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Gap duration discrimination for frequency-asymmetric gap markers: Psychophysical and electrophysiological findings

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Abstract

This study investigated gap duration discrimination (GDD) for frequency-asymmetric gap markers, where one marker was a two-tone complex consisting of a primary tone and a secondary tone, and the other marker was the primary tone alone. Three experiments were undertaken to examine the order effect wherein performance is better when the two-tone marker is the leading marker than when it is the trailing marker. Experiment 1 demonstrated that GDD for frequency-asymmetric markers is intermediate between the boundaries of within-frequency-channel vs. across-frequency-channel processing. Experiment 2 compared psychophysical performance with auditory brainstem responses (ABRs) elicited by the same stimuli. Whereas GDD thresholds were elevated for a complex trailing marker relative to a within-frequency-channel baseline, ABRs elicited by the complex marker were more robust. Experiment 3 tested the hypothesis that poor GDD performance with frequency-asymmetric markers is due to some form of non-energetic, or informational, masking. The results did not support a role for informational masking conferred by synthetic listening; however, informational masking conferred by the occurrence of novel spectral events provided a parsimonious account. One possible interpretation is that the capacity to accurately encode a gap is undermined by the occurrence of novel spectral events that engage limited attentional resources.

I. INTRODUCTION

The detection and discrimination of temporal gaps between two discrete stimuli is dependent in part upon the spectral similarity of the two stimuli. Sensitivity to gaps is most acute when the leading and trailing markers are spectrally similar, and declines when the spectral profiles of the markers diverge (e.g., Phillips et al., 1997; Formby et al., 1998a; Formby et al., 1998b; Grose et al., 2001; Phillips and Hall, 2002). In general, performance is poor when there is no spectral overlap between the markers, but is also elevated in cases where the differing bandwidths of the two markers allow the spectral content of the wider bandwidth marker to subsume the spectral content of the narrower bandwidth marker. Gap markers in this latter configuration, characterized by dissimilar but overlapping frequency content, are referred to as frequency-asymmetric markers. The study by Formby et al. (1998b) found an intriguing effect with frequency-asymmetric markers. When the leading marker was a two-tone complex consisting of a primary and secondary tone, and the trailing marker was the single primary tone alone, gap detection performance was significantly better than in the reverse configuration where the leading marker was the single primary tone and the trailing marker was the two-tone complex. This order effect was not subtle: When the two-tone marker was the trailing marker, thresholds were approximately five times greater than when the two-tone marker was the leading marker. Moreover, when the two-tone marker was the leading marker, thresholds were similar to baseline where both leading and trailing markers were the same single pure tone. This order effect is not restricted to acoustic hearing. Van Wieringen and Wouters (1999) tested

configurations of electrode channel asymmetries in cochlear implant listeners. When the leading marker was carried on a single electrode channel and the trailing marker was carried simultaneously on two or three electrode channels, gap thresholds were significantly elevated compared to the reverse configuration where the leading marker was carried on multiple electrode channels and the trailing marker was carried on a single electrode channel.

The reason for this order effect is unclear, and forms the motivation for this investigation. Formby et al. (1998b) pointed out that the pattern of results is counter-intuitive to a 'cueing' explanation. That is, a single-tone leading marker might be expected to cue the listener as to which frequency channel to attend to – or 'hear out' – in the trailing marker in order to achieve an optimal within-frequency-channel gap detection strategy (i.e., ignoring the remote frequency in the trailing two-tone marker). This would predict better performance in the configuration with the single-tone leading marker than with the two-tone leading marker where such a strategy is not possible, yet the converse is observed. Van Wieringen and Wouters (1999) conjectured that the multi-channel trailing marker might partially mask the single-channel leading marker, making this configuration more difficult for gap detection. However, they noted that this 'backward masking' might be cognitive and not physiological in nature. For example, the timbral change brought about by the abrupt onset of additional channels in the trailing marker might interfere in some way with the memory trace of the leading marker. (It is not immediately clear why this notion would not apply equally to the converse 'forward masking' configuration.) Oxenham (2000) also offered a suggestion for the order effect that focused on the role of onsets in gap detection. He raised the possibility that the simultaneous onset of the secondary tone in the trailing marker might stimulate neural units that would otherwise respond to the onset of the primary tone, thus diminishing the available within-channel information concerning the presence of the gap.

The notion that the presence of the secondary tone in the two-tone trailing marker in some way obscures information regarding the onset of the primary tone, and that this accounts for the decline in performance with the complex trailing marker, has an implicit premise. Specifically, it assumes that gap detection, even in the optimal within-channel configuration, is determined by the onset of the trailing marker. This premise appears reasonable given the plethora of onset-sensitive neurons in the auditory system coupled with the perceptual dominance of stimulus onsets (Heil, 1997; Fishbach et al., 2001; Phillips et al., 2002). However, the association of gap detection with onset detection (of the trailing marker) is not firmly established. On the one hand, both physiological (Barsz et al., 1998) and behavioral (Ison et al., 2002) work in mice has demonstrated that sensitivity to gaps is related to the abruptness of stimulus onset at the termination of the gap. On the other hand, work in humans has not found a benefit of abrupt onsets and offsets in gap detection (Allen et al., 2002). In that study, gaps were introduced into noisebursts using different ramp shapes, but with the gap duration held constant at the half-amplitude points of the markers (constant 'effective duration'). Results indicated that gap detectability was not related to the abruptness of the gap boundaries, with the caveat that this interpretation is somewhat dependent on the specification of 'effective duration.' Nevertheless, in that temporal gaps can be viewed as a special case of decrements in on-going sounds, the absence of an onset effect is supported by Plack et al. (2006) who found that sensitivity to increments and decrements near threshold was better modeled by the *magnitude* of change in level rather than by the *rate* of change. That is, for a given duration of increment or decrement, the shape of the transition ramp had little effect – in particular, abrupt rise times did not result in better detection. It is important to note that these studies have employed frequency-symmetric stimuli; i.e., stimuli on either side of the gap or transition have been spectrally similar. In the case of frequency-asymmetric markers examined here, a discontinuity is always perceptible – even in the absence of an incremented gap – due to the presence of the remote secondary tone.

