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The effect of pinnae cues on lead-signal localization in elevated, lowered, and diagonal loudspeaker configurations.

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ABSTRACT

In a follow-up to AES-143 #9832, this experiment employed a novel method that altered subjects' pinnae and examined the effects of modifying salient spectral cues on time-based vertical-oriented precedence in raised, lowered, and diagonal sagittal and medial planes. As suggested in the prior study, outcomes confirm perceptual interference from acoustic patterns generated via lead-lag signal interaction. Results provide clear physical and psychophysical evidence that reliable elevation cues may be rendered ineffective by stimuli such as those used in typical precedence-based experiments. Outcomes here demonstrate the salient and powerful influence of spectral information during lead-lag precedence-oriented tasks and suggest that prior research, in particular that concerned with so-called "vertical" precedence, may have been erroneously influenced by simple--yet profound--acoustic comb-filtering.

1 Introduction

This investigation was a follow-up to [1] where reliable auditory precedence in the elevated, ear-level, and lowered horizontal planes was observed. Results there confirmed that signal detection followed known precedence-based suppression models but also found evidence that observations in the vertical domain may have been due to pinna-based elevation cues contained within, or created by, the lead-lag stimulus. Therefore, in order to assess which of the two signals, the subject's head-related (HRTF) cues or the experimental stimuli, may have contributed to the observed phenomena, this experiment replicated [1] and added an examination of deconstructed time- and spectrum-based influences on auditory precedence [2] in the horizontal, diagonal, and vertical sagittal and medial planes.

The interests of the present investigation were the perceptual prompts at the intersection of time and spectrum associated with auditory suppression. Specifically, the spectral influences that govern the listener's detection of elevation and whether or not those cues might override or modify the stimulus locus in a lead-lag precedence task.

1.1 Brief Background

It is well known that auditory localization is mediated via timing and spectral cues generated by the HRTF [3, 4]. Binaural and monaural processes give rise to detectable differences in signals at each ear allowing a listener to localize sound in the horizontal and vertical domains. In the process, time-based percepts create auditory phenomena such as "fusion," "suppression," and the "echo threshold" in the horizontal plane while spectrum-based percepts are understood to facilitate elevation and locus origin cues in the vertical domain.

Auditory suppression is a well-researched sensory percept provoked by a two-loudspeaker, lead-lag signal paradigm. [5] through [11] contain excellent summaries of our understandings of the parameters, perceptual effects, and applications of the phenomena of auditory precedence, interaural time difference (ITD), interaural level difference (ILD), and the influence of upper-band HRTF spectral cues.

Historically, precedence investigations utilized ear-level loudspeakers assuming a horizontal azimuthal percept or headphones assuming an across or inside-the-head percept [12-16]. More recently, studies of so-called "vertical" precedence have investigated psychophysical performance with paired loudspeakers in front, back, side, the medial plane, and in various raised configurations [17-21]. However, once out of the medial plane where the time cue is theoretically zero, separating and controlling the two stimuli, time and spectrum, is a difficult task. Therefore, prior works have generally observed psychophysical performance in the presence of both types of cues with one or the other assumed to be the dominant factor.

