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The long-term [illegible] this project was a better understanding of auditory processes which use across-frequency or across-ear temporal envelope and modulation difference cues to aid performance. Areas of investigation included comodulation masking release (CMR), the masking level difference (MLD), temporal resolution, and the processing of amplitude and frequency modulation. The goals of the proposed experiments were to 1) examine the possible relation between CMR and auditory phenomena related to auditory grouping, or auditory scene analysis; 2) examine how CMR and MLD effects combine, and to examine the possible relation between CMR and the MLD for narrowband noise maskers; 3) to determine the extent to which across-frequency correlation of temporal envelope may influence gap detection for wideband stimuli; 4) determine whether masking release can be derived from cues based upon across-frequency coherence of frequency modulation; 5) examine a modulation masking phenomenon related to frequency modulation. The tasks involved signal detection in masking noise, temporal gap detection, and the detection of frequency modulation.

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AIMS

The long-term aim of this project was a better understanding of auditory processes which use across-frequency or across-ear temporal envelope and modulation difference cues to aid performance. Areas of investigation included comodulation masking release (CMR), the masking-level difference (MLD), temporal resolution, and the processing of amplitude and frequency modulation. The goals of the proposed experiments were to 1) examine the possible relation between CMR and auditory phenomena related to auditory grouping, or auditory scene analysis; 2) examine how CMR and MLD effects combine, and to examine the possible relation between CMR and the MLD for narrowband noise maskers; 3) to determine the extent to which across-frequency correlation of temporal envelope may influence gap detection for wideband stimuli; 4) determine whether masking release can be derived from cues based upon across-frequency coherence of frequency modulation; 5) examine a modulation masking phenomenon related to frequency modulation. The tasks involved signal detection in masking noise, temporal gap detection, and the detection of frequency modulation.

Abstract

Nine experiments were completed during the course of the project. Whereas a common theme through the five projects was the combination of information across auditory channels, each of the nine studies examined a unique aspect of across-channel analysis. The **first** project was the first to explore CMR in the context of noise backgrounds with more than one set of comodulated noise components present at the same time. The results suggested that noise bands distributed across frequency could be segregated into two different apparent objects by virtue of shared modulation. When the number of comodulated noise components was relatively small, this segregation was relatively poor, but when the number of bands comprising each apparent source was relatively large, segregation was good. The results suggested that auditory grouping by comodulation probably precedes the across-frequency comparisons that underlie CMR. We believe that the results are pertinent to the question of how the auditory system segregates multiple frequency components into separate auditory objects. The **second** experiment examined the detection of frequency modulation (FM) in the presence of FM at a separate frequency. The results indicated that the detection of FM in the presence of the second FM tone was worse than for either the signal presented in quiet or in the presence of the unmodulated tone. The results are analogous to the modulation detection interference phenomenon that has been demonstrated in the AM domain. The **third** study was concerned more with methods, and was aimed at determining why CMR

