Observer weighting strategies in interaural time-difference discrimination and monaural level discrimination for a multi-tone complex

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Two experiments measured listeners' abilities to weight information from different components in a complex of 553, 753, and 953 Hz. The goal was to determine whether or not the ability to adjust perceptual weights generalized across tasks. Weights were measured by binary logistic regression between stimulus values that were sampled from Gaussian distributions and listeners' responses. The first task was interaural time discrimination in which listeners judged the laterality of the target component. The second task was monaural level discrimination in which listeners indicated whether the level of the target component decreased or increased across two intervals. For both experiments, each of the three components served as the target. Ten listeners participated in both experiments. The results showed that those individuals who adjusted perceptual weights in the interaural time experiment could also do so in the monaural level discrimination task. The fact that the same individuals appeared to be analytic in both tasks is an indication that the weights measure the ability to attend to a particular region of the spectrum while ignoring other spectral regions. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.1861832]

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I. INTRODUCTION

In real-world listening situations in which multiple frequency components are present, a listener might wish to combine information across frequency or to attend to a particular frequency component while ignoring others. When a listener combines information across a number of frequencies, the listener is said to be processing the spectrum synthetically. When, on the other hand, the listener selectively utilizes information at one frequency component while effectively ignoring other components, the listener is said to be listening analytically. This distinction between analytic and synthetic listening dates back to Helmholtz (1859), and has been revived in the writings of Bregman (1990).

The extent to which a listener processes a stimulus synthetically or analytically can be described by a weighting function which estimates the relative weight given to individual stimulus elements in a given listening task. Several procedures for measuring weighting functions have been described in the literature (Berg, 1989; Richards and Zhu, 1994; Dye *et al.*, 1994; Lutfi, 1995). Although the specifics of the various procedures differ, computation of the relative weights is generally based on the extent to which the listener's trial-by-trial responses are related to trial-by-trial variation in the parameter values of the individual stimulus elements.

The issue addressed in the current paper is whether one's ability to be analytic in one auditory task generalizes to other auditory tasks. The two tasks we have used are monaural level discrimination and binaural interaural time discrimination, since considerable individual differences have been reported in the tendency to process these two cues either synthetically or analytically. The principle question is whether listeners who tend to be analytic in one task are also analytic in the other. Are some listeners simply better at focusing attention on the target frequencies while ignoring the distracting ones? A secondary question concerns the manner in which relative weights are distributed across the frequency domain. For cases in which analytic listening is impossible, do the same components tend to be weighted heavily for the two tasks? To address these two questions, it was important that the frequency range be the same for the two tasks. First, the manner in which individuals weigh monaural level differences and then interaural time differences will be reviewed.

Stellmack *et al.* (1997) presented three components to adults and preschool children under conditions in which listeners were instructed to attend to either the 250-, 1000-, or 4000-Hz component (in separate blocks of trials) while ignoring the other two. The ''correct'' interval was defined as the one in which the target component had the higher level and listeners were instructed to choose the interval in which the target component was ''louder.'' In these conditions, the listener could maximize percent correct by basing responses solely on the level change across intervals of the target component while ignoring the other (distractor) components. It was found that adults generally were able to alter their weighting strategy appropriately depending upon which component was defined as the target while the children tended to apply the same synthetic weighting strategy regardless of which component was the target. There were substantial individual differences, though, and some adult listeners also failed to alter their weighting strategy appropriately as the target component changed.

In a companion paper, Willihnganz *et al.* (1997) estimated the weighting functions of adult and preschool listeners in a level-discrimination task in which listeners were required to listen synthetically in order to achieve optimal performance. Stimuli consisted of the same three components as before (250, 1000, and 4000 Hz). The levels of each component for each interval were chosen randomly and independently from a Gaussian distribution with a mean of 62 dB SPL and a standard deviation of 1–9 dB. The standard deviation was chosen individually for each listener such that 70%–80% correct performance was achieved. Listeners were instructed to choose the ''louder'' interval, which was defined as the interval containing the larger mean level in dB SPL. Thus, in order to maximize percent correct, the optimal strategy would be to weight level information equally in all three stimulus components. In general, weighting functions differed across all preschool and adult listeners with few listeners displaying the optimal weighting strategy.

In a similar study, Doherty and Lutfi (1999) found that in a level-discrimination task both normal-hearing and hearing-impaired adult listeners varied their weighting strategies and generally gave greatest weight to the cued target component in a six-component complex (consecutive octave frequencies from 250 to 8000 Hz). There were, however, large individual differences in the ability to give the target the greatest weight, particularly when it was an intermediate (as opposed to an edge) frequency. In a companion paper in which synthetic listening was required on the part of listeners, Doherty and Lutfi (1996) found that normal listeners gave slightly more weight to the lower and higher frequencies of the same six-octave complex, deemphasizing intermediate frequencies. The data showed that hearing-impaired listeners consistently allotted the greatest weight to the frequencies falling on the sloping region of their hearing loss.

Kortekaas *et al.* (2003) asked listeners to detect a level increment in a multi-component complex consisting of 3, 7, 15, or 24 components. The complexes in their study had a spacing of one bark (critical band) unit, and were centered at 1600 Hz. In one experimental task, all components were incremented by an equal amount (in dB) in the signal interval. An additional random jitter was imposed on the overall level of each component in order to permit the computation of the relative weight given to each component. In this synthetic listening task, listeners could maximize percent correct by weighting all components equally. While nearly equal weight was given to all components, there was a general tendency to give slightly greater weight to the highest-two-to-four frequency components. The authors posited that the highest frequencies received more weight because of a tendency for higher frequencies to suppress lower frequency components (e.g., Moore and Glasberg, 1982). In a second task, the amount by which each component was incremented in level was varied such that the magnitude of the increment increased with increasing frequency. As a result, higher frequency components provided more information to allow listeners to perform the task. Listeners could maximize percent correct by giving weight to the level information in all components but the optimal weighting strategy is one in which the weight increases with increasing frequency. Generally, it was found that listeners did not vary the weight given to individual components when it was advantageous to do so. It should be noted that listeners were not informed of the variation in increment across frequencies and that it would be beneficial to base their responses more heavily on the higher-frequency components.

