Comments

Comment by Viemeister:

These experiments suggest that the binaural auditory system is sensitive to fairly rapid changes in ITDs. Stellmack and Viemeister (2001) have presented similar results for ILDs. More specifically our data indicate that differences between in-phase and phase-reversed interaural envelopes of a 4-kHz carrier can be detected at modulation rates of several hundred Hertz and are closely comparable to the monaural data. Unfortunately, the term "binaural sluggishness" has become code for binaural *motion* sluggishness and, as such, misleadingly suggests that the binaural system is not sensitive to rapid changes. We and Witton *et al*. agree that the binaural motion detection is sluggish. But the binaural system is not. It can utilize rapid changes in ILDs and ITDs.

Stellmack, M.A. and Viemeister, N.F. (2001) Detection of amplitude modulation and discrimination of interaural differences in modulation phase for high-frequency carriers. J. Acoust. Soc. Am. 109, 2485. (Abstract).

Comment by Bernstein on comment by Viemeister:

Dr. Viemeister, citing the data presented by Witton *et al*. and those obtained by Stellmack and Viemeister (2001), concludes that, because listeners can detect the presence of rapidly fluctuating interaural cues, the binaural system is not sluggish. The tacit assumption underlying Dr. Viemeister's comment is that binaural sluggishness can or should be conceived of as a running average or low-pass filtering of the *values* of the interaural disparities that fall within a temporal window of finite duration. The underlying analogy is to the *monaural* temporal modulation transfer function that has been successfully modeled as an averaging or low-pass filtering of dynamic changes in amplitude, such that, at high rates of modulation, listeners cannot distinguish a modulated from an unmodulated carrier. Such a scheme does not apply to binaural processing. A simple averaging or low-pass filtering of the dynamically-varying interaural disparities would operate such that, as the frequency of fluctuation of an interaural disparity is increased, more and more samples of that dynamically varying interaural disparity would fall within the averaging window and the effective value of the interaural disparity would tend toward its mean. If that mean is zero, as it is in virtually every experiment investigating binaural sluggishness, then the result would be that listeners would be unable to distinguish a diotic stimulus from one in which the interaural cues fluctuate at a high rate. As Grantham and Wightman (1978), among others, have demonstrated, this is simply not the case. At high rates of fluctuation, listeners can easily make that discrimination. *This does not mean that the binaural system is not sluggish*. The sluggishness of the binaural system is manifest, as demonstrated by Grantham and Wightman and others, as an inability of listeners to *follow* or to "track" dynamically varying interaural disparities as their rate of fluctuation is increased.

As discussed by Bernstein (1997), rather than conceiving of binaural sluggishness as an averaging or low-pass filtering of the interaural disparities themselves, a more successful approach is to conceive of binaural sluggishness as resulting from a "persistence" of activity of the neural coincidence detectors that compose the putative internal cross-correlation "surface." Such a notion was formalized by Stern and Bachorski (1983) who employed *low-pass filtering of the activity or output of neural coincidence units* in order to successfully model binaural sluggishness. Bernstein (1997) has discussed how this type of modeling appears to be able to account *both* for listeners' inability to *track* rapid dynamic fluctuations of interaural disparities and their ability to discriminate diotic stimuli from those in which interaural disparities fluctuate rapidly.

Considered from this point of view, the data obtained by Witton *et al.* and by Stellmack and Viemeister (2001) at high rates of fluctuation of the interaural cues are entirely consistent with modern notions of the processes that mediate binaural sluggishness. It is not "unfortunate" that the term "binaural sluggishness" refers to an inability to track or follow dynamic changes. Rather, it is accurate.

Bernstein, L. R. (1997) Detection and discrimination of interaural disparities: Modern earphone-based studies. in R. H. Gilkey and T. Anderson (Eds), *Binaural and Spatial Hearing,* Erlbaum, New Jersey.

Grantham, D. W. and Wightman, F. L. (1978) Detectability of varying interaural temporal differences. J. Acoust. Soc. Am. 63, 511-523.

Stellmack, M .A., and Viemeister, N. .F (2001) Detection of amplitude modulation and discrimination of interaural differences in modulation phase for high-frequency carriers. J. Acoust. Soc. Am. 109, 2485 (Abstract).

Stern, R. M., and Bachorski, S. J. (1983) Dynamic cues in binaural perception. in R. Klinke and R. Hartmann (Eds), *Hearing- Physiological Bases and Psychophysics*, Springer-Verlag, New York, pp. 209-215.

Reply by Witton:

Dr. Bernstein's response to Prof Viemeister's note does not seem to be directed to the material we presented but rather to a long-standing dispute about the use of words. No one doubts that rapid changes in the bearing of a sound source are difficult to track; tracking sound sources, however, is not the only function of the binaural system. It is at variance with the data to attribute to the entire "binaural system" a characteristic - "sluggishness" - of only one of its behavioural manifestations in the face of several sets of binaural measurements that do not show that characteristic (e.g., Stellmack and Viemeister, 2001; Witton *et al.,* this conference and 2000; 2003).

Stellmack, M.A. and Viemeister, N.F. (2001) Detection of amplitude modulation and discrimination of interaural differences in modulation phase for high-frequency carriers. J. Acoust. Soc. Am. 109, 2485 (Abstract)

Witton, C., Green, G.G.R., Rees, A., and Henning, G.B. (2000). Monaural and binaural detection of sinusoidal phase-modulation of a 500-Hz tone. J. Acoust. Soc. Am. 108, 1826-1833.

Witton, C., Simpson, M.I.G., Henning, G.B., Rees, A., and Green, G.G.R. (2003) Detection and direction-discrimination of diotic and dichotic ramp modulations in amplitude and phase. J. Acoust. Soc. Am. 113, 468-477.

