Measuring the latency of the frequency following response through group delay

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Introduction

To improve understanding and potential clinical use of FFR, previous studies have attempted to locate FFR sources within the auditory system [1,3,9]. Knowing sources could help explain individual differences in hearing ability or diagnosis of hearing impairments. Physiological responses to clicks from the auditory nerve are earlier (~1–2 ms) [7] than responses from the inferior colliculus (~4–6 ms) [4]. Can FFR latencies tell us about the nature of phase locking at difference sites in the auditory brainstem?

What is Group Delay?

Higher frequency tones progress through the phase of their cycles quicker than lower frequency tones. Different frequency tones move in and out of phase with time. Provided the frequency spacing between consecutive tones is close enough that their phases are less than one cycle apart, the phase response can be unwrapped to tell the elapsed time. This is shown in Fig. 1.

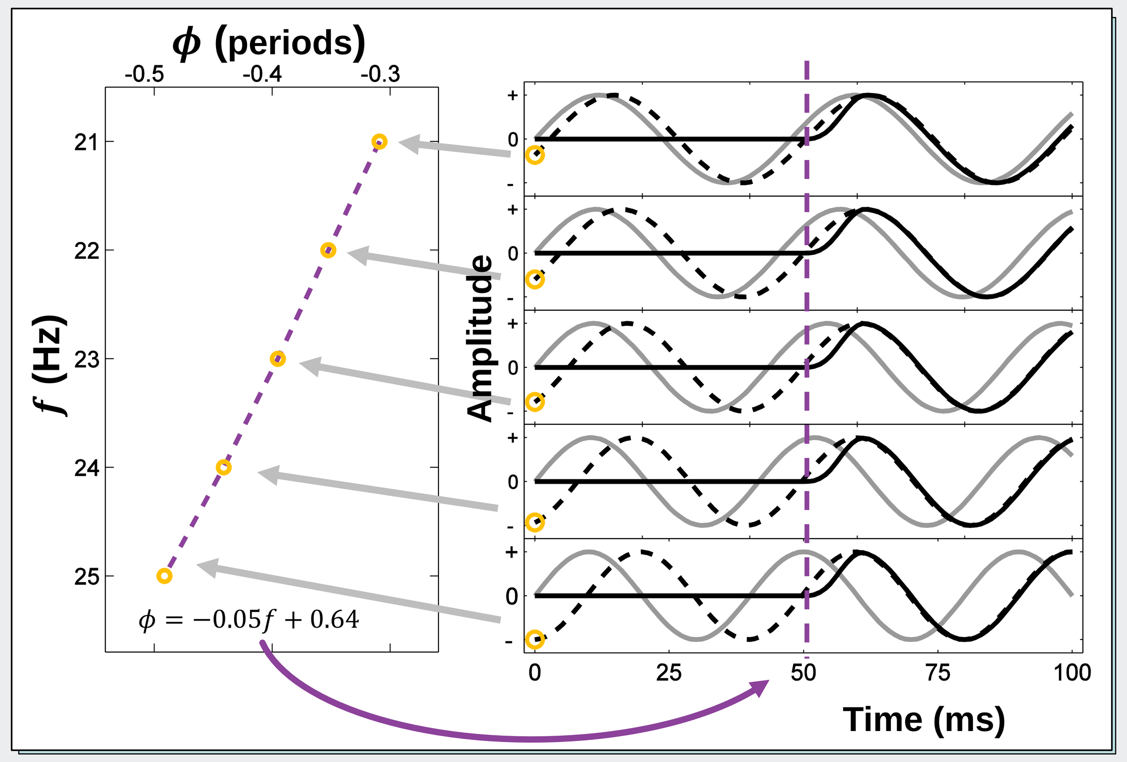

Figure 1: A diagram of a system with a group delay of 150 ms (purple dashed lines). Right Panel: Sine waves (grey) at 21 to 25 Hz are input with starting phases of 0. The output (solid black) starts 150 ms later; its Fourier Transform (dashed black) extrapolates back in time to different starting phases (yellow circles). Left panel: the transformed phase (relative to cosine) as a function of frequency. The slope of the fitted line is the negative sign of the delay in seconds.

Aim

To find out whether a horizontally-aligned electrode montage can record FFR from a peripheral source and a vertically-aligned electrode montage can record FFR from a central source, using group delay as an indicator of the response latency.

References

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Methods

Listeners

Twenty-three young listeners with audiometric thresholds below 25 dB HL.

Stimuli

AM tones were generated by summing equal-amplitude pure tones equidistant in frequency. The frequency spacing dictates the modulation rate. Five stimuli were used (Table 1).

