtrusive: All it did was pick up the fricatives such as "t" and "f". We jokingly call it a "t detector."

"COOKIE BITE" AUDIOGRAMS

A recent feature in the U.S. journal Hearing Instruments has been a column edited by Robert Sweetow and E. Robert Libby where readers are invited to send in special fitting problems. One such problem is shown as "Eric's audiogram" in Figure 9.

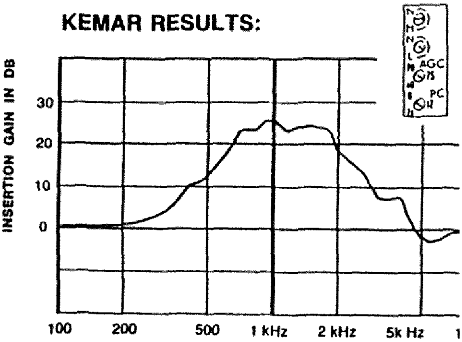
This attracted our attention because we already had a solution to that problem. (One of Piet Hein's "Grooks" goes: "Solutions to problems are easy to find: the problem's a great contribution. What is truly an art is to wring from your mind a problem to fit a solution.")



Eric's audiogram. FIG. 9

FIG. 10

KEMAR RESULTS:



We knew from experiements that when the low-pass earhook is used with regular earmold tubing (instead of the recommended "1.5 LP low-pass eartube"), the upper cutoff frequency increases from about 1500 Hz to about 2000 Hz. If that combination is used in an open-canal fitting with a hearing aid having a high-pass frequency response instead of the extended-low-frequency response normally used with the low-pass earhook, the insertion gain shown in Figure 10 results. Unlike the previous two examples, "the earhook does it all" in this case, since the open canal fitting is accomplished with a conventional (2 mm internal diameter) tube in a "free field" earmold.

Perhaps one complete example would be useful. Figure 11, blatently taken from one of our data sheets, gives a pictoral diagram of the combination which resulted in the measured insertion gain curve shown in Figure 10.

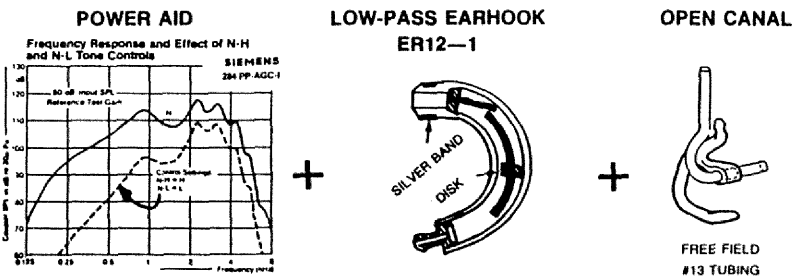
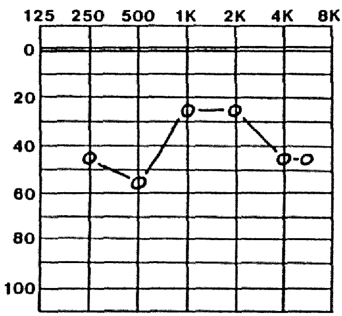


FIG. 11 COMBINATION OF ELEMENTS GIVING KEMAR RESULTS OF FIG. 10

"REVERSE COOKIE BITE" AUDIOGRAMS

My partner Ed DeVilbiss is the "sales" side of our small company, and he found himself becoming somewhat of a reluctant expert on special fitting problems. One of the problems that had no ready solution is illustrated in the audiogram of Figure 12.

FIG. 12 **OPPOSITE'S PROBLEM**



Here, again, an open canal fitting appears attractive but unlikely to work. We half-seriously suggested to one dispenser that perhaps two BTE aids could be fit behind his client's ear; one using a K-BASS fitting for the lows and one using a high-pass fitting for the highs. Although we had decided not take on another earhook project, here was a challenge that was impossible to resist: Design an all-acoustic solution to the problem of providing both low-frequency and high-frequency amplification in an open-canal fitting with no gain in the mid frequencies.

The result of another round of computer simulations, KEMAR measurements, and earhook prototypes was a fourth earhook, the "cookie-bite earhook" (it probably should have been called the "reverse-cookie-bite earhook"). The tiny inside diameter of the main tubing in Lybarger's twin-tube high-pass earmold helped shift the primary system resonance down to about 400 Hz, so we could obtain a "K-BASS"-like response at the low frequencies, while the Lybarger's resonator-horn section rescued the high-frequency output. The earhook only had to supress the response in the 1 to 2 kHz region, accomplished with a broadly tuned Helmholtz resonance acting as a "suckout" filter.