The purpose of this investigation was to determine the reliability of the order effect for frequency-asymmetric markers, and to test possible underlying mechanisms. The particular emphasis was on determining what factors account for the poor performance found with the complex trailing marker. Three experiments were undertaken. The preliminary experiment was designed to establish the order effect for a particular pairing of primary and secondary tones to be used throughout the investigation; this experiment had the specific focus of determining the magnitude of the order effect relative to the boundary conditions of within-frequency-channel *vs.* across-frequency-channel processing. The second experiment was designed to test for onset effects by comparing psychophysical results with auditory brainstem responses (ABRs) evoked by the same stimuli. The third experiment was designed to determine whether some form of non-energetic masking influences across-frequency gap discrimination.

II. EXPERIMENT 1. GAP DURATION DISCRIMINATION (GDD) FOR FREQUENCY-ASYMMETRIC MARKERS

The purpose of this experiment was to test the order effect using inharmonically-related tone pairs lacking abrupt onsets. In addition to frequency-asymmetric markers, with dissimilar but overlapping frequency content, boundary conditions were also tested that employed frequency-symmetric markers (within-frequency-channel) and markers with no frequency overlap (across-frequency-channel).

A. Methods

Subjects—Six observers aged 19 – 39 years (mean = 27 years) with normal hearing participated (Obs 1 – 6). All had audiometric thresholds ≤ 20 dB HL across the octave frequencies 250 – 8000 Hz (ANSI, 1996). All were given extensive training in the task by having each observer perform the entire experiment once for practice, including the collection of multiple replications per condition as stipulated below. The experiment was then repeated with retention of data.

Stimuli—The stimuli comprising the gap markers consisted of either a single primary tone or a two-tone complex (primary tone plus secondary tone). The frequency of the primary tone was 2285 Hz and the frequency of the secondary tone was 4000 Hz. This selection of frequencies was chosen because 2285 Hz is greater than half an octave below 4000 Hz, and gap detection is thought to become an across-frequency process beyond this interval (e.g., Formby et al., 1996). Moreover the 7/4 ratio between the two frequencies is essentially inharmonic. The nominal duration of each marker was 300 ms, including a 5-ms cosine-squared rise/fall ramp to reduce spectral splatter. The actual duration of each marker varied by $\pm 20\%$ of the nominal duration on a presentation-by-presentation basis in order to render the cue of overall stimulus duration (two markers plus gap) less reliable.

The gap was defined as the interval between the 0-voltage points separating the offset of the first marker and the onset of the second marker. The gap duration of the standard stimulus was always 0 ms. Note that because the 5-ms rise/fall ramps resulted in a perceptible temporal discontinuity even in the 0-ms standard gap configuration, the task was not one of gap detection but of gap duration discrimination (GDD). The stimuli were digitally generated at a rate of 20 kHz (TDT AP2), output through a DAC (TDT PD1), low-pass filtered (Kemo VBF 10M, 8 kHz), attenuated (TDT PA4) and delivered to the left phone of a Sennheiser 580 headset at a pressure spectrum level of 60 dB/Hz.¹ In order to further diminish any confounding effects of

¹Stimuli in all psychophysical testing were transduced by Sennheiser 580 headphones. These were calibrated using a flat-plate coupler seated on a Brüel & Kjær 4135 Artificial Ear. The coupler housed a Larson-Davis 0.5-inch microphone (Model 2559), and the microphone output was read by a Larson-Davis sound level meter (Model 800B) set to a linear (unweighted) scale.

spectral splatter, a continuous Gaussian background noise (0 – 8 kHz) was always present at a pressure spectrum level of 10 dB/Hz. An additional Gaussian noise low-passed at 750 Hz was added at 20 dB/Hz to provide further masking in the unlikely event that the complex marker generated an audible 2f1-f2 distortion product at 570 Hz.

Procedure—A three-alternative, forced-choice (3AFC) procedure was employed which incorporated a three-down, one-up adaptive rule that tracked the 79.4% correct point. Following three consecutive correct responses, the imposed increment in gap duration was decreased by a factor of 1.2; following one incorrect response, the imposed increment in gap duration was increased by the same factor. A threshold estimation run was terminated after 10 reversals in gap duration, and the geometric mean of the gap duration at the final six reversal points was taken as the threshold estimation for that run. Four conditions were examined: (1) iso-frequency GDD, where both gap markers consisted of the primary tone alone; (2) across-frequency GDD, where the leading marker consisted of the primary tone alone and the trailing marker consisted of the secondary tone alone; (3) frequency-asymmetric GDD, where the leading marker was the two-tone complex and the trailing marker was the single primary tone; and (4) frequency-asymmetric GDD, where the single primary tone was the leading marker and the two-tone complex was the trailing marker. For each observer, the conditions were blocked, in that all threshold estimates for a given condition were completed before the next condition was initiated, but the order of conditions was random across the observers. At least three replications, but occasionally four replications if time permitted, were collected per condition. Each observer's GDD threshold for a condition was taken as the geometric mean of all replications for that condition.

B. Results and Discussion

The results are shown in Fig. 1 where the individual data (open symbols) cluster around the group means (solid symbols ± 1 standard deviation). As expected, thresholds are lowest for the iso-frequency condition. Thresholds for the across-frequency condition appear poorest. Thresholds for the frequency-asymmetric configurations are intermediate but, for five of the six listeners, are lower when the leading marker is the two-tone complex than when it is the single tone. In order to assess this pattern of results, the data were submitted to a repeated-measures analysis of variance (ANOVA). In this, and in all subsequent analyses, the analysis was performed on the log transforms of the data. The analysis indicated a significant effect of condition ($F_{3,15} = 46.48$; $p < 0.001$), and pre-planned means comparisons for the three relevant comparisons confirmed the significance of the data pattern. That is, for the two frequency-asymmetric configurations, thresholds were significantly higher when the leading marker was the single tone than when it was the two-tone complex ($t_5 = 3.183$; $p = 0.024$). Nevertheless, thresholds for the configuration with the single-tone leading marker were not as poor as for the across-frequency configuration ($t_5 = 6.611$; $p = 0.001$). Finally, thresholds for the two-tone leading marker configuration were significantly elevated relative to the iso-frequency tonal baseline ($t_5 = 3.238$; $p = 0.023$). Although these data support an order effect for frequency-asymmetric markers, they are less striking than those of Formby et al. (1998b) in two respects. First, thresholds for the two-tone trailing marker configuration were, on average, about twice those of the two-tone leading marker, whereas Formby et al. observed about a five-fold change. Second, this experiment found that thresholds for the two-tone leading marker were elevated relative to the iso-frequency tonal baseline, whereas Formby et al. found similar performance across these two configurations (i.e., no elevation for the two-tone leading marker). It is likely that these discrepancies are due to procedural differences across the two studies, particularly in terms of stimulus parameters. These differences include: (1) the frequency range of the markers [2000 – 3100 Hz in Formby et al.; 2285 – 4000 Hz here]; (2) the rise/fall times of the gap boundaries ['instantaneous' in Formby et al.; 5-ms here]; and (3) extent of marker duration randomization [100 – 900 ms in Formby et al.; 240 – 360 ms here]. Besides procedural