Modulation	Lower tone	Fc	Higher tone
85	491	576	661
100	476		676
115	461		691
130	446		706
145	431		721

Table 1: The frequency components and modulation rates of the five stimuli (rows). Fc = centre frequency

Electrode montages

Vertical montage	Horizontal montage	Ground
+ C7 Vertebra – High forehead	+ Right mastoid – Left mastoid	Lower forehead

Table 2: The electrode placement sites.

Each stimulus was presented in positive and negative polarity per trial (Fig. 2). We added the responses to quantify the envelope FFR and subtracted the responses to quantify the fine structure FFR.

The five stimuli were tested separately in blocks of 1600 trials in each polarity. Stimuli were all presented to the right ear.

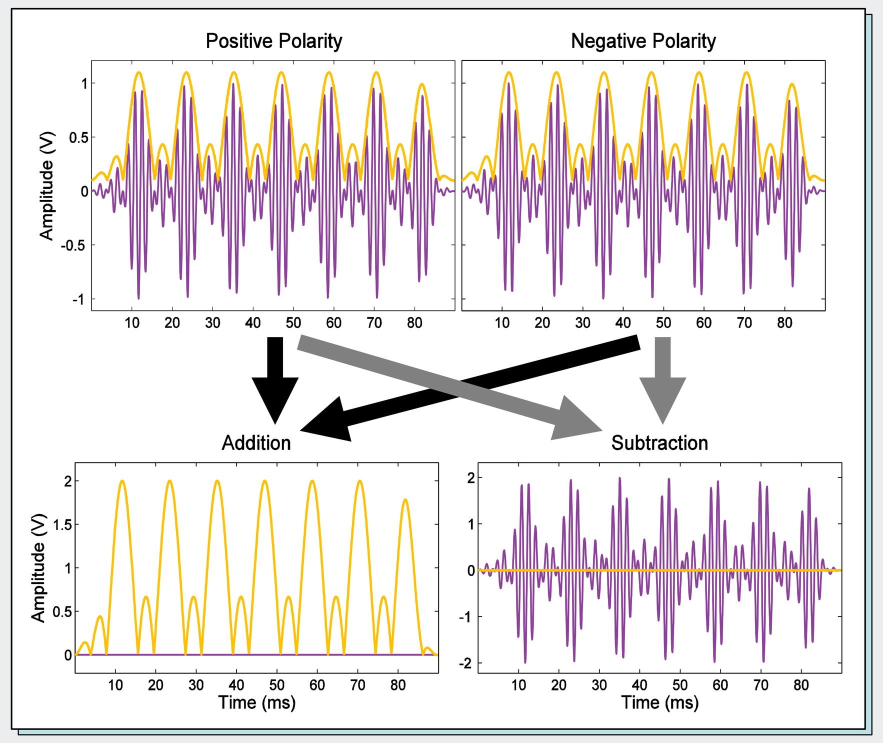


Figure 2: An example of the positive polarity (top left) and negative polarity (top right). Adding the two polarities enhances the envelope and cancels the fine structure. Subtraction cancels the envelope and enhances the fine structure.

Results

For each listener, the Discrete Fourier Transform (DFT) at the modulation frequency (Mod) was taken from the mean addition waveform. At the lower side-tone (LST) and higher side-tone (HST) frequencies, the DFT was taken from the mean subtraction waveform.

Was any FFR recorded?

FFR was accepted as present if the magnitude of the DFT was greater than the mean magnitude at frequencies surrounding it (the noise floor) by 2.57 standard deviations. The phase of the data points that passed this criterion was unwrapped for Mod, LST, and HST group delays separately. **Group delay was taken only if three or more data points passed.**

Unwrapping the phase

All possible unwrapping possibilities that could occur between elapsed times of 0 ms and 20 ms were calculated. The unwrapping that had the best linear fit was selected and the slope of that fit was taken as the group delay.

Figure 3 shows examples of group delay from two listeners, one with good FFR and with poor FFR. Across the different conditions, the number of participants with sufficiently strong FFR varied from 13 to 21 out of 23 listeners. The number of calculable group delays was less for the horizontal montage than the vertical montage (Table 3).