In a design similar to that described above for monaural level discrimination, Stellmack and Lutfi (1996) examined the weighting strategies adopted by listeners in an analytic binaural listening task. On each trial, listeners were presented with a cue tone followed by a single listening interval that contained a three-component complex (553, 753, and 953 Hz). The cue tone consisted of a diotic presentation of one of the three components in the complex. In the listening interval, a nonzero interaural difference of time (IDT) was chosen randomly and independently for each component from a discrete, rectangular distribution with a mean of zero. IDTs were ongoing delays, since the waveforms at the two ears were gated simultaneously. Listeners were instructed to attend to the cued component and to indicate whether the intracranial image associated with that component in the listening interval appeared to be to the left or right of the midline. In order to maximize percent correct, listeners had to give maximum weight to the target component and no weight to the distractor components. The data showed that the weighting strategy of only one of the six listeners (the first author of that paper) varied across conditions such that whichever component was defined as the target was given greatest weight. The remaining listeners generally gave equal weight to all three components or slightly greater weight to the highest frequency component regardless of which was cued as the target. It appeared that it was possible for listeners to vary their weighting strategy as the demands of the task dictated, but it was more difficult for less experienced listeners to do so.

Dye *et al.* (1996) ran conditions with two-component complexes in which either the target or the distractor was fixed at 753 Hz while the other component varied from 353 to 1153 Hz. The task was identical to the one used by Stellmack and Lutfi (1996). Only two of the eight listeners gave appropriate weight to the target when the target and distractor were spectrally remote, while the two frequencies were weighted about equally when the target and distractor were within 50 Hz of one another. The other six listeners consistently gave more weight to the higher of the two frequencies regardless of which was designated as the target. Weights were derived from the slope of the best linear boundary between left and right responses. One possible explanation for the high-frequency dominance that one observes for judgments based on IDT is that they are determined by wide band composite cross-correlation of the summed two- or three-component waveforms (Sayers and Cherry, 1957; Shackleton *et al.* 1992; Dye *et al.* 1996). The cross-correlation function of a periodic waveform is given by

$$\sum_{i=1}^{N} C_{Li} C_{Ri} \cos(2\pi f_i \tau + \delta_{Li} - \delta_R i), \tag{1}$$

where N is the number of components, C_{Li} and C_{Ri} are the rms values of the ith component at the left and right ears, respectively, and $\delta_{\mathrm{Li}} - \delta_{\mathrm{Ri}}$ is the interaural phase difference of the ith component (Lee, 1960). This function is periodic at the inverse of the greatest common divisor of the component frequencies, which is a full second for the studies of Dye *et al.* and Stellmack and Lutfi (since inharmonic complexes were used). The location of the peak in the composite cross-correlation function is more strongly influenced by the higher of the frequencies contained in the signal.

Interestingly, there is evidence from an analogous experiment that employed interaural differences of level (Dye, 1997) for low-frequency dominance. In this study, the target component was always presented at 753 Hz while the distractor was varied from 253 to 2753 Hz. Of the four listeners, two appeared ‘‘analytic’’ as long as the two components were at least 50 Hz apart. The other two always gave more weight to the lower frequency as long as the two components were within 400–500 Hz of one another (regardless of which was designated as the target). For wider separations, equal weight was given to the two components (753 and 2753 Hz in the extreme case). These last two listeners were characterized as spectrally synthetic. This pattern of low-frequency dominance is consistent with the upward spread of activation, and suggests that high-frequency dominance is not a general property of binaural processing.

While the adult listeners in the monaural listening tasks of Stellmack *et al.* (1997) were much more likely to vary their weighting strategy appropriately than the listeners in the binaural task of Stellmack and Lutfi (1996), it is possible that the difference in the frequency spacing of the components in the two experiments was a crucial factor. The components in the binaural task were much more closely spaced in frequency, which may have made it more difficult for listeners to perceptually segregate the target component from the distractors. It is possible that the same degree of interference would be seen in the monaural level discrimination task if the components had the same frequency spacing.

The goal of the present paper is to assess the weighting strategies used by listeners in two different listening tasks that utilize the same three frequency components. In one task, listeners performed a replication of the three-component, analytic IDT-discrimination task of Stellmack and Lutfi (1996) that was described above. In a separate set of conditions, listeners performed an analytic, monaural intensity-discrimination task similar to that of Stellmack *et al.* (1997). In both cases, the components were 553, 753, and 953 Hz. In separate blocks of trials, listeners were cued to one of the three components as the target. In order to maximize percent correct, it was necessary for listeners to vary their weighting strategy accordingly. Additional synthetic listening tasks were run in the binaural and monaural conditions in which correct responses were based on the mean value across components of the parameter of interest (either IDT or monaural level). In these conditions, listeners could maximize percent correct by weighting all three components equally. The monaural and binaural listening tasks in and of themselves presumably depend upon very different auditory mechanisms and, as such, there is no *a priori* reason to assume that the weighting strategies will be similar across the two tasks. This experiment addresses the question of whether the weighting strategy utilized by a listener is specific to a particular type of listening task or whether it reflects a listener’s general ability to listen synthetically or analytically as necessary across a variety of listening tasks. As in previous studies, it was found that only a small subset of the listeners were able to vary their weighting strategy appropriately for the different listening tasks. In general, those who did so for the binaural task were most likely to do so for the monaural task as well.

II. METHODS

A. Procedure

Each trial consisted of the presentation of a cue followed by the presentation of three-tone signals to be judged. For the interaural time discrimination task, the cue was contained during the first interval and consisted of a diotic presentation of the target frequency to mark the intracranial midline and to cue the listener to the pitch of the target. For the level discrimination task, the first two intervals contained cues. The first interval provided a monaural (left ear) presentation of the target frequency to cue the listener to the pitch of the target. The second cue interval presented the three components to the left ear such that all three components had a level of 57 dB SPL. This interval served to indicate to the listener the reference level of the target component, in the context of two other components. Listeners found it impossible to judge the level of a single frequency with the same component presented as part of a three-tone complex, thus necessitating this second cue interval.