differences across studies, it is also possible that individual differences in GDD performance for frequency-asymmetric markers may have played a role.

The results of this experiment confirm the order effect in that GDD for frequency asymmetric-markers is poorer for most listeners when the complex tone is the trailing marker than when it is the leading marker. The elevation in threshold for the two-tone trailing marker occurs even when the onset of the trailing marker transitions over a 5-ms interval. In order to examine the role of trailing marker onset further, a second experiment was undertaken that incorporated an electrophysiological test sensitive to stimulus onsets. At issue is the deterioration in performance that occurs when a secondary tone is added to the trailing marker.

III. EXPERIMENT 2. ABR MEASURES OF FREQUENCY-ASYMMETRIC GDD

As noted earlier, it has been suggested that the order effect for frequency-asymmetric markers might be a reflection of the dominant role of stimulus onsets (in contrast to offsets) in auditory processing, such that the onset of the secondary tone in the trailing complex marker obscures the onset of the primary tone at some level of neural processing (Oxenham, 2000). There are several ways in which the primary tone onset might be obscured by the presence of the secondary tone, and two possible schemes will be considered here. Both are based on the assumption that the leading primary tone marker forward masks the trailing primary tone, but has essentially no effect on the trailing secondary tone. Within this context, it is further assumed that the cue for gap duration when both markers consist of the primary tone alone (within-frequency-channel) is linked to the degree to which the response to the trailing marker has recovered from forward masking; i.e., the onset response strength elicited by the trailing primary tone constitutes the gap duration cue. This suggestion is in line with traditional models of gap detection that are based on recovery from forward masking (e.g., Plomp, 1964). In the two schemes considered below, the response strength associated with the trailing primary tone onset is directly affected by the onset of the secondary tone. Both schemes also incorporate a central 'onset detector' that is broadly tuned to onset information originating from different frequency regions.

The first possible mechanism for onset masking of the primary tone is a form of inhibition. Take, for example, the model of neural circuitry within the ventral cochlear nucleus proposed by Pressnitzer et al. (2001). In this model, the output from a particular cochlear location (here, the frequency channel associated with the primary tone) feeds two cell types in the cochlear nucleus. One, a narrow-band cell, is excited only by the primary tone frequency. The second cell type has a wide-band receptive field and responds not only to the primary tone but also to the secondary tone. The response of this wide-band cell is a fast-acting inhibition of the narrow-band cell response. The level of inhibitory input to the narrow-band cell responding to the primary tone is therefore greater when the secondary tone is present than when it is not. The interest here is not in testing this particular model; the model is described simply to illustrate that neural circuitry along these lines could conceivably provide a mechanism of onset masking in the context of GDD for frequency-asymmetric markers. Suppose that a mechanism of this sort resulted in mutual inhibitions between the two tones of the complex marker, where the magnitude of inhibition exerted by each tone on the other was proportional to their relative response strengths. For a short gap, where the primary tone response strength is diminished by forward masking, the inhibition exerted by the secondary tone onset onto the primary tone onset is predominant and, correspondingly, the primary tone exerts minimal inhibition of the secondary tone. For a long gap, where forward masking effects have mitigated, the mutual inhibition of the response onsets by the two tones is more equivalent. From the point of view of a central broadly tuned onset detector, two outcomes are conceivable. First, the onset information derived from the primary tone channel is diminished in the presence of the secondary tone (i.e., onset masking has occurred). Second, the registration of onset across

frequency may not necessarily be more robust with increases in gap duration in the two-tone marker case since, for short gaps, the secondary tone onset is not inhibited, while for long gaps, the primary and secondary tone onsets are mutually inhibited.

The second scheme is simpler in that it does not involve inhibition. Instead, the central onset detector responds proportionally to the input it receives and is dominated by the most robust input. For a short gap, the onset response from the secondary tone is more robust than the onset response from the primary tone (which is in a state of forward masking), and therefore the overall response of the onset detector is dominated by the secondary tone onset at the expense of the primary tone onset. This constitutes onset masking. For a long gap, the onset responses from both tones are equally robust and so the overall response of the onset detector is greater than for a short gap, but it is not dominated by one tone onset over the other. As the scheme is presented here, no prediction is made regarding whether frequency specific onset information is available to the listener, or whether onset information is irrevocably pooled across frequency.

In summary, two hypothetical schemes have been presented that both result in onset masking. In one, the masking is effected by diminishing the onset response through inhibition; in the other, the masking is effected by allowing the dominant onset to ‘capture’ the whole response. Given this focus on onset responses, it was considered informative to explore their role using an electrophysiological analog of GDD. Experiment 2 therefore undertook to compare ABRs evoked by iso-frequency pure-tone markers with those evoked by frequency-asymmetric markers having a pure-tone leading marker and a two-tone trailing marker. Because the ABR is essentially an onset response, where the magnitude of the response corresponds to the degree of synchronous neural firing at stimulus onset (Hecox et al., 1976; Folsom and Aurich, 1987), this measure is sensitive to how well the onset of the trailing marker *as a whole* is encoded. In addition, experiment 2 included psychophysical GDD assessment for the same stimuli used to elicit the ABRs in order to enable direct comparison between electrophysiological and psychophysical performance.