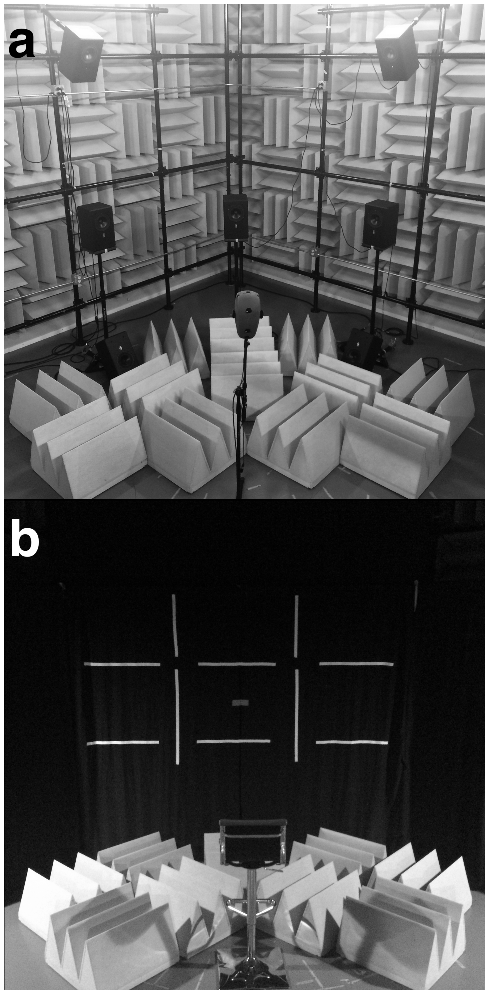
Utilizing headphones and a simple localization task, [22] created conflict between the spectral character via the minimum-phase HRTF [23] and the lower-frequency interaural group delay [24] for loci on the horizontal plane. There, conflicting pairs of stimuli significantly increased variability suggesting an influence of the unique spectral character from each associated azimuthal position. Assuming a similar effect, the present experiment aimed to answer the question, "How will a time-based vertical-oriented precedence outcome change in the raised, lowered, and diagonal sagittal or medial planes when the salient spectral cues are altered or removed?"

1.2 Experimental Focus

To investigate the effect of spectral information an experiment was executed where robust precedence-based percepts in the elevated, lowered, and diagonal planes were elicited with both normal and deviant pinna cues, and under conditions where pinna cues were eliminated. Follow up analyses examined the influence of the pinna cue when in concert and competition with the binaural and monaural time cues in the medial, sagittal, and horizontal planes. As in [1], outcomes were expected to follow the experimental null hypothesis where lagging loudspeaker configuration does not affect lead-signal detection and therefore, localization was predicted to concentrate at the leading loudspeaker orientation and elevation.

2 Methods

The experimental set up replicated that employed in [1]. Loudspeaker setup and experimental condition are shown on photographs 1a-b.

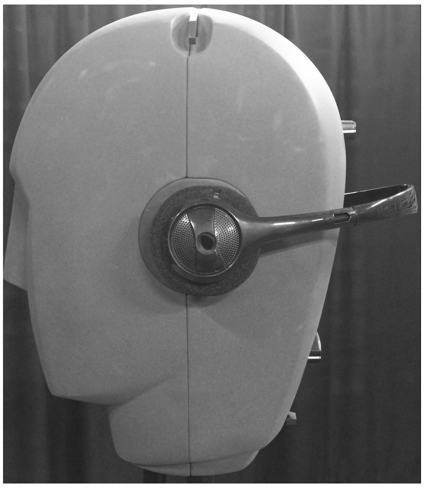


Photographs 1a-b. Loudspeaker (a) and experimental condition (b).

2.1 Stimuli

Consistent with [1] stimuli were a series of band-limited 500 ms noise bursts with 500 ms of silence between presentations. However, here two different noise bursts were utilized; one with high- and low-pass (48-dB octave) filters set at 50 Hz and 15 kHz respectively and a second with the low-pass filter set at 5 kHz. The former served as a reference signal with potential for robust pinnae cues and the latter functioned as an alternative where influential pinnae cues were not likely to be present. Stimuli presentations were altered by changing the lead-lag configuration between the active pair of loudspeakers (elevated, ear-level, or lowered) and by utilizing a head-worn device (disruptor) designed to acoustically alter the listener's HRTF without changing the timing or overall spectral energy of the signal.

The "pinna disruptor" comprised a lightweight supra-aural stereophonic headphone set with loudspeaker drivers replaced with a small rubber tube about the diameter of the typical ear canal (photograph 2). A dense foam packing filled the cavity around the tube. Device design was based on the principal of direct concha excitation; the assumption that the posterior concha is a primary source of elevation-related reflections into the ear canal [25].



Photograph 2. Binaural head wearing the pinna-cue "disruptor" device.

Constructed of hard-reflective plastic, the disruptor covered the external ear of the listener. It was convex in shape on the outer surface and had a foam ear pad that laid flat against the user's ear. The device was fitted so that the open tube was directly aligned with the user's ear canal. The shape with dampening was intended to eliminate upper-fold pinna reflections; thereby, restricting salient spectral alterations to the time-based components of the stimuli (i.e., an altered posterior concha). The goal was to retain the ITD while creating spectral elevation patterns that would be unfamiliar and potentially confusing to the listener.