For the interaural time discrimination task, the second interval presented the to-be-judged stimulus. It consisted of a three-tone complex consisting of 553, 753, and 953 Hz, with the level of each component at 57 dB SPL. On each trial, the interaural differences of time (IDTs) of the three components were independently selected from a Gaussian distribution having a mean of 0 μs and a standard deviation of 50 μs. The interaural delays were ongoing delays, since the waveforms at the two ears were gated simultaneously. Participants were instructed to indicate by pressing one of two keys on a keyboard the laterality (left versus right) of the *target component* compared to the intracranial midline as marked by the cue tone presented during the first interval. Listeners were told to ignore the two distractor components. Visual feedback that indicated whether the target frequency led to the left channel or to the right channel was presented on a monitor after each trial.

For the monaural level discrimination task, the third interval presented the to-be-judged stimulus. It consisted of three-tone complexes of 553, 753, and 953 Hz presented to the left ear, with the level of each of the three components chosen from a Gaussian distribution with a mean of 57 dB and a standard deviation of 3 dB. The task for the listener was to attend to the target frequency, indicating whether its level in interval 2 or 3 was greater by pressing one of two keys on a keyboard. They were told to ignore the two distractor components. Visual feedback that indicated whether the target frequency had been increased or decreased during the third interval was presented on a monitor after each trial.

For both tasks, separate conditions were run in which the target was 553, 753, or 953 Hz, with the other two frequencies serving as distractors. All stimulus intervals that comprised a trial were 200 ms in duration and were separated by 350 ms. The starting phases of the three components were randomized during the two intervals. During the to-be-judged interval, the target and distractors were gated simultaneously with 10-ms $\cos^2$ gating functions. All stimulus differences were limited to within ± 2.5 standard deviations of 0.0 ($\pm 125\ \mu$s for interaural time discrimination and ± 7.5 dB for monaural level discrimination). Data were gathered in blocks of 100 trials. Before each block of trials, subjects were allowed to listen to practice trials, which were identical to those presented during the experimental session (with target and distractor values varying from trial to trial). When ready, the listeners initiated a block of test trials. During the interaural time discrimination trials, listeners were instructed to adjust the position of the headphones during practice trials so that the diotic cue tone sounded intracranially centered. Fifteen hundred trials were run for each of the three different target frequencies. Which component served as the target was fixed until all 1500 judgments were obtained for that condition. All data from the interaural time task were collected prior to the initiation of monaural level discrimination. The order that the three different conditions were run was randomly determined for each listener. Data were collected in sessions that lasted approximately 1.25 h, during which each listener made 600–800 target judgments.

As a last condition for the interaural time discrimination task, listeners were given a set of 1500 trials during which they were to respond according to the ‘‘composite’’ lateral position, with feedback based upon the interaural difference of time averaged across frequency. Similarly, listeners were given a set of 1500 judgments of ‘‘composite’’ level, with feedback consistent with the average level (in dB) of the three components at the end of the monaural level discrimination experiment.

B. Stimulus generation and presentation

Signals were generated digitally on IBM-compatible PCs interfaced to Tucker Davis Technologies (TDT) systems. The digital signals were converted to analog waveforms at a rate of 20 kHz per channel by 16-bit digital-to-analog converters (TDT DD1). The signals were low-pass filtered by matched pairs of programmable filters (TDT PF1) set to 7.5 kHz for signal reconstruction. The final levels of the signals were adjusted with attenuators (TDT PA4) before being led to stereo headphone buffers (TDT HB6), which were used to drive Sennheiser 520 headphones. For the monaural level task, signals were presented to the left earphone only. Listeners were seated in a sound-attenuating chamber.

C. Participants and training

Three of the listeners were the authors of this paper: S1–S3. Eight were undergraduates at Loyola University Chicago who were paid an hourly wage for their participation (S3–S10). Seven (S1–S5, S8, and S10) had participated in other lateralization experiments, while the other three (S6, S7, and S9) had participated in other psychoacoustical experiments. Three were males (S1–S3) and seven were females (S4–S10). Except for S1 and S2, the listeners were in their early 20s; S1 was in his early 30s and S2 was in his mid 40s. All data were collected for the lateralization of tones before any subject judged the level of target components. Prior to data collection, all listeners received at least 10 h of training during which they lateralized low-frequency tones. Before the level discrimination task, they were given another 10 h of training during which they judged the level in isolation as well as in the presence of other components.

D. Data analysis

Three quantities were computed for each target condition. First, weights were obtained from binary logistic regressions (Hosmer and Lemeshow, 1989) for which responses were treated as a binary variable (coded as 0 and 1) and the interaural delays/levels of the three components were used as predictor variables (covariates, X_i).[1] The estimated probability of a ‘‘1’’ response given covariates X_1, X_2, and X_3 is expressed as

$$P(response=1|X_1,X_2,X_3) = \frac{\exp(\alpha+\beta_1X_1+\beta_2X_2+\beta_3X_3)}{1+\exp(\alpha+\beta_1X_1+\beta_2X_2+\beta_3X_3)}. \quad (2)$$

The dependent variable in logistic regression is the logit, the natural log of the likelihood ratio,

$$\ln\left[\frac{P(response=1|X_1,X_2,X_3)}{P(response=0|X_1,X_2,X_3)}\right]. \quad (3)$$

Much like linear regression, logistic regression gives each predictor variable a coefficient, β_f, that assesses the contribution to the variability in the dependent variable. In this instance, however, the coefficients reflect the change in log likelihood as the covariate changes one unit. β_f's were found using SPSS 11.01, which uses an iterative procedure that yields maximum likelihood estimation of parameters. β_f's were then converted into normalized weights:

$$\omega_f=\frac{\beta_f}{|\beta_{553}|+|\beta_{753}|+|\beta_{953}|} \quad \text{for} \quad f=553,\ 753,\ \text{and}\ 953\ \text{Hz}. \quad (4)$$

Note that β_f is normalized by the sum of the absolute values of the three coefficients. This ensures that the weights will not exceed 1.0 in the event that one or more of the coefficients is negative. To test the significance of weights, the β_f's were evaluated with the Wald test statistic to determine if they were statistically different from 0.0 ($p<0.05$). In the figures, the weights associated with coefficients that were not statistically different from 0.0 are plotted as open symbols. It should be noted that one logistic regression was carried out for each condition on the two types of trials (left versus right; softer versus louder), since the stimulus variable (interaural difference of time; intensity) was sampled from one distribution. Berg (1989) derived weights separately for the two types of trials, but then his two types of trials were sampled from distributions having different mean values.