In order to facilitate complementary measures of psychophysical GDD and ABRs evoked by the same stimuli, two changes were made to the stimulus configurations used in experiment 1. First, the markers were reduced in duration since the use of nominal durations of 300 ms made the overall stimulus duration (two markers plus gap) untenable for reasonable ABR recordings. Second, the frequencies of the primary and secondary tones were switched. The rationale for stipulating 4000-Hz as the primary tone here was that any effect of adding the secondary tone (now 2285 Hz) could not be attributed to a more basal cochlear shift of the site of stimulation. The ABR for wide-band stimuli is known to be dominated by the heightened neural synchrony associated with the base of the cochlea (Eggermont and Don, 1980). A basalward shift in site of stimulation would be expected to result in a reduced response latency. Two marker configurations were tested: (1) a baseline within-frequency-channel configuration where both the leading and trailing markers were the primary tone alone; and (2) a frequency-asymmetric configuration where the leading marker was the primary tone alone and the trailing marker was the two-tone complex.

A. Method

Subjects—Six observers aged 23 – 43 years (mean = 29.3 years) with normal hearing participated (Obs 4, 7 – 11). All had audiometric thresholds ≤ 20 dB HL across the octave frequencies 250 – 8000 Hz (ANSI, 1996). Only Obs 4 had participated in experiment 1.

Stimuli—The leading marker was always the 4000-Hz primary tone presented in isolation. In the baseline condition, the trailing marker also consisted of the primary tone presented in isolation. In a second condition, the trailing marker consisted of the primary and secondary tones presented simultaneously. Both the leading and trailing markers had nominal durations

of 100 ms, but the actual duration of each marker varied by $\pm 50\%$ on each and every presentation. The actual duration included cosine-squared rise/fall ramps that were 2 ms in duration for the rise and 8 ms in duration for the fall. These rise/fall times were selected to facilitate synchronous neural responses to the marker onsets but not the offsets in the ABR procedure (see below, Fig. 3). The markers were generated digitally at a rate of 20 kHz (TDT AP2), output through one channel of a 16-bit DAC (TDT PD1), and low-pass filtered at 8 kHz (Kemo VBF-8). For the ABR procedure, a TTL trigger pulse was simultaneously output through a second DAC channel. This pulse was synchronous with the onset of the trailing marker and was used to externally trigger the ABR recording system (Bio-logic Systems Traveler, 8-bit analog-to-digital converter). The average interval between successive triggers was approximately 300 ms for a 0-ms gap. (This trigger interval, of course, varied with the random marker duration.) This meant that, given the average marker duration of 100 ms, the interval between the offset of the trailing marker in one marker pair and the onset of the leading marker in the next following marker pair was about 100 ms. Markers were presented to the left ear at a spectrum level of 65 dB SPL through an Etymotic ER-2 insert phone.² No background masker was employed.

Psychophysical GDD Procedure—Psychophysical GDD was measured as in experiment 1. For each of the two conditions, listeners practiced the task until performance was stable. At this point, data collection was initiated, and at least four replications of threshold estimate were collected for each condition. The final threshold for that condition was taken as the geometric mean of all estimates collected.

ABR Procedure—Each listener was prepared for single-channel ABR recordings by placing surface electrodes on the high forehead (Fz, non-inverting), left earlobe (A1, inverting), and low forehead (Fpz, ground). Electrode impedances were maintained at $< 2 \text{ k}\Omega$ throughout the recording sessions. Listeners reclined in a chair in a darkened, sound-treated room and were encouraged to sleep. The raw EEG was band-pass filtered from 100 – 3000 Hz, and a gain of X150,000 applied. The recording window was 20 ms in duration, and 1500 sweeps were averaged for a single recording. For each condition, at least 3 replicate traces were recorded. Given that each stimulus consisted of a fixed-duration gap bounded by two markers with nominal durations of 100 ms (see below), the recording time for a single 1500-sweep trace exceeded 9 minutes. A single recording session lasted no longer than 2 hours, and multiple sessions were required on different days to complete the data collection.

ABR recordings were time-locked to the onset of the trailing marker. In a control condition, no leading marker was presented and the ‘trailing’ marker consisted of the 4000-Hz primary tone alone. This condition provided a reference for the ABR elicited by a 4000-Hz tone with a nominal duration of 100 ms presented at 65 dB SPL in the absence of forward masking. In the within-frequency-channel condition set, the trailing marker continued to be the primary tone alone, but now the leading marker was re-introduced. Here, ABRs were recorded for fixed gap durations between the two primary tones of 0, 4, 8, 16, 32, and 64 ms. In this set of conditions, the ABRs can be considered to be responses to a 4000-Hz tone that is forward-masked by a preceding 4000-Hz tone. In a third set of conditions, the trailing marker consisted of the primary and secondary tone pair. The ABRs were recorded for fixed gap durations between the leading and trailing markers of 0 and 64 ms.³ It is important to note that, because the actual durations of both leading and trailing markers varied randomly on a presentation-by-presentation basis ($100 \text{ ms} \pm 50\%$), and because the trigger pulse synchronized the recording

²Stimuli transduced with the ER-2 insert phones in the ABR study were calibrated using a GRAS 2-cc coupler (IEC 126, Type RA0038). The same microphone and sound level meter were used as noted previously.

³The minimum gap duration for Obs 7 in this condition set was 4 ms, not 0 ms, but for the purposes of analysis this datum was treated as 0 ms.

to the onset of the trailing marker, the recording was not time-locked to the onset of the leading marker.

B. Results and Discussion

The results of the psychophysical GDD task are shown in Fig. 2 where the individual data (open symbols) cluster around the means (solid symbols ± 1 standard deviation). Thresholds in the baseline within-frequency-channel condition are higher than those observed in the respective baseline condition of experiment 1 (cf. Fig. 1) and this is likely due to a combination of a shorter nominal marker duration coupled with an increase in the degree of duration randomization allowed in experiment 2. It is known that gap detection performance can depend on overall marker duration (Schneider and Hamstra, 1999; Snell and Hu, 1999), and deteriorates with increases in marker duration variability (Penner, 1976). Although, on average, the thresholds are elevated in the frequency-asymmetric condition relative to baseline, it is evident that for two of the six listeners (Obs 10 & 11) there was little or no apparent effect of the addition of the secondary tone. Nevertheless, as a group, the difference between the two conditions was significant ($t_5 = 2.88$; $p = 0.034$).