When used in an open-canal fitting with an extended-low-frequency power aid whose coupler response showed about the same gain between 200 and 400 Hz as between 2000 and 4000 Hz, the combination of Lybarger high-pass tube and "cookie bite" earhook gave the measured insertion gain shown in Figure 13.

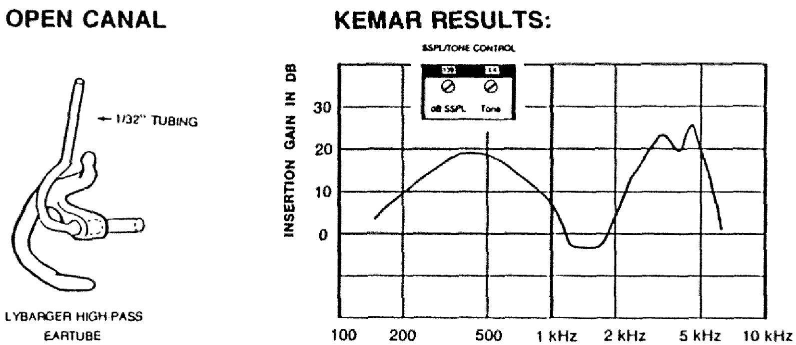


FIG. 13 RESPONSE OF LOW-FREQUENCY-EMPHASIS AID WITH ER12-4 EARHOOK AND LYBARGER EARTUBE

NOTCH FILTER EARHOOK

When faced with an individual whose audiogram looks like the one in Figure 14, with a narrow region of normal hearing at (for example) 2 kHz, but a substantial hearing loss everywhere else, one's first reaction is to simply provide amplification right thru that region. Certainly mine was. After all, the supra-threshold equal loudness curves often appear fairly flat regardless of audiometric configuration, expecially near discomfort loudness levels. John Macrae of the NAL in Australia discovered, however, that a fair percentage of those individuals found such amplification annoying and were better satisfied with a fitting which provided a "notch" in the insertion gain curve near 2 kHz.

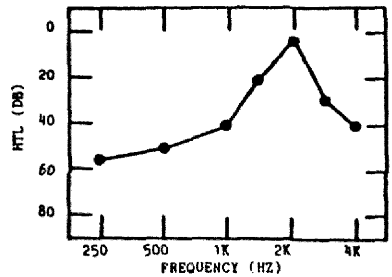


FIG. 14 ***Audiogram of a hearing loss with normal hearing in a narrow frequency band centered on 2000 Hz.***

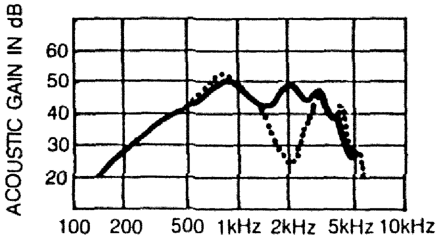


FIG. 15 RESPONSE OF POWER AID WITH:
(—) STANDARD EARHOOK
(•••) NOTCH-FILTER EARHOOK

Macrae (1983) described two earmold configurations that could provide such a notch. These worked quite well, but were mechanically inconvenient. Once we had the low-pass and high-pass earhook designs completed, we realized it would be a relatively simple matter to adapt Macrae's Helmholtz resonator version of the notch filter to an earhook construction. We didn't expect many orders for this version, but decided that it was worth doing simply because it rounded out the "product line" to have three instead of two filter earhooks on the data sheet. Figure 15 shows the effect on the coupler response of a wideband hearing aid produced by substituting the notch-filter earhook for the regular earhook. Note that this is a closed-mold or vented-mold fitting, not an open-canal fitting.

Despite my personal misgivings, our sales of the notch-filter earhooks have equalled the sales of each of the other two original earhooks. Moreover, Ora Buerkli-Halevy (1987) reported on two cases in which the individual much preferred the sound of the hearing aid with the notch-filter earhook in place, and I recently had a chance to talk to a sophisticated hearing aid wearer who told me his auditory life was much better after his dispenser substituted the notch filter earhook. So even in this case, the principle "Don't amplify in a region of normal hearing" appears to hold for at least some individuals.

"CORNER AUDIOGRAM"

One of the problems experienced by the person with severe to profound hearing loss and a "corner audiogram" has been the embarrassment of discovering that everyone nearby was being annoyed by the squeal from his hearing aid, but he couldn't hear it himself!

One successful use of the low-pass earhook has been in fitting such individuals. Here the low-pass earhook is used with a closed earmold (of course). Its function is simply to permit full-gain operation of the hearing aid without feedback setting in at a frequency beyond the range of hearing of the wearer.