The second measure computed was simple proportion correct [P(Correct)]. This is the proportion of responses consistent with the information carried by the target frequency. The third measure computed was the proportion of responses accurately predicted [P(Accounted)] for a model that assumes the decision variable used in the task to be a linearly weighted (ω_i) combination of information (X_i, either an interaural difference of time or a level change) at each frequency,

$$DV=\sum_{i=1}^{3} \omega_i X_i, \tag{5}$$

where the ω_i's are the listeners' weights computed as described above.^{2}

One response is predicted if the computed decision variable is negative (''left'' in the IDT task, ''quieter'' in the level task) and the other response is predicted if the computed decision variable is positive. For the interaural delay conditions, the stimulus variable was taken as the actual interaural delay of each component (in μs) during the second interval. In the case of the level discrimination task, the stimulus variable (X_i) was computed as the difference in dB between intervals 2 and 3.

III. RESULTS

Figure 1 shows the component weights from conditions in which low-frequency tones were to be lateralized on the basis of interaural delay. Keep in mind that optimal performance would be obtained in the analytic tasks if the normalized weights for the target frequency were 1.0 and the distractor weights were 0.0. Weights that were not significantly different from 0.0 are plotted as open symbols. Of the 120 component weights represented in the figure, only one was not significantly different from 0.0 (for S1, the 953-Hz component when 553 Hz served as the target). For the synthetic condition, best performance would be obtained if the weights given to each of the frequency components were equal to one another (0.333). The first four panels show the results for four listeners who adjusted their weighting strategy to be consistent with the demands of the task, although the four listeners did not do so to the same extent. The first two (S1 and S2) gave the target frequency more weight than either of the two distractor components. S3 and S4 behaved similarly, both failing to give the 753-Hz target the greatest weight when it was the target. S3 gave the greatest weight to the 953-Hz component, while S4 gave the greatest weight to 553 Hz. The other six listeners showed no ability to adjust their weights. S5–S9 gave greatest weight to the highest frequency regardless of which component served as the target. S10 gave nearly equal weight to the three components regardless of which component served as the target. For listeners S5–S10, the weights obtained for the synthetic condition were indistinguishable from those obtained in the other three conditions. In summary, only four of the ten listeners appear to be spectrally analytic in their use of interaural delays. Only two (S1 and S2) showed evidence of being able to adjust their weights in a manner consistent with the demands of the listening task, e.g., gave greater weight to the component that served as the target.

Table I shows the proportion of responses accounted for by the weighted average model [P(Accounted) from Eq. (5)], along with the proportion of correct responses [P(Correct)]. Notice that the first two listeners, the ones who made spectrally analytic judgments about the interaural delays of components show the smallest discrepancy between proportion correct and the proportion of responses accounted for by the weighted average model. After all, when a listener gives no weight to the two distractor frequencies, the two proportions, P(Correct) and P(Accounted), converge. However, if listeners give significant weight to information carried by nontarget components so that the decision variable is a weighted combination of information from the three components, then P(Accounted) should exceed P(Correct). Listeners 3–10 all show larger differences between P(Correct) and P(Accounted), with P(Accounted) the larger of the two. In order to ascertain whether the differences between P(Correct) and P(Accounted) were statistically significant, a series of four correlated groups *t*-tests were carried out, one for each listening condition (553, 753, and 953 Hz, and synthetic listening). All statistical results are given for P(Accounted) and P(Correct) that have been arcsine transformed in order to normalize variances (Collett, 1991). For cases in which 553, 753, and 953 Hz served as targets, the differences between P(Accounted) and P(Correct) were significant [$t(9)=4.45$, 8.11, and 5.64, respectively, all $p<0.01$]. Finally, when participants were instructed to combine information across the three components (synthetic condition), the difference between P(Accounted) and P(Correct) was also significant [$t(9)=3.80$, $p<0.01$].

Figure 2 shows the weights for the level discrimination task for the same ten observers (the subject numbers are the same across conditions). S1–S3 and S6 appear to be the only listeners able to adjust the manner in which the sources of monaural level information were weighted. None of the other seven listeners appeared to be able to differentially weight level information, although caution must be exercised in the interpretation of these weights. Table II shows P(Correct) and P(Accounted) for the ten listeners in the monaural level-discrimination task. One can see that listeners generally performed worse in the monaural level task than in the interaural time task (compare Tables I and II). Only S1 and S3 ever obtained performance better than 80% correct. The mean proportion correct (across the ten listeners and all four conditions) was only 0.64 and the mean proportion of responses accounted for by the weights was only 0.68. The comparable numbers from the interaural time discrimination task were 0.71 and 0.78, respectively. Even though P(Accounted)'s were generally lower, we wanted to assess the contribution of nontarget components to judgments by testing the differences between P(Accounted) and P(Correct). Once again,