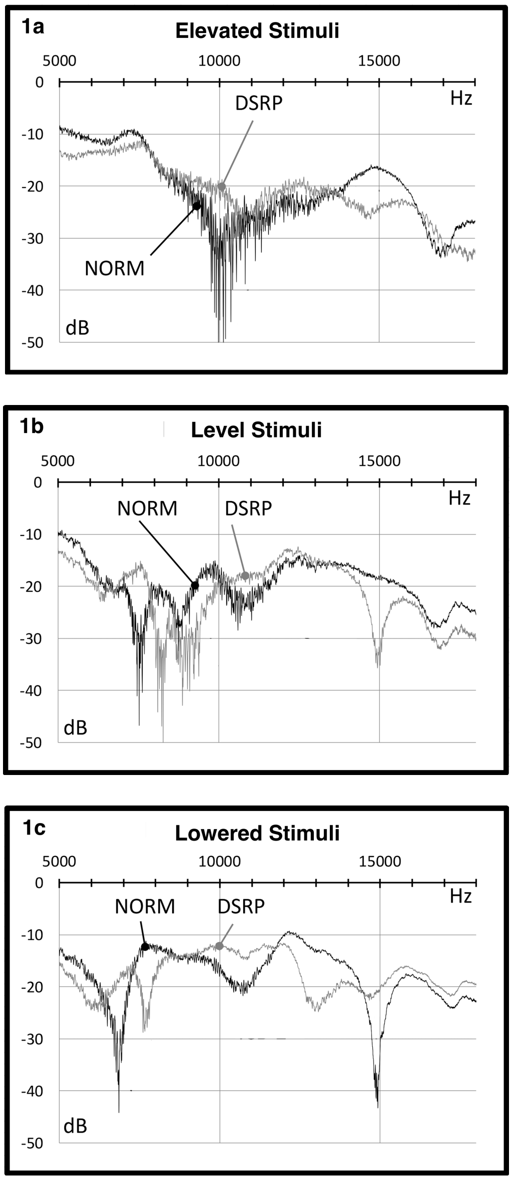
Utilizing the two filtered noise bursts and the disruptor apparatus, three test conditions were generated; (1) full-band normal stimuli (NORM) where the subject's individual pinnae cues had no alterations, (2) full-band disrupted stimuli (DSRP) with the subject's pinnae cues altered by the headphone device, and (3) low-pass filtered stimuli where the subject also wore the headphone apparatus, thus altering any remaining cues or annihilating pinnae cues altogether (ANIL).

Figures 1a-c plot impulse FFT sine-sweep (20 Hz - 20 kHz) recordings from a binaural head for the NORM and DSRP conditions. Note in all three, the disruptor device significantly altered the HRTF spectral characteristics of the signal while maintaining the overall energy across the spectrum. As expected, spectral energy above 5 kHz was absent in the ANIL stimuli.

2.2 Trials

The sequence of conditions was randomly assigned and stimuli were presented across three randomized sequences. A set of 3 bursts comprised a single trial. The lag stimulus was delayed by 1.0 ms in order to fully excite the precedence effect [13]. Fifteen left and right sagittal combinations were presented four times each. Additionally, subjects were asked to complete 15 medial trials. These trials were done by simply rotating the subject to face a vertical loudspeaker column.

In total, 60 sagittal and 60 medial trials were employed across three sessions. The first testing



Figures 1a-c. FFT of sine-sweep binaural recordings of stimuli generated at the level, elevated, and lowered loudspeakers (note: linear scale is used to better depict differences between stimuli).

session was completed in two stages with NORM and ANIL stimuli. A second listening session employed the DSRP stimuli. Both sessions resulted in 360 trials per-subject across three conditions each with eight stimuli types.

Single loudspeaker, ear-level medial trials were intermixed with horizontal and vertical lead-lag loudspeaker paired presentations. These stimuli served as controls for examination of the effect of the three stimuli types in isolation without the confluence of a delayed signal.