The ABR waveforms are portrayed in Figs. 3 – 5. A preliminary analysis was performed to confirm that the marker envelope shape was effective in eliciting an onset response, but not an offset response. In Fig. 3, ABR waveforms elicited by a single primary tone marker are shown for trigger pulses positioned either at the onset of the marker (left panels) or at the offset (right panels). The responses from three observers are shown in the lower rows: the individual waveforms are shown overlaid on the left side of each pair of panels, and the weighted grand average of all collected sweeps on the right. The arrow marks the position of wave V. It can be seen that the 2-ms onset ramp generated sufficient neural synchrony to elicit a measurable response, whereas the 8-ms offset ramp did not. This result ensures that the ABR elicited by a trigger positioned at the onset of the trailing marker is indeed associated with that trailing marker onset and not with the offset of the leading marker.

Fig. 4 shows a set of ABR results from one observer. The overlaid traces in the left column are individual sweeps and the right column shows the associated weighted grand average. The upper row depicts responses where the leading marker was absent. These reference traces indicate responses elicited by the primary tone ‘trailing’ marker in the absence of any forward masking. The middle block of rows shows responses for the within-frequency-channel condition set, where the leading and trailing markers both consisted of the primary tone alone. Each row shows responses for a fixed gap duration. The lower block of rows shows responses for the frequency-asymmetric condition set. The vertical dashed line in the right column is positioned at the wave V latency for the unmasked reference condition. Two main findings are evident in this individual data set. First, for the within-frequency-channel condition set (middle block), wave V latency increased and waveform morphology deteriorated as the gap duration decreased. This pattern has been interpreted in terms of the forward masking of the trailing marker by the leading marker (e.g., Walton et al., 1999). The second finding is that the presence of the secondary tone in the frequency-asymmetric trailing marker largely overcame the forward masking effect such that response latency did not shift appreciably with gap duration, and response morphology remained robust. Indeed, comparing the frequency-asymmetric traces (bottom) and the reference traces (top) in Fig. 4, it is apparent that the ABR evoked with the two-tone trailing marker has a larger wave V amplitude than that evoked with a single-tone trailing marker, even in the absence of forward masking.

To demonstrate that this pattern was common across observers, Fig. 5 shows the weighted grand average responses from each of the six observers in separate columns. In general, the presence of the secondary tone in the frequency-asymmetric trailing marker leads to a larger wave V amplitude and nullifies any latency prolongation associated with the forward-masking

effects of the leading marker, even for a gap duration of 0 ms and even though the secondary tone is lower in frequency than the primary tone. To quantify these latency shifts and amplitude changes, the wave V latency and amplitude for each grand average waveform was measured relative to the respective values in the unmasked reference.⁴ The results are shown in Fig. 6 where latency shift (upper panel) and amplitude change (lower panel) are plotted as a function of gap duration. The thick solid line is the mean for the within-frequency-channel condition set and the dashed line is the mean for the frequency-asymmetric condition set. The individual data are plotted as filled and open symbols for the two condition sets, respectively. A repeated-measures ANOVA was undertaken on the latency shifts for gap durations of 0 ms and 64 ms for the two different condition sets. The analysis indicated that the main effects of gap duration and condition were significant ($F_{1,5} = 61.44$; $p = 0.001$ and $F_{1,5} = 31.63$; $p = 0.002$, respectively), as was the interaction between these factors ($F_{1,5} = 9.71$; $p = 0.026$). The significant interaction arose because the difference in latency shifts between condition sets was greater for a gap duration of 0 ms than for 64 ms. However, even for a gap duration of 64 ms the difference in latency shifts was still significant, as indicated by a Bonferroni-corrected means comparison ($t_5 = 3.63$; $p = 0.015$). No significant latency shift was observed for the frequency-asymmetric condition set between a gap duration of 0 ms and 64 ms ($t_5 = 2.15$; $p = 0.084$). The corresponding analysis for the amplitude changes indicated significant main effects of gap duration and condition ($F_{1,5} = 27.1$; $p = 0.003$ and $F_{1,5} = 9.9$; $p = 0.025$, respectively). The interaction between these factors was not significant ($F_{1,5} = 1.38$; $p = 0.29$).

The ABR data clearly indicate that the evoked potentials elicited by a complex trailing marker are more robust than those elicited by a trailing pure-tone marker, presumably due largely to the fact that the secondary tone is not being forward-masked by the leading primary tone. This suggests that the elevated thresholds seen in the psychophysical data are not due to some sort of physiological onset masking wherein mutual inhibitions between the two tones of the complex marker result in the onset of the complex marker being less well encoded relative to that of the single primary tone marker alone. Rather, the results suggest that the onset of the complex trailing marker is dominated by the onset of the secondary tone (which is free of forward masking by the primary tone). If this onset dominance translates to a perceptual dominance, then the psychophysical GDD task becomes predominantly one of across-frequency-channel temporal processing rather than within-frequency-channel temporal processing. That is, the perceptual dominance of the secondary tone biases the GDD task towards across-frequency-channel temporal processing and, because across-frequency-channel GDD is poorer than within-frequency-channel GDD (see experiment 1), this leads to an elevation in threshold.

The notion of perceptual dominance provides a framework to account for the psychophysical order effect seen for frequency-asymmetric markers. The occurrence of novel spectral events associated with the complex trailing marker dominates the percept and biases the GDD task to one of across-frequency-channel processing. In the reverse configuration with the pure-tone trailing marker there are no novel spectral events associated with the trailing marker and therefore the temporal task is less biased towards across-frequency-channel processing. Another way of expressing this is in terms of a form of informational masking: the secondary tone in the complex trailing marker exerts informational masking over the primary tone because of its perceptual dominance, and this biases the task towards across-frequency-channel temporal processing, undermining performance. Less informational masking occurs when the

⁴For the purposes of measurement, wave V was identified as the peak in the 6.5 – 8.4 ms latency window. Its amplitude was measured as the voltage difference between this peak and the following trough (V'). For each grand average waveform, positioning of the actual V and V' markings was determined visually based on the pattern of overlap of the multiple individual traces making up the grand average. Three judges, all experienced in ABR testing, contributed to the waveform markings. Although no formal cross-checking across judges was undertaken, informal comparisons indicated agreement among judges.

secondary tone is part of the leading marker because it is not as perceptually dominant (the primary tone is not being forward-masked). The interpretation of the order effect for frequency-asymmetric markers in terms of the perceptual dominance of the secondary tone suggests that if this dominance could be reduced, then the order effect would diminish. That is, if the amount of informational masking exerted by the secondary tone is attenuated, the elevated GDD thresholds should recover. The final experiment was designed to test this possibility.