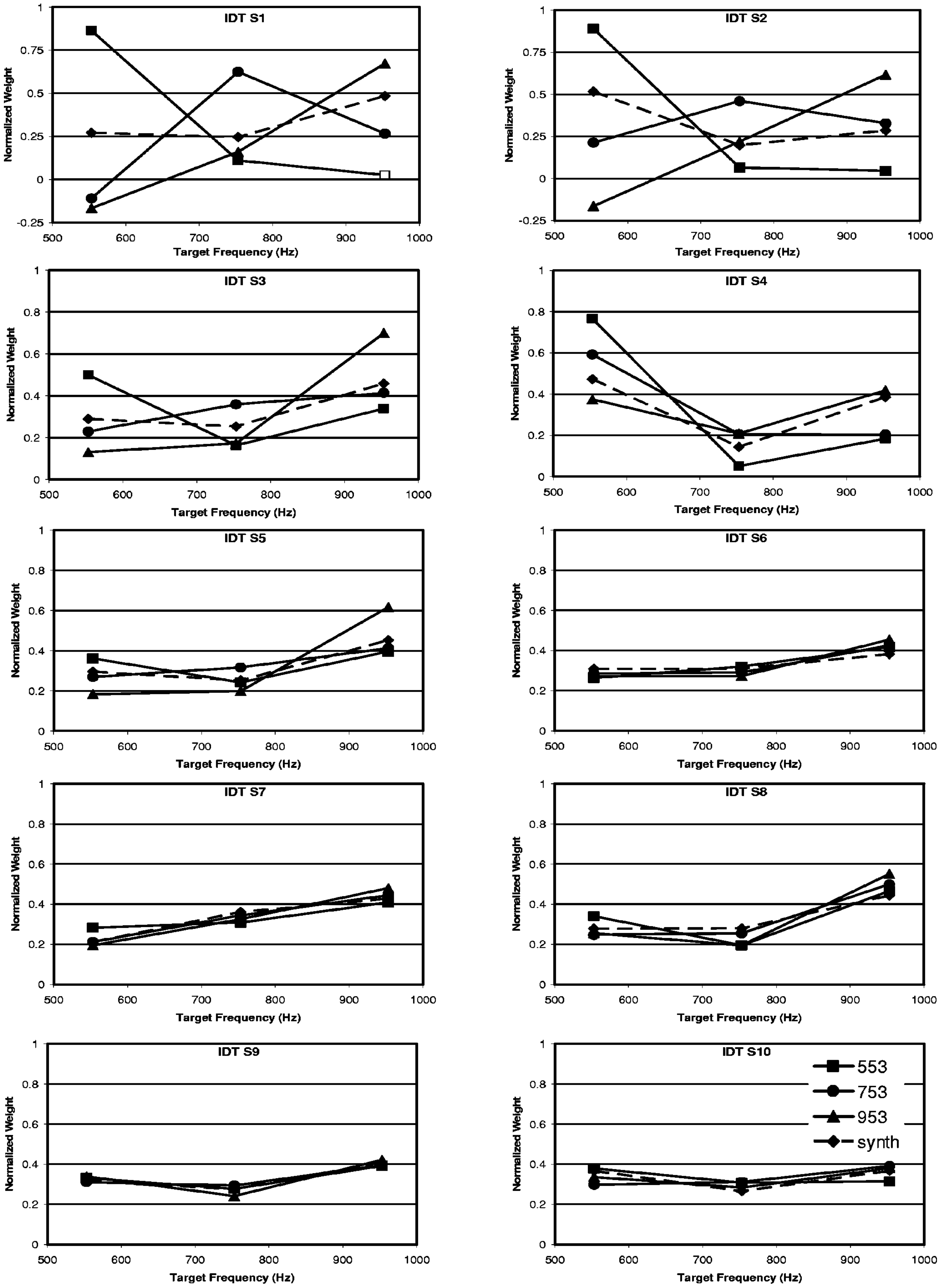

FIG. 1. Normalized weight is shown as a function of frequency for the four different interaural time listening conditions. All weights are significantly different from 0.0 at the 5% level except those plotted as open symbols. Data are presented for each individual participant.

TABLE I. The proportion correct and proportion of responses predicted from the weights are shown for the interaural time discrimination task.

	IDT	P(Correct)	P(Accounted)
S1	553	0.890	0.900
	753	0.800	0.840
	953	0.810	0.850
	Synth	0.820	0.840
S2	553	0.848	0.850
	753	0.620	0.664
	953	0.670	0.687
	Synth	0.790	0.836
S3	553	0.730	0.797
	753	0.640	0.757
	953	0.820	0.839
	Synth	0.840	0.844
S4	553	0.800	0.803
	753	0.590	0.765
	953	0.640	0.715
	Synth	0.770	0.803
S5	553	0.640	0.745
	753	0.610	0.729
	953	0.750	0.784
	Synth	0.730	0.746
S6	553	0.600	0.775
	753	0.620	0.769
	953	0.660	0.711
	Synth	0.810	0.815
S7	553	0.590	0.704
	753	0.650	0.758
	953	0.710	0.766
	Synth	0.720	0.724
S8	553	0.620	0.750
	753	0.620	0.793
	953	0.690	0.729
	Synth	0.850	0.869
S9	553	0.670	0.819
	753	0.650	0.815
	953	0.700	0.803
	Synth	0.810	0.819
S10	553	0.670	0.810
	753	0.630	0.769
	953	0.670	0.772
	Synth	0.790	0.800

correlated groups *t*-tests were performed on arcsine transformed P(Accounted) and P(Correct). The differences between P(Accounted) and P(Correct) were significant for all three analytic listening conditions [$t(9)=4.29$, 4.25, and 2.76 for target frequencies of 553, 753, and 953 Hz, respectively, all $p<0.05$]. The difference between P(Accounted) and P(Correct) for the synthetic condition was also significant [$t(9)=3.64$, $p<0.05$].

In order to compare the ability of listeners to adjust weights in the two tasks, various metrics for capturing this ability were considered. The one that will be used is the average normalized weight given to the target component, $\overline{\omega}_T$. The weights for the synthetic condition were not used in this analysis. As an example, imagine an observer who is generally able to adjust the weights appropriately, giving a weight of 0.7 to the target component regardless of which frequency served as the target. Assume the other two components are given equal weight (0.15, in this case). This observer would have an average target weight of 0.7 when averaged across the 553-, 753-, and 953-Hz conditions. On the other hand, an observer who applies a single weighting strategy in all conditions, regardless of the particular pattern of weights, will have an average target weight of 0.333. As such, the average target weight reflects the extent to which an observer varies weighting strategy across conditions. Thus, $\overline{\omega}_T$'s were computed for the interaural time discrimination task and for the monaural intensity discrimination task. These are presented in Table III. Note that the participants who had high average target weights for the interaural time discrimination task also have them for the monaural level task (S1–S3). S4 was generally more analytic in the interaural time task, while S6 was more analytic in the monaural level task. The Pearson *r* between the average weights in the two tasks was 0.70 ($N=10$, $p<0.02$). It can safely be said that listeners who were spectrally analytic in one task were spectrally analytic in the other task.

Of the five listeners who were not able to adjust their weights in either task (S5 and S7–S10), there was qualitative agreement across the two tasks for S5, S7, and S9. These three listeners tended to give greater weight to the highest frequency component in both IDT and monaural level discrimination tasks. S10 showed this same tendency in the monaural level task, but not the IDT task (in which she gave equal weight to the three components). S8 showed the largest differences in weighting strategies between the two tasks, displaying high-frequency dominance in the IDT task and low-frequency dominance in the monaural level task.