Subjects were not informed of the focus of the experiment and were simply asked to point a laser to the location from which they perceived the signal to originate. There were 6.0 seconds of silence between each trial, allowing the user sufficient time to indicate the perceived stimulus location. Localization percepts were noted and marked as having fallen within one of the nine zones shown in figure 1 of [1]. Zone hit count and percent correct identification of the lead loudspeaker orientation (left, right, center) and elevation (elevated, ear-level, lowered) were the dependent variables used to examine the interaction of precedence and the pinna cue in the sagittal and medial horizontal and vertical planes.

2.3 Subjects

Subjects were five postgraduate and four undergraduate audio engineering students. Subject ages were clustered in the mid-20s. All subjects reported normal hearing and had completed either a graduate- or undergraduate-level course in critical listening, had some level of musical training, and would generally be considered more experienced than "novice," but not yet "expert" listeners. All subjects completed the first listening session under the NORM and ANIL conditions. Seven of the nine subjects completed the DSRP condition.

3 Results

3.1 Control Trials

Repeated measures two-way between subjects ANOVA for Condition (NORM, DSRP, ANIL) and Presentation (Sagittal, Vertical) revealed a significant main effect of the three types of stimuli ($F(2,2) = 27.23$, $MSE = 0.54$, $p = 0.03$). The main effect of Presentation, whether or not the stimulus was intermixed within the horizontally or vertically paired stimuli was not significant. Fisher LSD *post hoc* tests revealed significant differences between both the DSRP and ANIL group mean scores when contrasted with NORM scores. No significant differences between the DSRP and ANIL group mean scores were indicated. Descriptive statistics and significant ($p < 0.05$) *post hoc* results for the control trials are tabled in the Appendix.

3.2 Lead Signal Identification

With elevation removed as a scoring factor, correct identification of the leftward or rightward sagittal orientation of the leading loudspeaker was 99% for the NORM and DSRP conditions and 97% correct for the ANIL condition.

3.3 Horizontal Presentations

Repeated measures three-way between subjects ANOVA found a significant main effect of the NORM, DSRP, and ANIL conditions ($F(2, 220) = 98.42$, $MSE = 8.04$, $p < 0.0001$) and a significant main effect of the elevated, level, and lowered presentations ($F(4, 220) = 5.89$, $MSE = 0.48$, $p < 0.0001$). There was no main effect of the sagittal (SAG) orientation (left or right) of the stimulus. There was also a significant interaction of Condition and Elevation ($F(8, 220) = 2.91$, $MSE = 0.24$, $p = 0.004$). Percent correct *M* scores for the DSRP and ANIL stimuli were consistently significantly lower than those for the NORM stimuli (see appendix for descriptive statistics and *post hoc* results).

3.4 Vertical Presentations

Repeated measures three-way between subjects ANOVA revealed significant main effects of the NORM, DSRP, and ANIL conditions ($F(2, 132) = 3.09$, $MSE = 0.25$, $p < 0.049$) as well as the elevated, level, and lowered positions ($F(2, 132) = 61.95$, $MSE = 4.99$, $p < 0.0001$). No main effect of direction, whether or not the stimulus originated from in front or to the side of the listener was detected. Fisher LSD *post hoc* tests revealed significant differences between ANIL scores when contrasted with NORM scores as well as significant contrasts between the center and vertical lowered, and between the vertical elevated and vertical lowered elevations within several of the group comparisons. No significant differences between the DSRP and ANIL *M* scores were observed (see appendix).

4 Discussion

This experiment examined the spectral influences that governed the listener's detection of elevation in a precedence-suppression task. The precedence effect was elicited *via* ear-level, raised, and lowered loudspeaker pairs across three horizontal and two vertical planes. In contrast to prior art, where no accommodations were made for the influence of the pinnae-generated elevation percept, this study altered and eliminated pinnae cues and then measured the outcome on lead-signal localization. Performance measures provided robust and sufficient evidence to reject the null hypothesis--localization percepts did *not* concentrate at the leading loudspeaker orientation and elevation in the experimental conditions.