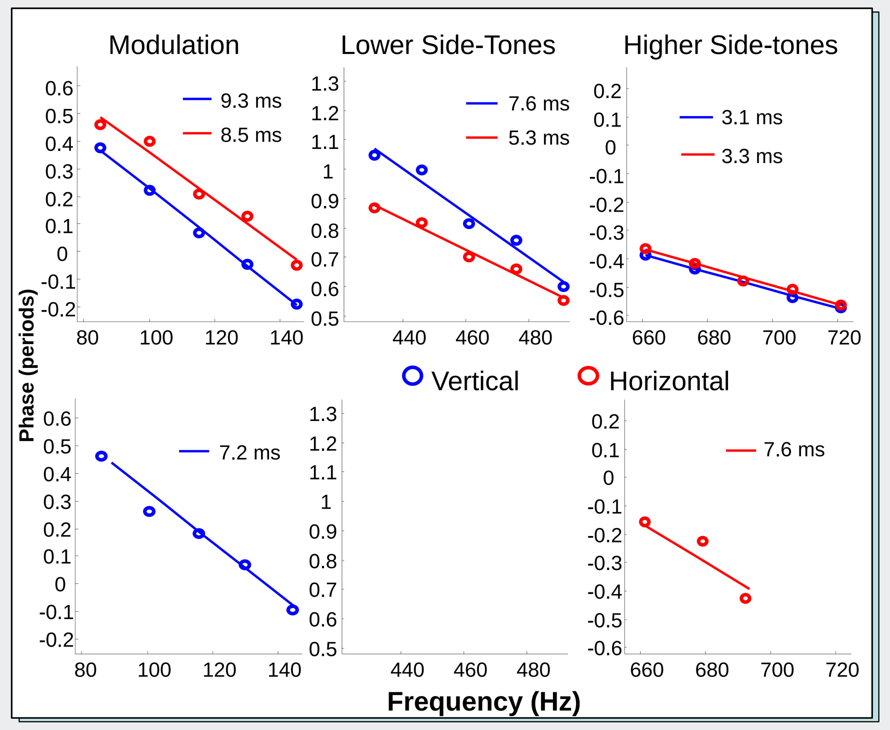


Figure 3: Example data from two listeners (by row). The top row shows a full set of FFR points with all six group delays within the accepted range. The bottom row shows incomplete data with many FFR points not above noise floor, and consequently missing group delays.

Table 3: The number of listeners with usable group delays by condition.

	Mod	LST	HST
Vertical	20	20	18
Horizontal	14	15	17

Due to the lack of complete datasets from every listener, the differences between the montages were assessed independently for each frequency region with paired samples t-tests. An overall effect of montage or an interaction between of frequency region and montage could not be tested.

Means

Figure 4 shows the mean group delays for the two montages by frequency region. Number of listeners (N), Cohen's d, Student's *t*, and the *p* value for each paired t-test are inset.

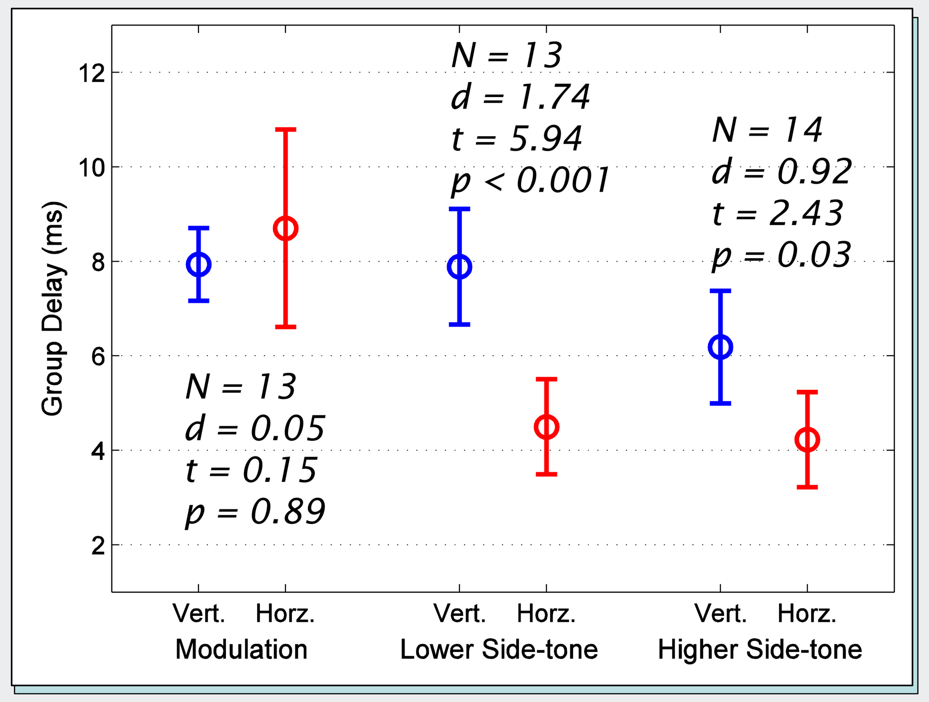


Figure 4: Mean Group Delay (+/- 95% CI) for the two montages from listeners who had acceptable group delay in both vertical and horizontal montages (statistics inset).

Discussion

These results support previous claims that horizontal and vertical montages record FFR from earlier and later sources respectively [3, 9]. Here, we show this for FFR to the fine structure of AM tones, but this may not be the case for envelope FFR. It is possible that envelope encoding is not prominent until later in the brainstem pathway.