IV. DISCUSSION

The findings (Figs. 1 and 2) show that listeners who are able to adjust perceptual weights for the individual components in the task involving interaural time discrimination are generally the ones who can do so in the task involving monaural level discrimination. This is confirmed by the significant positive correlation between $\overline{\omega}_T$'s obtained for interaural time and monaural level discrimination. Optimal performance in all of the conditions in which maximal weight should be given to the target and no weight given to the distractors can only be obtained if listeners are able to ‘‘hear out’’ the target component, perceptually segregating it from the other concurrent frequencies. In the case of interaural time discrimination, this requires identifying the frequency of the target component and then determining whether its intracranial position is to the left or right of the midline. In monaural level discrimination, one must identify the frequency of the target (as marked by interval one) and then indicate whether its level increases or decreases between intervals 2 and 3. Both of these tasks require ‘‘analytic listening.’’

For both interaural time and monaural level discrimination, performance was measured for conditions in which listeners were asked to perform the tasks ‘‘synthetically.’’ This can be accomplished in two ways. First, the listener could extract independent information from each of the three com-

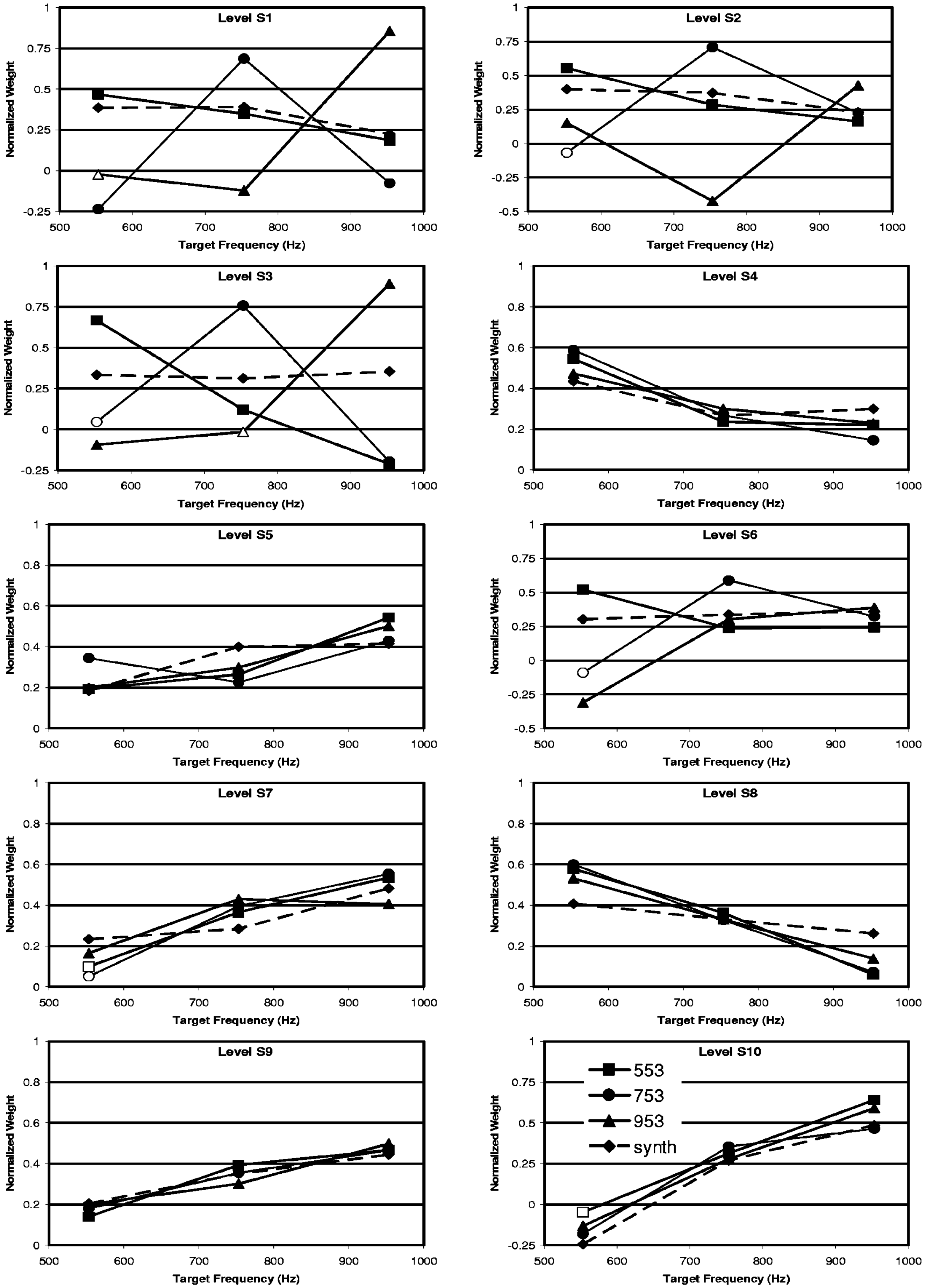

FIG. 2. Normalized weight is shown as a function of frequency for the four different monaural level listening conditions. All weights are significantly different from 0.0 at the 5% level except those plotted as open symbols. Data are presented for each individual participant.

TABLE II. The proportion correct and proportion of responses predicted from the weights are shown for the monaural level discrimination task.

	Level	P(Correct)	P(Accounted)
S1	553	0.693	0.781
	753	0.833	0.852
	953	0.820	0.820
	Synth	0.843	0.861
S2	553	0.731	0.790
	753	0.706	0.709
	953	0.650	0.740
	Synth	0.755	0.770
S3	553	0.740	0.754
	753	0.730	0.755
	953	0.860	0.861
	Synth	0.810	0.815
S4	553	0.660	0.688
	753	0.543	0.600
	953	0.570	0.704
	Synth	0.650	0.654
S5	553	0.530	0.614
	753	0.530	0.619
	953	0.570	0.579
	Synth	0.640	0.651
S6	553	0.580	0.598
	753	0.590	0.613
	953	0.550	0.600
	Synth	0.600	0.600
S7	553	0.530	0.645
	753	0.520	0.641
	953	0.560	0.645
	Synth	0.570	0.618
S8	553	0.700	0.751
	753	0.600	0.745
	953	0.540	0.745
	Synth	0.730	0.733
S9	553	0.520	0.614
	753	0.570	0.627
	953	0.610	0.620
	Synth	0.600	0.615
S10	553	0.480	0.694
	753	0.580	0.656
	953	0.660	0.669
	Synth	0.670	0.717

ponents, and then compute an average value, using the mean as the decision variable. A second possibility is that the listener simply performs ‘‘wideband’’ listening, computing the interaural delay of the composite waveform in the interaural time task, or computing the total power of the signals in the monaural level task. These two possibilities are reminiscent of Ashby and Townsend’s (1986) distinction between decisional and perceptual integrality.