Perceptual data are displayed here for four of the eight categories of stimuli presented. Each figure depicts the observed elevated, ear-level, and lowered responses for each of three conditions--Normal, Disrupted, and Annihilated. Boxes indicate lead-loudspeaker target locations. Each dot represents one percent of the responses for its respective stimuli and condition. Dots in and around a boxed area signify target identifications and those not in boxed areas represent locations of elevation perceptual error (EPE). EPE magnitude (%) is cited for each condition and stimulus type.

4.1 Control Performance & Disruptor Efficacy

Control-test data (figure 2) show EPE increased dramatically when pinnae cues were disrupted. In this case EPE appeared to migrate to the lower plane. In the ANIL condition, when the above 5 kHz spectral cues were eliminated altogether, EPE increased further and scattered fairly evenly above and below the horizontal plane. Data here clearly confirmed the perceptual influence of the disruptor device and the three types of experimental stimuli.

At first glance an anomaly appears to have materialized in the DSRP control presentations where response error seems to have systematically concentrated in the lowered elevation (center plot). Upon investigation it was found the disruptor device created a distinctive high narrow *fc* notch nearly identical to that observed in the NORM lowered-elevation stimuli (see figure 3).

Unknown to the authors, the altered spectral pattern presented subjects a robust and salient locus cue pointing to a below-horizontal origin. In essence, the device served to "retune" subjects' HRTFs. Response patterns here were unexpectedly reasonable and actually served as confirmation of the saliency and power of the altered HRTF spectral patterns.

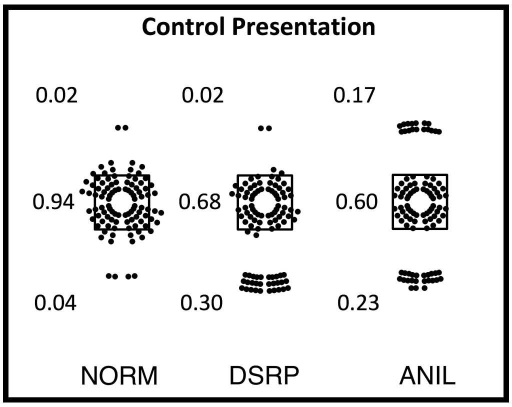


Figure 2. Elevation percepts for the control (ear-level center) presentation for each condition.

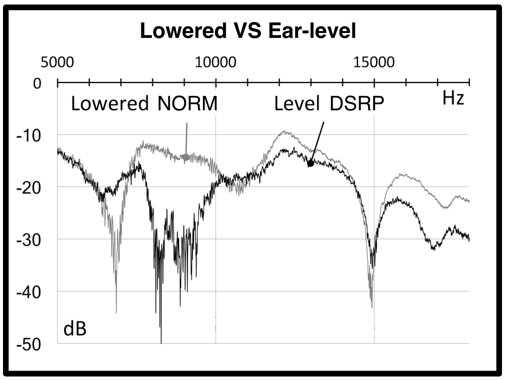


Figure 3. Overlay of lowered NORM FFT with the level DSRP FFT.

Evidence here reflected the extraordinary sensitivity of the auditory system to HRTF-generated spectral information. Most important to the present study, results demonstrated a robust, if not systematic influence of the disruptor device and indicated successful parsing of the HTRF-generated spectral information from the ITD. Similar to [22], control analyses confirmed the salient spectral components of the HRTF in the experimental stimuli were effectively and independently manipulated.

4.2 Horizontal Performance

Overall error patterns were fairly consistent with those observed in the control condition. EPE immediately jumped to significant magnitude and increasingly spread both above and below the horizontal plane in the DSRP and ANIL conditions (see figure 4).

Examination of disruptor alterations of the elevated and lowered stimuli suggests the former retained a somewhat smoothed version of its general shape and character while the latter took on the character of the ear-level stimuli (ref. figures 1a-c).

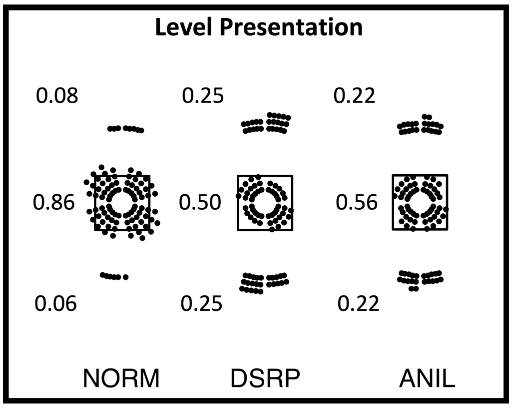


Figure 4. Elevation percepts for the level horizontal presentation for each condition.