has varied so much in magnitude across studies. The main results was that CMRs were often much larger and less variable for the Gaussian noise rather than multiplied noise. It was found that some subjects had very low thresholds even in the baseline condition for multiplied noise. It was hypothesized that a strong within channel cue exists in multiplied noise that does not exist in random Gaussian noise. The latter type of noise is probably preferable. The **fourth** study examined whether a masking release for masking energy having coherent frequency modulation (FM) existed similar to that for comodulation masking release (CMR) observed for common AM. On the whole, the results of this study indicated a masking release due to common FM, and were consistent with the hypothesis that common FM is one stimulus feature that can contribute to auditory grouping. However, the masking release effects observed for common FM were small when contrasted with those found with common AM. The **fifth** study consisted of several experiments that examined what specific portions of the masker envelope contribute to CMR. The results of this study consistently demonstrated that masking release was obtained only in the low energy or "dip" portions of the masker envelope. While the results were not completely compatible with Buus' dip listening model of CMR in its present form, they indicated that any viable model of CMR must place emphasis on the analysis of energy in masker dip regions. The **sixth** study examined the relation between modulation detection interference (MDI) and auditory grouping. To some extent, the study supported such a relationship, showing that MDI could be reduced by gating the interfering and target stimuli asynchronously, or by associating the interfering stimulus with other spectral components that would group with the interfering stimulus and segregate it from the target. However, the results of a further study did not support the idea that MDI was due specifically to the target and interferer being grouped together by common modulation. Instead, the idea was supported that MDI reflected a poor ability of the auditory system to link modulation with the carrier frequency of the modulation. The **seventh** study examined the hypothesis that the wide critical band found for binaural analysis (specifically, detection of $NoS\pi$ stimuli) is related to across-frequency analysis of envelope information. The study indicated that when noise envelopes are correlated across frequency, the presence of flanking noise energy actually aids $NoS\pi$ detection; however, when the envelopes are uncorrelated across frequency, the presence of flanking energy hurts binaural analysis. The interpretation of this result is that a CMR-type (envelope comparison) analysis is an essential part of binaural analysis in background noise. The **eighth** project was aimed at determining whether in temporal gap detection the total stimulus bandwidth was the factor primarily affecting performance, or whether the performance was affected primarily by the number of quasi-independent auditory filters activated by the stimulus. The results indicated that in cases where the cumulative bandwidth of the stimulus was relatively narrow (and, therefore, performance was very poor for any single band) there was a significant advantage in spreading the energy out over independent auditory filters. These results indicated that across-frequency temporal processes can improve temporal processing performance under difficult listening conditions. Three experiments are currently in progress. One is investigating modulation detection interference in a gap detection paradigm; the second is investigating whether CMR occurs for comodulated signals; the third is evaluating whether advantages for gap detection with multiple narrow bands of noise are due to "multiple looks" or whether they are due to analysis of across-frequency differences in temporal envelope. The **ninth** study examined the question of whether the auditory system can use across channel temporal envelope information to aid in the detection of a temporal gap at a given frequency. Gap detection was examined for a narrow band noise in the presence of a flanking noise that was either comodulated or noncomodulated with the target band. The main result was that gap detection deteriorated markedly with the addition of a second noise band, irrespective of its modulation pattern. This result appears to be related to the phenomenon of modulation detection interference.

Summaries of Completed Projects

A. Comodulation masking release and auditory grouping

The detectability of a pure-tone signal masked by a band of noise centered on the signal can be improved by the addition of flanking noise bands, provided that the temporal envelopes of the flanking bands are correlated with that of the on-signal band. This phenomenon is referred to as comodulation masking release (CMR). This study examined CMR in conditions in which some flanking noise bands were comodulated with the on-signal band, but other flanking bands (termed "deviant" bands) were not. Past research has indicated that CMR is often substantially reduced when deviant bands are present at spectral locations close to the signal frequency. We investigated whether the disruptive effects of such bands could be reduced by factors related to auditory grouping. The signal frequency was 1000 Hz. In one condition, only 20-Hz-wide comodulated bands, centered on 400, 600, 800, 1000, 1200, 1400, and 1600 Hz, were present. The CMR for this condition, referenced to threshold for the on-signal band only, was approximately 15 dB. In a second condition, two deviant bands were added at 900 and 1100 Hz; their presence reduced the CMR to only 3-4 dB. The number of deviant bands was then increased progressively, from two to eight bands. Deviant bands either shared a common envelope (codeviant), or had unique envelopes (multideviant). The number of bands that were comodulated with the on-signal band was held constant at six. The rationale was that as more deviant bands were added, the auditory system would be more likely to group the deviant bands near the signal frequency with the other deviant bands, rather than with the on-signal band, and therefore the disruptive effects of the proximal deviant bands would be reduced. A second manipulation was to provide an onset/offset asynchrony between the on-signal and comodulated bands, and the deviant bands. The rationale was that the asynchrony would enhance the segregation of the comodulated bands from the deviant bands. Both of the above stimulus manipulations (increasing the number of distally placed deviant bands, and providing onset/offset asynchrony) reduced the disruptive effects of the deviant bands. The results of dichotic conditions showed that the disruptive effects of deviant bands placed at 900 and 1100 Hz could also be reduced by adding codeviant bands (placed at 300, 500, 700, 1300, 1500, and 1700 Hz) in the ear contralateral to the signal. These results indicate that CMR may occur subsequent to stages of auditory grouping or object formation.

Hall, J.W. and Grose, J.H. (**1990**). "Comodulation masking release and auditory grouping." Journal of the Acoustical Society of America **88**, 119-125.