The fact that the same individuals appear to be analytic in both tasks (when the conditions demand it) is an indication that the weights are most likely measuring the ability to attend to a particular region of the spectrum (ignoring other portions). Bregman (1990) has written that attention is ‘‘strongly biased toward listening to streams,’’ but that ‘‘we are capable, with effort and with practice, of listening to individual features of sounds...’’ (p. 138). Since the three frequencies were gated simultaneously, there was probably little basis for segregation of the individual components. Our results show that individuals differ considerably in their abilities to attend to individual spectral components (features) of complex sounds. Much of the discussion that follows is an attempt to identify factors that have been found to promote analytic listening.

TABLE III. Average target weights are computed for each of the ten participants.

	IDT	Level
S1	0.720	0.669
S2	0.655	0.562
S3	0.518	0.772
S4	0.463	0.347
S5	0.432	0.307
S6	0.336	0.499
S7	0.369	0.300
S8	0.382	0.348
S9	0.349	0.331
S10	0.357	0.299

Darwin and Hukin (1998, 1999) have argued that interaural differences of time are weak cues for inducing perceptual segregation, but may enhance segregation based on other stimulus cues (e.g., onset asynchrony). Studies of lateralization of low-frequency tones on the basis of IDT have found that only a minority of listeners is capable of judging the laterality of one component independent of concurrent components. Dye *et al.* (1996) found 2 of 8, while Stellmack and Lutfi (1996) found 1 of 6, compared to 4 of 10 in the current study.

It is interesting to note that several studies from the mid-1960s found evidence of analytic processing of IDTs for multiple component complexes (Sayers, 1964; Toole and Sayers, 1965). For instance, Toole and Sayers (1965) asked observers to judge the lateral position of individual components comprising a complex as a function of the interaural delay. Even when as little as 20 Hz (600 and 620 Hz) separated components, the trajectories were cyclic with the period of the to-be-judged component. Even for harmonic complexes with a fundamental frequency of 167 Hz, their observers were able to track trajectories of up to the fifth or sixth harmonic. The attention of the observers was directed to particular harmonics by, at the listener’s request, presenting the target frequency alone. These studies were all carried out with stimuli that remained on until judgments were made. This contrasts with the 200-ms signals used by Stellmack and Lutfi (1996), Dye *et al.* (1996), and the current study. Dye *et al.* (1994) found that most listeners gave greater weight to the target frequency as the duration of the two-tone complex (753-Hz target, 553-Hz distractor) was extended out to 400 ms. Perhaps the fact that Toole and Sayers used continuous stimuli explains why their listeners were generally more analytic than those in studies that used limited duration stimuli.

Blauert (1978) has argued that experienced listeners tend to hear dichotic stimuli analytically, while those with less experience hear fused intracranial images. He presented critical-band wide noises centered at 540 and 840 Hz along with a third band at a variable frequency. All three bands had the same interaural delay, either 200 or 400 μs. As the variable band was increased in frequency beyond 1500 Hz, experienced listeners heard it out as a separate auditory event with an intracranial image that was closer to the midline. Inexperienced listeners described a single, spatially extended image to which they could ascribe an average displacement. Thus, it appears that experience and training also contribute to the ability to listen to binaural stimuli analytically. S1 and S2, two of the participants who were spectrally analytic in both tasks in the current study, were the most experienced listeners in the study. S4, who tended to be analytic in the interaural time discrimination study, had participated in three prior lateralization studies. S3, a listener who was analytic in both tasks, had participated in one prior lateralization experiment.

Stellmack *et al.* (1997) and Doherty and Lutfi (1999) have reported that some adult listeners were able to adjust perceptual weights in monaural level discrimination tasks in which analytic listening was required. Most relevant to the current experiment are those conditions in which Stellmack *et al.*'s listeners were presented all three components (250, 1000, and 4000 Hz) at the same mean level. Two of the five listeners gave greatest weight to whichever component served as the target and two more gave the target frequency the greatest weight in some conditions but not others. Particularly difficult was the case in which central component of 1000 Hz served as the target. The fifth listener essentially gave equal weight to all three components regardless of which served as the target. All five of the pre-school age children in the experiment gave the three components equal weight regardless of which served as the target. Doherty and Lutfi (1999) also found listeners somewhat able to weight the target frequency highest in a level discrimination task (250, 500, 1000, 2000, 4000, 8000 Hz, with 250, 1000, and 4000 Hz serving as the targets). Of their 15 normal-hearing listeners, all gave greatest weight to the 250-Hz target, but only six gave maximum weight to the target in all three target conditions. Two gave nearly equal weight to all six components regardless of which frequency served as the target. The current study, which cued the target frequency on every trial, identified four of ten listeners as giving maximal weight to the target component in all three analytic listening conditions.

Neither Stellmack *et al.* (1997) nor Doherty and Lutfi (1999) cued the target frequency on each trial. Instead, to acquaint listeners with the target frequency, Doherty and Lutfi presented a series of 100 trials consisting of the target component alone before each new target frequency was introduced.[3] Stellmack *et al.* (1997) afforded their listeners the opportunity to manipulate the stimuli during practice to allow familiarization with the target frequency.