Not surprisingly, as shown in figures 5 and 6, horizontal and diagonal elevated and lowered response patterns followed those predicted by the altered HRTF spectral prompts as described above. Elevated presentations generally remained elevated with increased EPE that migrated downward in the DSRP and ANIL conditions. In contrast, lowered presentations' EPE quickly moved upward to the ear-level orientation in the DSRP condition and continued to migrate to a distributed pattern around ear-level in the ANIL condition. In general, loci patterns were reliably similar across horizontal planes. All started solidly at the target elevation and progressed to a predominantly ear-level, largely random distribution in the ANIL condition.

Consistent with the point-source stimuli, horizontal performance unmistakeably confirmed the powerful influence of altered elevation-oriented pinnae cues in a lead-lag precedence task. Results clearly suggest that without support of robust HRTF-generated spectral stimuli, the best and possibly only thing a listener can do reliably during a precedence-elicited task is determine the overall sagittal orientation of the leading stimuli.

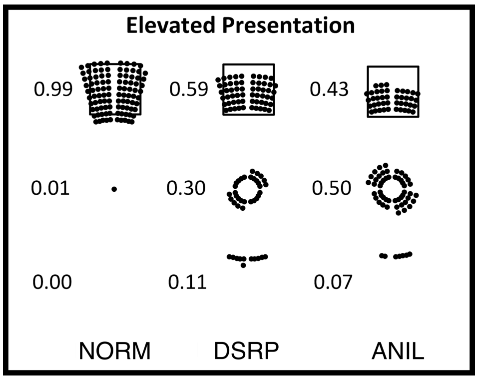


Figure 5. Elevation percepts for the elevated horizontal presentations for each condition.

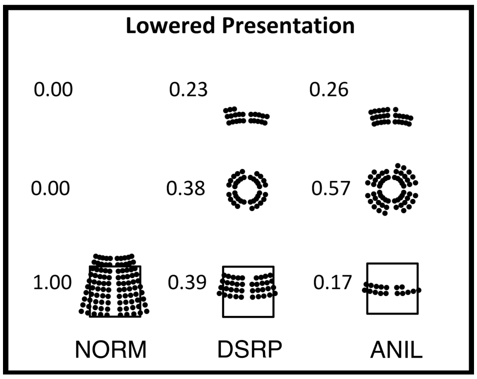


Figure 6. Elevation percepts for the lowered horizontal presentation for each condition.

4.3 Vertical Performance

Response patterns for vertical presentations show increasing EPE similar to that depicted in the horizontal presentations. However, in stark contrast, while vertical-elevated results appeared reasonable given the observed changes in HRTF character noted above, the vertical-lowered results simply--and clearly--were not.

Remarkably, vertical-elevated and -lowered EPE patterns, figures 7 and 8 respectively, were almost identical showing muted influences of the lowered leading loudspeaker *and* the HRTF. Had either time or spectrum cues significantly dominated the vertical percept, the former would have resulted in a larger magnitude of target hits and the latter should have produced greater EPE within the ear-level plane.

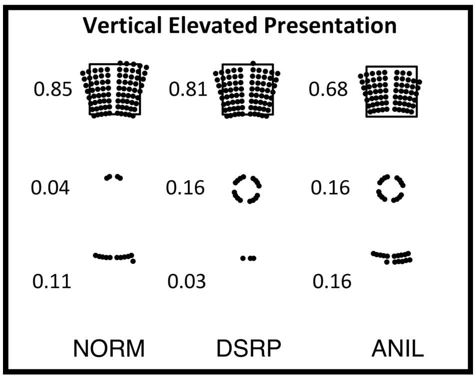


Figure 7. Elevation percepts for the vertical-elevated presentation by condition.