Group delay, in theory, may be more precise than previously used methods (response onset latency [9] or stimulus-response cross correlation [3]). However, the need for clear responses to multiple frequencies (in separate test blocks) means that, in practice, group delay may prove impractical for diagnostic or clinical use. Also, group delay assumes one source per montage, but in reality multiple sources may convolute the group delay estimate.

It may be useful to compare FFR group delay with click-evoked auditory brainstem responses (ABR). Normative data are available on the latencies of ABR wave peaks which reflect activity from distinct stages of the auditory pathway [4,7,8].

Conclusions

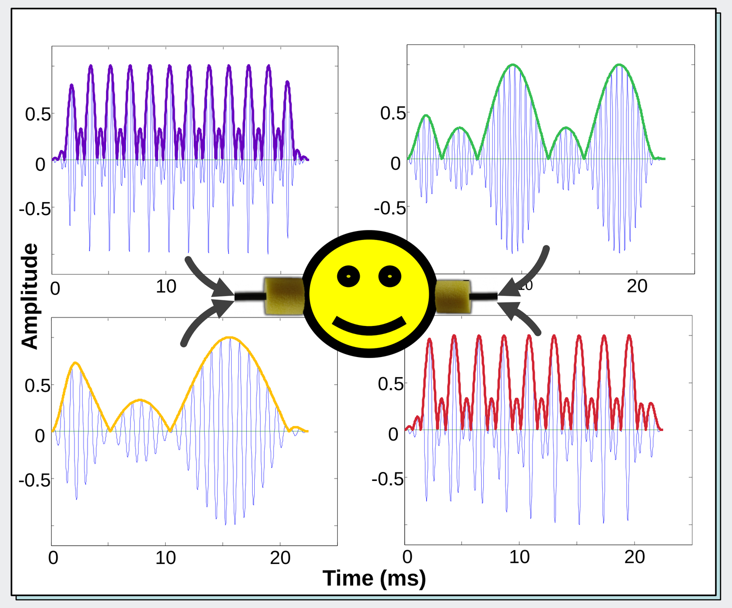
- Horizontally-recorded FFR to the fine structure of AM tomes arises earlier in the auditory pathway than vertically-recorded FFR
- Envelope FFR did not did not differ in latency between montages
- FFR signal-to-noise-ratio was sometimes poor, and a reasonable group delay was not always calculable. Online quality check of data is recommended.

Further Study

A subsequent study will look at age-related changes in FFR. Measuring complete datasets from enough young and old listeners may prove to be too difficult, or impractical, for group delay to be useful. Studying age-related changes to sources of FFR through delay or latency may be problematic as ABR latency is complicated by interactions among gender, age, and hearing loss [2, 4, 5].

Instead, the coherence of phase locking in FFR across trials will be compared with behavioural measures of temporal processing across age [6]. To save time, all FFR conditions will be tested simultaneously with the composite stimuli in Fig 5. Figure 6 shows some preliminary data.

Figure 5: A diagram showing the composite stimuli of 4 AM tones presented, two to each ear. Each ear receives one tone with slow modulation, one tone with fast modulation, one tone with low frequency fine structure and one with high frequency fine structure.



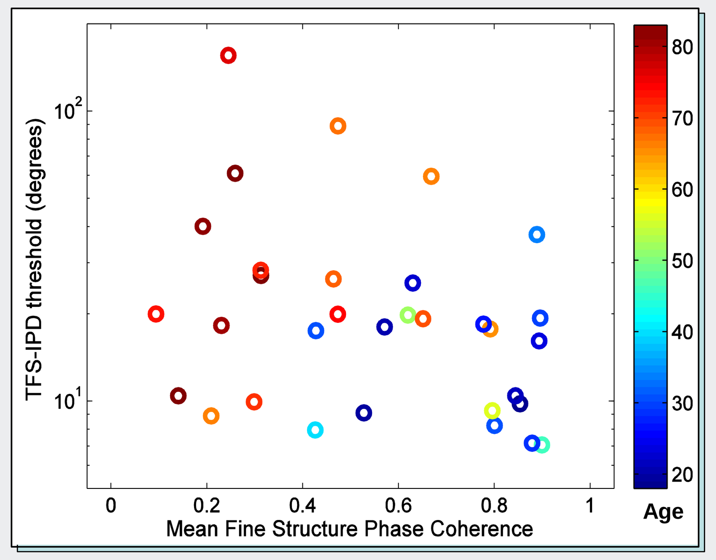


Figure 6: The phase coherence of fine structure FFR over 10,000 trials plotted against their interaural phase difference discrimination thresholds in the fine structure of AM tones (Fc = 500 Hz). One data point per listener with age labelled by marker colour.