IV. EXPERIMENT 3. INFORMATIONAL MASKING AND GDD FOR FREQUENCY-ASYMMETRIC MARKERS

The premise of this experiment is that informational masking exerted by the secondary tone over the primary tone undermines the listener's ability to make use of optimal within-frequency-channel cues. This informational masking has been described above in terms of the perceptual dominance of the secondary tone rendering the primary tone less salient. There are actually at least two – not mutually exclusive – ways in which this reduced saliency could come about. The first is that the perceptual dominance of the secondary tone might 'capture the attention' of the listener, effectively diverting auditory processing power away from the primary tone. The second way is that the secondary tone might promote synthetic listening (in contrast to analytic listening) rendering the primary tone less salient because it is perceptually fused with the tonal complex. These distinctions will be revisited later but, to begin with, informational masking will be treated generically as a form of non-energetic masking reflecting perceptual dominance of the secondary tone. The purpose of this experiment was to test the hypothesis that reducing the potential for informational masking leads to a recovery in GDD performance. Two stimulus manipulations were implemented that were designed to reduce informational masking by promoting perceptual segregation between the primary and secondary tones, thus enhancing primary tone saliency. The first manipulation (Test 1) varied the mode of secondary tone presentation such that it was delivered either to the ear contralateral to the primary tone (dichotic) or to both ears simultaneously (diotic); the reference condition was the monaural presentation of both primary and secondary tones. The rationale here is that informational masking using simple tonal sequences is largely constrained to configurations where both target and masking tone sequences are presented to the same ear; contralateral presentation of the masking tone sequence typically has minimal effect (Kidd et al., 2003). The second manipulation (Test 2) involved placing the primary tone between *two* secondary tones such that the frequency spacing of the 3-tone complex was uniform on a log scale. In addition, the flanking secondary tones could be frequency modulated. The rationale here is that perceptual fusion between a single component embedded in a complex and the remaining components of the complex can be diminished if the tone does not share a harmonic relationship with the complex (Moore et al., 1986). Furthermore, a primary component can be perceptually isolated (i.e., it will 'pop out') if the secondary components vary in frequency while the primary remains invariant (McAdams, 1989; Kidd et al., 1994).

A. Method

Subjects—Different crews of normal-hearing adults participated in the two tests. The six observers from experiment 1 (Obs 1 – 6) participated in Test 1. Seven observers (Obs 4, 12 – 17) participated in Test 2. They ranged in age from 21 – 48 years (mean = 33 years) and included one listener who had participated in both experiments 1 and 2.

Stimuli—For Test 1, the frequencies of the primary and secondary tones, as well as their temporal parameters, were the same as described in experiment 1. Here, the frequency-asymmetric marker conditions of experiment 1 were repeated, but with the secondary tone presented either to both ears (diotic) or only to the ear contralateral to the ear receiving the primary tone (dichotic). For Test 2, the frequency of the primary tone remained 2285 Hz, but

several other stimulus parameters were changed relative to experiment 1. First, two secondary tones were added to the primary tone to form the complex marker: the higher of these secondary tones was 4000 Hz (the same frequency as used in the previous experiments) and the lower was 1306 Hz. These three frequencies are equally spaced on a log scale. The second stimulus modification was that, in some conditions, frequency modulation (FM) was applied to the flanking secondary tones (but never to the primary tone) according to the equation:

$$x(t) = A \sin [(2\pi f_c t + \theta) + m \sin (2\pi f_m t)]$$

The rate of FM (f_m), when present, was 10 Hz with a modulation index (m) of 10, and the starting phase of the modulator was always 0 rad; the starting phase (θ) of each secondary tone (f_c) was randomly selected on a presentation-by-presentation basis. In order to make marker duration an unreliable cue, while at the same time retaining complete 100-ms cycles of FM, two fixed marker durations were permitted, 200 ms and 300 ms, and the duration selection for each marker in a stimulus was random on a presentation-by-presentation basis. The stimuli in Test 2 were presented at a sound pressure level of 65 dB/Hz in a broadband background noise (low-passed at 8000 Hz) having a pressure spectrum level of 10 dB/Hz.

Procedure—The procedure was the same as that employed in experiment 1. For the observers in Test 1 at least three, but occasionally four, replications were obtained per condition, and the final estimate was taken as the geometric mean of all replications obtained. For the observers in Test 2, at least four, but often five if time permitted, replications were obtained per condition, and the final estimate was taken as the geometric mean of all replications obtained. All observers repeated their entire assigned conditions, with stipulated number of replications, once for practice and once for data retention.

B. Results and Discussion

The results for Test 1, where the secondary tone was presented dichotically or diotically, are shown in Fig. 7. Because the same listeners participated in experiment 1, the reference monaural frequency-asymmetric data are replicated from Fig. 1. The order of the frequency-asymmetric markers is shown by the number of tones in the leading and trailing markers (leading » trailing). For each mode of secondary tone presentation, the individual data are shown as open symbols connected by lines. The mean data are shown as solid circles with error bars. It is evident that the order effect seen in the monaural conditions of experiment 1 was retained here for most listeners in both the dichotic and diotic conditions of Test 1; however, exceptions exist (Obs 3 in monaural and Obs 2 in dichotic and diotic). A two-factor repeated-measures ANOVA was undertaken to assess the effect of marker order (2 levels) and mode of secondary tone presentation (3 levels). The analysis indicated a significant effect of marker order ($F_{1,5} = 6.881$; $p = 0.047$), but no effect of mode of presentation and no significant interaction between these two factors. This result indicates that, as a group, performance was worse when the trailing gap marker was the two-tone complex than when it was the single tone, irrespective of whether the secondary tone was presented to the ipsilateral ear, contralateral ear, or simultaneously to both ears. The continued observance of the order effect, even when the secondary tone is presented to the contralateral ear, is further evidence against a peripherally based onset masking mechanism.