B. Detection of Frequency Modulation (FM) in the presence of a second FM tone

A series of three experiments was undertaken to investigate detection of sinusoidal frequency modulation (FM) in the presence of FM at a separate frequency. The first experiment measured detection of modulation for an FM tone with a modulation frequency (f_m) of 6 Hz as a function of carrier frequency (f_c) under three conditions: 1) in quiet; 2) in the presence of a 2500-Hz pure tone; 3) in the presence of a 2500-Hz FM tone with f_m = 6 Hz, modulating in phase with the signal. Detection of FM in the presence of the second FM tone was worse than for either the signal presented in quiet or in the presence of the unmodulated tone. Threshold varied as an inverse function of frequency separation between the signal and the masker. In the second experiment, FM detection for a signal with f_c = 1900 Hz and f_m = 6 Hz was measured as a function of the modulation frequency (f_m = 2-18 Hz) of the 2500-Hz masker tone. FM detection improved significantly with increasing difference between the modulation frequencies of the signal and the masker. The final experiment measured detection of FM for a signal (f_c = 1900 Hz, f_m = 6 Hz) in the presence of a second FM tone (f_c = 2500 Hz, f_m = 6 Hz) as a function of the relative phase of the 6-Hz modulators. Detection of FM improved monotonically as a function of increasing phase difference between the two modulators. The results are discussed in terms of modulation masking and perceptual grouping.

Wilson, A.S., Hall, J.W. and Grose, J.H. (**1990**). "Detection of frequency modulation (FM) in the presence of a second FM tone," Journal of the Acoustical Society of America 88, 1333-1338.

C. Accounting for the variability in CMR

This study examined some f the factors which can affect the magnitude of CMR. In experiment 1, psychometric functions were measured for the detection of a 1-kHz sinusoidal signal in a "multiplied" narrowband noise centered on 1000 Hz, and that noise with two comodulated flanking noise bands present. The functions were slightly steeper for the case where the flanking bands were present. Thus, CMR measured at a high percent correct were slightly larger than when measured at a lower percent correct. Large individual differences were found for the reference condition, but not in the condition with flanking bands present. Experiment 2 compared CMRs obtained with multiplied noise, versus CMRs obtained with Gaussian noise. CMRs were larger and less variable for the Gaussian noise. This was due primarily to the fact that some subjects had very low thresholds for he baseline condition for multiplied noise. For Gaussian noise, thresholds for the reference condition are relatively stable across subjects, and CMRs tend to be substantial, even for flanking band frequencies remote from the signal frequency.

Moore, B.C.J., Hall, J.W., Grose, J.H. and Schooneveldt, G.P. (**1990**). "Some factors affecting the magnitude of comodulation masking release," Journal of the Acoustical Society of America 88, 1694-1702.

D. The effect of modulation coherence on signal threshold in frequency-modulated noise bands

A series of four experiments was undertaken to ascertain whether signal threshold in frequency-modulated noise bands is dependent upon the coherence of modulation. The specific goal was to determine whether a masking release could be obtained with frequency modulation (FM), analogous to the comodulation masking release (CMR) phenomenon observed with amplitude modulation (AM). It was hypothesized that an across-frequency grouping process might give rise to such an effect. In experiments 1 - 3, maskers were composed of three noise bands centered on 1600, 2000, and 2400 Hz; these were either comodulated or noncomodulated with respect to both FM and AM. In experiment 1, the modulation was sinusoidal and the signal was a 2000-Hz pure tone; in experiment 2, the modulation was random and the signal was an FM noise band centered on 2000 Hz. The results obtained showed that, given sufficient width of modulation, thresholds were lower in a coherent FM masker than in an incoherent FM masker, regardless of the pattern of AM or signal type. However, thresholds in multi-band maskers were usually elevated relative to that in a single-band masker centered on the signal. Experiment 3 demonstrated that coherent FM could be discriminated from incoherent FM. Experiment 4 gave similar patterns of results to the respective conditions of experiments 2 and 3 but for an inharmonic masker with bands centered on 1580, 2000, and 2532 Hz. While within-channel processes could not be entirely excluded from contributing to the present results, the experimental conditions were designed to be minimally conducive to such processes.