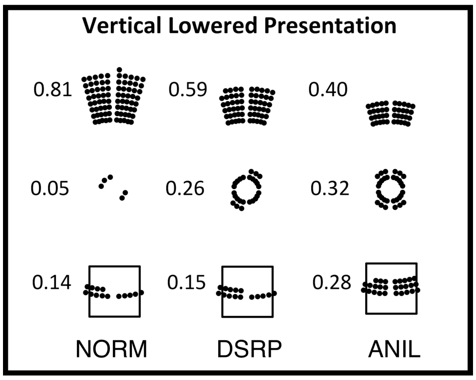


Figure 8. Elevation percepts for the vertical-lowered presentation by condition.

When compared to observed horizontal results, patterns here implied something critically different in the vertical stimuli.

4.3.1 *Brief Examination of Vertical Stimuli*

Shown in figure 9 are sine-sweep impulse FFTs of binaural recordings from recreated stimuli with vertical-plane elevated and lowered loudspeakers. In the top panel, spectral patterns from individual elevated and lowered signals (controls) show distinctive HRTF characteristics consistent with figures 1a and 1c. In the bottom panel, the clearly destructive result of lead-lag signal interaction is evident. Essentially, the unique spectral character of the elevated and lowered signals was destroyed by the interaction of the lead-lag signals at the entrance of the ear-canal; only remnants of their original shapes remained as both signals were inundated with systematic deep narrow notches spanning the upper spectrum from 5 Hz to 18 kHz; a pattern typical of feedforward comb filtering [26].

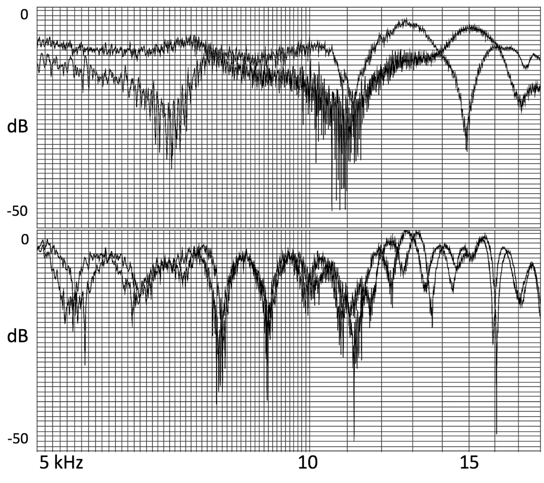


Figure 9. Impulse FFT of sine-sweep binaural recordings from the elevated and lowered point-source (top) and lead-lag signals (bottom).

Apparently the elevated and lowered vertical stimuli were nearly identical; and therefore, *so were subject outcomes*. Once again, subject response, in an unforeseen and surprising manner, confirmed the powerful influence of elevation-oriented pinnae cues in a lead-lag precedence task. Unfortunately, this finding also comes with a twist: lead-lag signals in a vertical precedence paradigm undeniably wreak havoc with perceptual elevation cues.

5 Summary & Conclusion

Interest for this study arose when [1] found evidence for potential influence of pinna-based elevation cues during a precedence-based experiment.

In this experiment, unaltered pinna cue performance served as a control and reference for comparison to other stimuli. Altered pinna cues served as a means to directly observe and gain insight into the interaction of spectrum with time-based localization mechanisms. Removal of the pinna cue served to investigate the efficacy of time-based mechanisms to detect elevation without the assistance of associated spectral cues.

While no subjects' individual HRTF measures were taken, evidence strongly supports the supposition that the novel method used here systematically and substantially altered subjects' HRTF-generated elevation cues while leaving fully functional precedence-based timing cues intact.

Firstly, this experiment demonstrated the salient and powerful influence of spectral information during lead-lag precedence-oriented tasks.

Secondly, this experiment provided clear physical *and* psychophysical evidence showing that reliable elevation cues were largely rendered ineffective by the interaction of lead-lag signals in the vertical sagittal and medial planes.

Finally, findings here imply that prior research, in particular that concerned with so-called "vertical" precedence, may have been influenced by simple--yet profound--acoustic interactions.