The results for Test 2 are shown in Fig. 8. The left panel shows the baseline iso-frequency condition where both the leading and trailing markers were the single primary tone. The center panel shows the pair of frequency-asymmetric conditions where the secondary tones were pure tones. The right panel shows the frequency-asymmetric conditions where the secondary tones were FM tones. The order of the frequency-asymmetric markers is indicated by the number of tones in the leading and trailing markers (leading » trailing). Individual data are shown as open symbols connected by lines; mean data are shown as solid circles. Although the majority of

listeners exhibited the expected order effect for frequency-asymmetric markers, wherein performance is poorer for a complex trailing marker than a complex leading marker, there were noticeable exceptions (Obs. 15 & 16). In addition, the pattern of data is grossly similar across the pure-tone and FM-tone marker complexes. The data for the frequency-asymmetric markers were submitted to a two-factor repeated-measures ANOVA to assess the effects of complex marker type (pure-tone, FM-tone) and order (2 levels). The analysis indicated no effect of either the FM factor or the order factor ($F_{1,6} = 1.639$; $p = 0.248$ & $F_{1,6} = 2.559$; $p = 0.161$, respectively). The lack of an order effect is not surprising given the marked individual variability in the data patterns. (If the data of Obs. 15 and 16 are omitted, the analysis now reveals a significant effect of marker order [$F_{1,4} = 25.04$; $p = 0.007$], but the factor of FM remains insignificant [$F_{1,4} = 0.043$; $p = 0.846$]).

The results of this experiment reinforce the general observation made in experiments 1 and 2 that the order effect for frequency-asymmetric markers is characteristic of most listeners, but is not without exception. That is, whereas most listeners find GDD to be more challenging when the complex marker is the trailing marker, a few observers exhibit either no effect or actually find the complex leading marker to be the more difficult configuration. (Recall that one of the four cochlear implant listeners in the Van Wieringen and Wouters (1999) study also showed no order effect.) The presence of marked variability across listeners itself constitutes indirect support for the role of informational masking in the frequency-asymmetric marker effect: Individual variability is characteristic of informational masking, where some listeners appear to be more susceptible than others to non-energetic masking (Neff and Callaghan, 1988; Durlach et al., 2003).

If a role for informational masking in GDD for frequency-asymmetric markers is to be entertained, the results of experiment 3 shed light on how this informational masking should be understood. As noted earlier, one possible form of informational masking is that the secondary tone promotes synthetic listening and this renders the primary tone less salient because it is perceptually fused with the tonal complex. If this is the case, then it would be expected that stimulus manipulations that weakened perceptual fusion should diminish the effect. However, the results of Test 1 strongly suggest that failure of analytic listening is not the key: the order effect remained intact even with contralateral presentation of the secondary tone. Kidd et al. (2003) have shown that contralateral presentation of informational maskers largely negates their masking effectiveness. In Test 2, the imposition of FM on the secondary tones also did not affect performance. McAdams (1989) has shown that differential FM can lead to parsing of complex sounds; thus the Test 2 results also do not support an ‘unmasking’ due to release from synthetic listening. Furthermore, the notion of informational masking conferred by synthetic listening in frequency-asymmetric GDD is not supported by the original work of Formby et al. (1998b). They found that performance with the two-tone trailing marker remained poor even when a temporal asynchrony of several tens of milliseconds was introduced between the primary and secondary tones. Most studies of informational masking observe a release from masking in the presence of temporal asynchrony between the target and interfering tones (e.g., Kidd et al., 1994; Hall et al., 2005).⁵ The results of this experiment therefore do not support a role of informational masking conferred by synthetic listening.

A second possible form of informational masking is a type of distraction effect wherein the perceptual dominance of the secondary tone draws the listener’s attention away from the primary tone, thus reducing the saliency of the primary tone. The perceptual dominance of the

⁵In fact, the listeners in experiment 1 also undertook a condition where, for the complex leading marker, the secondary tone began 75 ms *after* the onset of the primary tone (both tones were coterminous at the gap onset). There was no ‘masking release’ effect observed for this temporal asynchrony ($t_5 = 0.956$; $p = 0.383$), again suggesting that informational masking conferred by synthetic listening was not a key factor.

secondary tone in the complex trailing marker is likely due in part to its spectral novelty and in part to the fact that the primary tone is in a state of recovery from forward masking by the leading primary tone marker. The ABR data of experiment 2 indicate that the primary tone is still undergoing some degree of forward masking at the gap durations corresponding to discrimination thresholds. In other words, the primary tone is internally represented with less fidelity than the secondary tones (which are not being forward masked). This combination of unmasked secondary tones and partially masked primary tone might contribute to the perceptual dominance of the secondary tones. If this hypothesis is correct, then it is predicted that the perceptual dominance of the secondary tones in the complex trailing marker should be partially mitigated by introducing a longer recovery interval between the leading and trailing markers. That is, if the primary tone in the trailing marker is no longer being forward masked by the leading primary tone marker its relative salience should recover.

To test this hypothesis, a supplementary set of conditions was undertaken on six of the seven observers who participated in Test 2. Here, the reference and pure tone frequency-asymmetric conditions of Test 2 were repeated but with a simple prolongation of the standard gap to 100 ms. All other details of the procedure remained unchanged. The results of the supplementary conditions are shown in Fig. 9. As expected, the baseline thresholds were elevated with respect to the 0-ms standard gap (Fig. 8) since GDD is proportional to the standard gap duration (e.g., Abel, 1972; Penner, 1976; Grose et al., 2006). The key finding, however, is that for most listeners the order effect remained intact. This was confirmed with a repeated-measures ANOVA on the three conditions. The analysis indicated a significant effect of condition ($F_{2,10} = 8.267$; $p = 0.008$), with post-hoc contrasts indicating that thresholds for the complex leading marker were lower than for the complex trailing marker ($F_{1,5} = 15.967$; $p = 0.01$). Remarkably, this effect was evident for the two listeners (Obs 15 & 16) who showed a reversed order effect for the 0-ms standard gap duration. The results of the supplementary conditions therefore indicate that informational masking due to the perceptual dominance of the secondary tones in the complex trailing marker is unlikely to be due to the primary tone being in a state of partial forward masking. Rather, the results are consistent with an interpretation that the perceptual dominance of the secondary tones is due to their spectral novelty.⁶