Bernstein:

Witton *et al.* are correct that it is entirely inappropriate to characterize *all aspects* of binaural processing as being "sluggish" on the basis of measurements that reveal listeners' inability to "track" or to follow rapidly-varying interaural disparities. A major point of my previous comment is that it is *that inability alone* that *defines* binaural sluggishness. To conclude, on the basis of other types of measures (such as those cited by Witton *et al*. in their reply), that the binaural system is not sluggish involves a misappropriation of the term and a misunderstanding of what is meant by "binaural sluggishness." Furthermore, the expectation that these other measures would reveal some additional type or aspect of sluggish binaural processing is inconsistent with our current understanding of the binaural system. Properly defining and applying "sluggishness" is of critical importance to communication and to interpretations of experimental findings.

Comment by Grantham and Culling:

The authors have provided some very interesting data, showing that the pattern of dichotic FM detection depends on whether the carrier is a tone or a band-limited noise. These data indicate that there are some important differences in binaural processing, depending on the bandwidth of the carrier. However, we believe there is a problem of interpretation when making conclusions from these data about binaural sluggishness. Grantham and Wightman (1978, experiment 1) found that when the reference stimulus is diotic, as in these experiments, the dichotic FM detection task can be solved not only by tracking the instantaneous changes in intracranial image position, but also by attending to image width. We would argue that any binaural discrimination based on image width is not necessarily related to temporal limitations in binaural processing. "Sluggishness", as traditionally employed in the literature, refers to the limitation in tracking changes in interaural cues. We think that this limitation is best studied using discrimination tasks in which the stimuli in the two intervals are identical in long-term statistics (e.g., interaural correlation – Grantham and Wightman's experiment 2).

The authors correctly point out the distinction between the "movement tracking" cues subjects use at low modulation rates and the other "temporal cues" employed at high rates. We would go farther and state that thresholds obtained at the high rates, where image width is a potential cue to detect the dichotic FM, do not allow any definitive conclusions concerning binaural sluggishness.

Reply:

The binaural advantage seen in the detection of phase modulation in a tone when the modulation also produces interaural phase modulation (Witton *et al.* 2000) suggested to us that, with sinusoidal carriers, the discrimination of diotic phase modulation from the same modulation when it results in interaural phase modulation should be easy. That is what we have found: Contrary to the findings of Grantham and Wightman (1978) with wide band carriers, the *threshold* depth of modulation of sinusoidal carriers decreases with increasing modulation rates from 2 to 20 Hz. The major stimulus difference between our experiments and that of Grantham *et al.* (1978) lay in the bandwidth of the carrier. When we increased the carrier bandwidth, our results resembled theirs. That is what we now report.

Although we record (informally and only insofar as verbal descriptions are possible) the cues that observers report using, it is on the measurements that we rely for insights into the auditory mechanisms that support the discrimination. We are reluctant to introduce additional stimulus differences in the hope that we might prevent our observers using some cue which we cannot quantify – "width", or "splitness", say - because the results of such manipulations are inherently equivocal; if the manipulation produces no effect, then either it failed to remove the cue, or it removed the cue and added a different cue; if the manipulation produces some effect, then it was either successful in removing the intended cue, or the cue never had an effect and new factors have been introduced by the stimulus manipulation.

Our data do not, of course, allow us to determine the mechanism or mechanisms underlying the results we report. One of many possible causes lies in the difference in the way in which irregularities in the instantaneous phase of the output of a "critical-band" filter increase with increasing modulation rate when the carrier is wide band but not when the carrier is sinusoidal. It might be that the increasing phase irregularity rather than the increasing rate *per se* is responsible for the poorer performance observed with increased modulation rate when the carrier is wide band. Another possibility is that the varying interaural time differences result in the auditory information being directed to different "bearing channels" each responding to a different band of interaural delays (Jeffress 1948). With increasing modulation rates, the duration of information that is being directed into a given channel decreases and it is the decrease in effective duration rather than the increasing rate *per se* that leads to poorer performance with increasing rate (Zwicker and Henning 1984, 1985). Or it might be that the binaural system as a whole is sluggish.

Our results certainly do not allow us to decide which of the several possible explanations of our results is correct. We prefer to wait for evidence that will allow us to discriminate reliably among the many possible interpretations.

Zwicker, E. and Henning, G.B. (1984) Binaural masking-level differences with tones masked by noises of various bandwidths and levels. Hear. Res. 14, 197-183.

Zwicker, E. and Henning, G.B. (1985) The four factors leading to binaural masking-level differences. Hear. Res. 19, 29-47.

Jeffress, L.A. (1948) A Place theory of sound localisation. J. Comp. Physiol. Psychol. 41 35-39.

Comment by Divenyi:

At the slowest modulation rate, that is, when a movement of the source is heard, the thresholds are inversely proportional to bandwidth. This relation was shown to derive from a Gábor-type uncertainty following from the physics of moving sources, as I reported at the 9th ISH (Divenyi and Zakarauskas 1992).

Divenyi, P. L., and Zakarauskas, P. (1992) The effect of bandwidth on auditory localization: An estimation theory model. In Y. Cazals, L. Demany and K. Horner (Eds.), *Auditory Physiology and Perception,* Pergamon Press, London, pp. 563-570.

Reply:

Our observers' performance at the lowest modulation rate we used did indeed improve with increasing bandwidth. However, with only three values of bandwidth, we are reluctant to attempt to estimate the functional form of the relation nor do our data allow much insight into the effective number of independent frequency channels on which such a dependence hinges.