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Appendix: *Post hoc* test results (*$p < 0.001$)

Control Trials

Group	*M*	*SD*	*n*	Trials
ANIL	0.62	0.37	18	215
DSRP	0.73	0.31	14	168
NORM	0.96	0.07	18	216
SAG	0.82	0.31	25	99
VRT	0.73	0.31	25	500

Table A-1. Descriptive Statistics for the control trials.

Contrast	Factor	Dif.	Score	*p*
ANIL/NORM	GRP	-0.34	7.26	*
DSRP/NORM	GRP	-0.23	4.55	*
ANIL/DSRP	SAG	-0.18	2.57	0.013
ANIL/NORM	SAG	-0.36	5.43	*
DSRP/NORM	SAG	-0.18	2.51	0.015
ANIL/NORM	VRT	-0.32	4.84	*
DSRP/NORM	VRT	-0.28	3.93	*

Table A-2. Significant *post hoc* results for the control trials.

Horizontal Presentations

Group	*M*	*SD*	*n*	N
ANIL	0.32	0.33	90	343
DSRP	0.49	0.38	70	294
NORM	0.91	0.19	90	360
D-LWR	0.44	0.43	50	198
D-ELV	0.62	0.39	50	191
LVL	0.66	0.32	50	204
LWR	0.52	0.43	50	198
ELV	0.67	0.38	50	206
SAG-L	0.55	0.40	125	487
SAG-R	0.61	0.40	125	496

Table A-3. Statistical data for the horizontal presentations.

Contrast	Factor	Dif.	Score	*p**
ANIL/DSRP	GRP	-0.17	3.72	*
ANIL/NORM	GRP	-0.58	13.7	*
DSRP/NORM	GRP	-0.41	9.09	*
D-LWR/D-ELV	GRP	-0.18	3.10	0.002
D-LWR/LVL	GRP	-0.22	3.81	*
D-LWR/ELV	GRP	-0.23	4.05	*
LVL/LWR	GRP	0.13	2.33	0.020
LWR/ELV	GRP	-0.15	2.58	0.010
D-LWR/D-ELV	ANIL	-0.44	3.23	0.001
D-LWR/LVL	ANIL	-0.43	3.16	0.002
D-LWR/ELV	ANIL	-0.34	2.54	0.011
D-LWR/LWR	ANIL	0.38	2.82	0.005
LVL/LWR	ANIL	0.37	2.75	0.006
ANIL/NORM	D-LWR	-0.75	5.56	*
DSRP/NORM	D-LWR	-0.46	3.19	0.001
ANIL/NORM	D-ELV	-0.31	2.34	0.020
DSRP/NORM	D-ELV	-0.39	2.70	0.007
ANIL/NORM	LVL	-0.32	2.40	0.016
DSRP/NORM	LVL	-0.37	2.60	0.009
ANIL/NORM	LWR	-0.81	5.98	*
DSRP/NORM	LWR	-0.50	3.47	*
ANIL/NORM	ELV	-0.52	3.85	*
DSRP/NORM	ELV	-0.50	3.47	*

Table A-4. Significant *post hoc* results for the horizontal presentations.

Vertical Presentations

Group	*M*	*SD*	*n*	N
ANIL	0.51	0.36	54	497
DSRP	0.58	0.36	42	476
NORM	0.65	0.44	54	504
CNTR	0.77	0.31	50	599
V-LWR	0.22	0.28	50	782
V-ELV	0.75	0.30	50	695
MED	0.57	0.41	75	1500
SAG	0.59	0.38	75	576

Table A-5. Statistical data for the vertical presentations.

Contrast	Factor	Dif.	Score	*p**
ANIL/NORM	GRP	-0.14	2.49	0.014
CNTR/V-LWR	GRP	0.56	9.82	*
V-LWR/V-ELV	GRP	-0.54	9.45	*
CNTR/V-LWR	ANIL	0.38	2.83	0.005
CNTR/V-LWR	DSRP	0.45	2.94	0.004
V-LWR/V-ELV	DSRP	-0.36	2.35	0.020
CNTR/V-LWR	NORM	0.83	6.22	*
V-LWR/V-ELV	NORM	-0.65	4.87	*
ANIL/NORM	CNTR	-0.36	2.70	0.008

Table A-6. Significant *post hoc* results for the horizontal presentations.