It is of interest to conjecture why spectral novelty may result in a form of informational masking in this paradigm. One possibility already mentioned is that spectral novelty confers a perceptual dominance, and this perceptual dominance translates to a spectral biasing that makes the GDD task more of an across-frequency-channel temporal process than a within-frequency-channel process. Another possibility is that the occurrence of a novel event – in this case spectral – entails a compulsory allocation of limited attentional resources to the novel event, with the result that less capacity is available for the coding of other aspects of the stimulus – in this case the gap duration. This notion of limited attentional resources has been proposed in a number of contexts to model deficits in temporal processing in complex listening tasks (e.g., Fitzgibbons et al., 1974; Phillips et al., 1997; Vanneste and Pouthas, 1999). If the onset of a novel spectral event engages attentional resources that would otherwise be devoted to registering the characteristics of the silent interval, it is possible that the fidelity with which the interval is encoded is compromised. This reduced fidelity could apply to any or all aspects of the interval (i.e., offset, elapsed time, or onset). This possibility is reminiscent of the suggestion by Van Wieringen and Wouters (1999) that the abrupt perceptual change associated

⁶Analysis of the supplementary conditions also revealed the unexpected finding that performance for the complex leading marker condition was better than for the baseline iso-frequency condition ($F_{1,5} = 9.059$; $p = 0.03$). There does not appear to be any precedence for this finding in the literature; that is, GDD thresholds for complementary conditions with minimal standard gaps are either similar to (Formby et al., 1998b), or elevated with respect to (e.g., Grose et al., 2001; Pichora-Fuller et al., 2006), the iso-frequency baseline. It is possible that the presence of multiple frequency components enables some listeners to improve the coding of the offset of the leading marker, thereby enhancing the gap discrimination performance, but further work is required to clarify this.

with the onset of the complex trailing marker might interfere with the memory trace of the leading marker.

V. SUMMARY AND CONCLUSION

The three experiments in this study were designed to examine the nature of the order effect for frequency-asymmetric markers wherein GDD performance is poorer when the complex marker is the trailing marker than when it is the leading marker. Experiment 1 confirmed the order effect and demonstrated that it resulted in thresholds that are intermediate between within-frequency-channel processing and across-frequency-channel processing. However, the effect was less striking and more variable than the report by Formby et al. (1998b). Experiment 2 demonstrated that, whereas the addition of a secondary tone to the trailing marker led to a decline in GDD performance, the ABR elicited by this stimulus was more robust than in the absence of the secondary tone. Experiment 3 indicated that informational masking associated with synthetic listening is unlikely to underlie the order effect. Instead, informational masking resulting from the occurrence of novel spectral events in the complex trailing marker provides an account that is consistent with the pattern of results. The wide range of individual performance indicates that susceptibility to informational masking in this paradigm is observer-dependent. In conclusion, this study demonstrated that the order effect associated with frequency-asymmetric gap markers in the GDD paradigm is typical of most, but not all, listeners and is likely due to a form of informational masking.

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Figure 1.

GDD thresholds for individual observers (open symbols) and group mean (solid symbol) for the 4 conditions of experiment 1. Error bars are ± 1 standard deviation.

Figure 2. GDD thresholds for individual observers (open symbols) and group mean (solid symbol) for the 2 conditions of experiment 2. Error bars are ± 1 standard deviation.

Figure 3.

Upper schematics illustrate the position of the trigger pulse relative to the 2-ms onset ramp (left) and the 8-ms offset ramp (right). The 50-ms stimulus duration is for illustration purposes only. Lower panels show ABR waveforms from 3 observers elicited by stimulus onset (left pair of panels) and stimulus offset (right pair of panels). For each observer, the overlaid traces in the left-hand panel are individual sweeps, and the single trace in the right-hand panel is the weighted average of the individual sweeps. The arrows mark the position of wave V.

Figure 4.

ABR waveforms from one individual. The left column shows individual traces overlaid and the right column shows weighted averages. The upper row shows the reference condition where the leading marker was removed and only the primary tone trailing marker was present. The center block of rows shows the responses for the baseline within-frequency-channel condition set where the leading and trailing markers consisted of the primary tone alone. Each row depicts a fixed gap duration as stipulated in the inset. The bottom block of rows shows responses for the frequency-asymmetric condition set. The vertical line in the right column is positioned at the wave V latency for the reference condition.

Figure 5.

Weighted average ABR traces from 6 observers. Upper row denotes the reference condition with no forward masking, with the dashed line indicating the latency of wave V. The center block of traces are elicited by the iso-frequency markers with fixed gap durations as indicated in the left column. The lower block of traces are elicited by frequency-asymmetric markers at two fixed gap durations.

Figure 6.

Wave V latency shift from baseline as a function of gap duration. Filled symbols connected by lines are individual data for the iso-frequency condition set. The thick solid line indicates the group mean. Unfilled symbols are individual data for the frequency-asymmetric condition set. The dashed line indicates the group mean.

Figure 7. GDD thresholds for Test 1 of experiment 3. For each mode of presentation (Monaural, Dichotic, Diotic), individual data for 2-tone leading marker (2»1) and 2-tone trailing marker (1»2) are shown as connected open symbols. Solid circles are mean data, with ± 1 standard deviation error bars.

Figure 8.

GDD thresholds for Test 2 of experiment 3. Left panel shows baseline iso-frequency thresholds. Center panel shows thresholds for the frequency-asymmetric marker pair where the secondary tones were pure tones. Right panel shows thresholds for the frequency-asymmetric marker pair where the secondary tones were FM tones. In each panel, individual data for 3-tone leading marker (3»1) and 3-tone trailing marker (1»3) are shown as connected open symbols. Solid circles are mean data, with ± 1 standard deviation error bars.

Figure 9.

GDD thresholds for a standard gap duration of 100 ms. Left panel shows baseline iso-frequency thresholds. Right panel shows thresholds for the frequency-asymmetric markers plotted as a function of the number of tones in the leading and trailing markers. Solid circles are mean data, ± 1 standard deviation, and individual data are shown as open symbols.