MINIMIZING FEEDBACK

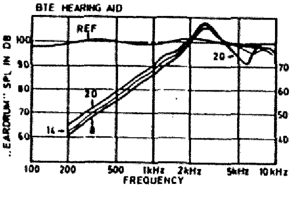
Using Lybarger technique described elsewhere in these proceedings, we obtained the "vent response" and "feedback" SPL data shown in Figures 16 and 17. Note in Figure 16 that at low frequencies the greatest eardrum SPL results from a deep placement of the eartip, while Figure 17 shows the feedback SPL is independent of insertion depth at low frequencies. At low frequencies, all the sound velocity inserted into the earcanal comes back out unchanged regardless of where the eartip is placed, somewhat like irrigating an ear with an intact eardrum. At low frequencies, therefore, the deeper the eartip the more the available gain before feedback in an open canal fitting.

At high frequencies, however, two surprising things occur. First, above 3 kHz Figure 16 shows that the deeper the eartip the less the eardrum SPL produced. This comes about because the external ear is approaching half wave resonance at 5.4 kHz (twice the 2.7 kHz quarter-wave resonance we normally think about), and the impedance looking into one end of a half-wave resonant tube goes thru a minimum at that frequency if the other end is open. Near 5.4 kHz, therefore, there is very little to impedance available to hold the sound in the earcanal.

For similar reasons, plus some horn action, the feedback sound leaking out of the earcanal increases above 3 kHz as the eartip is placed deeper and deeper in the earcanal, as shown in Figure 17.

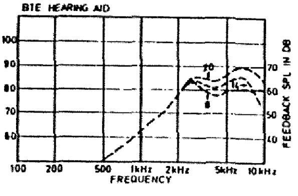
The net result is that the greatest gain before feedback at high frequencies occurs with a shallow insertion of the eartip. Figure 18 summarizes these data, taking also into account the normal gain of the external ear in order to estimate the maximum insertion gain available at several frequencies.

FIG. 16 Effect of insertion depth on:



the frequency response of a BTE instrument. (Adapted from Killion & Wilson)

FIG. 17 Effect of insertion depth on:



on feedback SPL at hearing aid microphone (Adapted from Killion & Wilson)

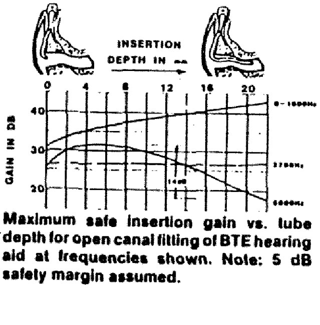


FIG. 18 Maximum safe insertion gain vs. tube depth for open canal fitting of BTE hearing aid at frequencies shown. Note: 5 dB safety margin assumed.

NOTES AND ACKNOWLEDGEMENTS

Further technical details about many of the fittings discussed above can be found in Etymotic Research data sheets "ER-12 K-HOOK response modifying earhooks" and "Earhooks for Cookie-bite audiograms". Part of the organization of this paper was based on the application note "Hard to fit clients--Special fitting solutions via the use of response modifying tone hooks" by Ora Buerkli-Halevy (1987), which contains additional technical information that I highly recommend to the interested reader.

Acknowledgement should also be made of the earlier high-pass tone hooks described by Berland (1975).

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DISCUSSION

Hartvig Jensen: In Eric's case the IG measurements came out with the correct gain for the frequencies where you had the hearing loss - but aren't you afraid of upward spread of masking in such a case of a "basin curve" ? Was the hearing aid treatment successfull ?

Killion: This was a solution to a case I read about, and I don't know if my advice was followed.
I do know of a case where I was really concerned about upward spread of masking. We provided a 8-year old boy who had only low frequency loss with about 20 dB of gain. My first reaction was that this was a mistake but it showed to be O.K. to provide a moderate amplification even at the low frequencies.

Pascoe: You mentioned that you used a high power hearing aid. Were you putting the good high frequency hearing into any danger ?

Killion: I don't believe so.

Pascoe: After all it is a child who is going to use the hearing aid for several years. For the audiograms of the opposite type with good hearing at the low frequencies and very severe losses at the high frequencies where the children wear high power hearing aids I have seen that after ten years they have been loosing their good hearing at the low frequencies.

Laukli: In the mentioned case it could be a deaf ear in the low frequency range and the measured hearing could in fact be the tuning curve. What about amplifying the low frequency range to the deaf ear ?

Killion: At Gallaudet University they have a case with a patient who by all measures had no hearing left at the low frequencies. They did extensive measurements and were convinced, that everything they got at the low frequencies was the result of the tails of the tuning curve. In this case they got higher intelligibility when they provided low frequency amplification which they interpreted as using the periodicity from the low frequency signals. Even in the high frequency neurons there was information of the periodicity in the low frequencies which aided intelligibility. Even in this extreme case some low frequency amplification was beneficial.