Kortekaas *et al.* (2003) found that none of their four listeners were able to adjust perceptual weights between a condition in which all components should be weighted equally and one in which the weights should increase with frequency. Kortekaas *et al.* used 3-, 7-, 15-, and 24-component complexes in which the frequency spacing was equal in critical band (bark) units. The complexes were centered at 11.5 barks (1600 Hz). In one set of conditions, the average levels of all components were equal, and listeners should have given equal weight to all components. However, listeners tended to give greater weight to the highest two-to-four components for most conditions. For complexes with large numbers of components (15 and 24), there was a tendency for some of the listeners to give greater weight to the lower frequencies. With 7 or 15 components, conditions were run in which the average level difference increased progressively with barks, such that

$$\Delta L(z) = \Delta L_o \cdot k^{(z-z1)}, \tag{6}$$

where $\Delta L(z)$ is the level increment (in dB) for the component at bark z, ΔL_o is the nominal level increment, and z_1 is the bark of the lowest component frequency in the complex. As such, the level average level increment for the highest component was a factor of 1.78 greater than that of the lowest frequency component for 7-component complexes and a factor of about 3.8 greater for 15-component complexes. While Kortekaas *et al.* (2003) anticipated listeners being able to change their weighting patterns to accommodate the greater magnitude of level changes at higher frequencies, no such changes were found. It should be noted that their listeners (except for the first author) were not aware of this level manipulation. Furthermore, the general tendency to give the higher-frequency components greater weight when the average increments across the spectrum were equal would tend to make finding the effect of such a subtle manipulation difficult or impossible. Kortekaas *et al.* emphasized the ability of listeners to *combine* information across critical bands, and that this last manipulation cannot really be viewed as promoting analytic listening.

In summary, the factors that appear to promote analytic listening are (1) experience and training and (2) familiarity with the target component. The second of these factors can be promoted either by explicit trial-by-trial cuing (as was done in the current experiments) or by allowing the participants the opportunity to hear the target frequency in isolation (a 1a Doherty and Lutfi, 1999). Blauert (1983, p. 322) warned that these would be key in allowing listeners to report the properties of multiple concurrent auditory events.

Another task in which analytic versus synthetic listening strategies are thought to play a role is in informational masking paradigms. Substantial amounts of informational masking have been created through the introduction of trial-to-trial variability in the acoustic stimulus, especially with regard to the spectral characteristics of the maskers. It has been proposed that informational masking is due to a failure of listeners to focus attention on the target signal, instead basing responses on the uninformative maskers (Leek *et al.*, 1991; Kidd *et al.*, 1994; Neff, 1995; Wright and Saberi, 1999; and Oh and Lutfi, 2000). In support of this claim, Richards *et al.* (2002) and Tang and Richards (2003) measured informational masking and weighting functions for a group of listeners and found a tendency for those displaying nonoptimal weighting strategies (i.e., giving significant weight to nonsignal frequencies) to show larger amounts of informational masking. Alexander and Lutfi (2004) have looked explicitly at this relationship, finding that higher levels of weighting efficiency[4] yield lower amounts of informational masking.

Oxenham *et al.* (2003) found that musicians showed less informational masking than nonmusicians, arguing that part of musical training involves learning to perceptually segregate the melodic line. As such, individuals with a higher level of musical training would be better able to listen analytically in the multitone masking conditions than nonmusicians. Of our three listeners who were able to adjust perceptual weights in both the interaural time and monaural level tasks, only one had extensive musical training. Two of the seven remaining listeners were practicing musicians at the time that the experiment was performed, and studied piano through their mid-teens. As a consequence, differences in musical training do not appear to account for the individual differences found in the current study.

Neff *et al.* (1996) claim that males show less informational masking than do females. Of our ten participants, three were male. They happen to be the three who were analytic in both interaural time and monaural level discrimination tasks. If one believes that superiority in conditions with multiple maskers is due to a tendency to process stimuli analytically, this is consistent with Neff *et al.*'s findings. It should be noted that Oxenham *et al.* (2003) found no effect of gender in their study.

Durlach *et al.* (2003) have recently demonstrated that reducing target-masker similarity reduces the amount of informational masking. They performed a series of five experiments in which a tonal target signal was detected against a multitone masker whose frequency components varied randomly from trial to trial. For each of the five experiments, the signal was a 1000-Hz tone and the maskers were eight components chosen randomly (on a logarithmic frequency scale) between 200 and 5000 Hz with a protected region of 800–1200 Hz around the signal. In each of the experiments, conditions were run in which the signal was ''similar'' (S) or ''dissimilar'' (D) to the maskers to promote grouping or segregation. Two of their five observers showed significant S-D differences in four of the five experiments, one showed significant S-D differences in three, and two showed significant S-D differences in only one. They conclude that there were ''large intersubject differences in susceptibility to informational masking'' with ''substantial, but far from perfect, intrasubject consistency...'' (Durlach *et al.*, 2003, p. 378).

We know of no other studies in psychoacoustics that have examined weighting functions from different tasks. While we find large individual differences in weighting patterns, the main finding of our study is that individuals who were able to adjust their perceptual weights in an interaural time discrimination task were also able to do so in monaural level tasks. Lutfi *et al.* (2003) found that individual differences in informational masking can be explained by a single factor. They speculate that this factor is the ''attentional bandwidth,'' the number of independent auditory filters that contribute to the decision variable. The data from the current study argue that one's ability to adjust and restrict this ''attentional bandwidth'' generalizes across psychophysical tasks.

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[1] Logistic regression is recommended by statisticians when one is attempting to predict a dichotomous dependent variable, since it makes no assumptions regarding the distributions of the predictor variables (Hosmer and Lemeshow, 1989). Frankly, it was recommended by an anonymous reviewer who was concerned about the low levels of performance for the monaural level task. Weights were computed in earlier drafts via point-biserial correlations (Lutfi, 1995), and they did not differ substantially from those computed via binary logistic regression. Those derived from logistic regression, however, tended to allow us to predict a higher proportion of responses, particularly for the monaural level discrimination task. This was particularly true for S7.

[2] Occasionally logistic regression would return a significant constant, α. When one runs a logistic regression in SPSS, a classification table is generated that shows the proportion of correct classifications predicted from α, β_{553}, β_{753}, and β_{953}. Instead of using this proportion as P(Accounted), we chose to drop the constant term and simply use the β_f's to make this computation. In the 80 binary logistic regressions that were performed, the percentage of responses correctly predicted from SPSS classification table, which included the constant, were never more that 1% greater than the percentage of responses predicted from the weights alone [$100 \times$P(Accounted)].

[3] Doherty and Lutfi also selected the target level from one of two distributions, separated by a level difference yielding $d = 1.0$. The fact that the target component was presented at a greater average level during one interval should have enhanced the ability of listeners to perform the task analytically.

[4] Alexander and Lutfi (2004) first determined the root-mean-square (rms) of the difference between the obtained normalized weights and the normalized weights of an ideal observer who gives a weight of 1.0 to the signal frequency and weights of 0.0 to all other components. Weighting efficiency was defined as $1 - \text{rms}$.

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