Grose, J.H. and Hall, J.W. (**1990**). "The effect of coherence of modulation on signal detection in frequency modulated noise bands," Journal of the Acoustical Society of America **88**, 703-710.

E. Relative contributions of envelope maxima and minima to comodulation masking release

Comodulation masking release (CMR) is a phenomenon which demonstrates the sensitivity of the auditory system to across-frequency differences in the temporal modulation pattern of a complex waveform. In this paper, we review briefly some of the data on the physical parameters that affect CMR, and describe models that have been proposed to account for CMR: namely, models based upon envelope equalization/cancellation, across-frequency envelope correlation, and "dip listening." The present literature is ambiguous with regard to the relative importance of energy in the peak and dip regions of the waveform envelope. We therefore performed a series of experiments to investigate this issue. In the first experiment, we examined CMR for signals which resulted in either a uniform increment or uniform decrement in the masking noise centered on the signal frequency. This was accomplished by using a 20-Hz-wide noise band centered on 700 Hz as both the masker and as the signal, adjusting the phase angle between the signal and masker to either 0° (increment) or 180° (decrement). Conditions were examined where either zero, one, two, four, or six comodulated flanking bands were present. Results indicated positive CMRs for all conditions in which a comodulated flanking band was present. CMR increased as the number of flanking bands increased for intensity increments, but not for intensity decrements. The remaining experiments examined conditions where signals were present only in masker peaks, or only in masker dips. The results of these experiments indicated relatively large CMRs when the signal occurred in dip regions, but no CMR when the signal occurred in peak regions. Whereas the results of the above experiments were not compatible with the dip listening hypothesis of CMR, they did indicate that the stimulus cues which give rise to CMR appear to be derived primarily from the dip regions of the masking noise.

Hall, J.W. and Grose, J.H. (**1991**). "Relative contributions of envelope maxima and minima to comodulation masking release," Quarterly Journal of Experimental Psychology, **43A**, 349-372.

F. Consequences of temporal asynchrony for modulation detection interference

The ability to detect the existence of amplitude modulation at a target frequency is reduced when amplitude modulation exists at a flanking frequency. This effect has been termed modulation detection interference (MDI) (Yost and Sheft, 1989). One explanation for MDI holds that the masking and target frequencies are grouped together by the auditory system such that it is difficult to analyze the modulation at each frequency separately. The present study investigated conditions where the asynchrony of temporal gating of the target and flanking frequencies was manipulated in order to make the frequencies more or less likely to be grouped together by the auditory system and perceived as originating from a single putative source. A second experimental manipulation attempted to perceptually segregate the masking and target frequencies on the basis of harmonicity. The results of the experiments indicated that manipulations that were intended to enhance the segregation of the masking and target frequencies reduced the magnitude of MDI effects. This generally supported an interpretation that MDI is related in some way to auditory grouping. A final experiment was done in which the subject had to detect the presence of amplitude modulation, but also had to identify which of two frequency components carried the modulation. The results showed that subjects were often poor in discriminating which of two frequencies was amplitude modulated, even when the modulation itself was clearly audible. It was concluded that part of the MDI effect might be due to the poor ability of the auditory system to associate modulation with the carrier of the modulation. The results of the present study did not specifically support the idea that MDI is related to auditory grouping by common modulation.

Hall, J. W. and Grose, J. H. (**1991**). "Some effects of auditory grouping factors on modulation detection interference (MDI)," Journal of the Acoustical Society of America **90**, 3028-3035.

G. Masker envelope fluctuations and binaural masking release

Several studies have indicated that the MLD can be reduced by the presence of energy that is relatively remote from the signal frequency. One interpretation of this result has been that the frequency selectivity for binaural hearing is relatively poor. The present experiments were designed to examine this issue further. In baseline conditions, a 500-Hz So or Sπ pure-tone was masked by a 40-Hz wide No narrowband noise centered on 500 Hz. In the experimental conditions, three 40-Hz-wide No flanking bands were also present, centered at 250, 750 and 1000 Hz. The flanking bands were either comodulated with the band centered on 500 Hz, or they were comodulated between themselves but independently from the 500-Hz band, or each of the flanking bands had an independent envelope. The results can be summarized as follows:

1) For uncorrelated envelopes, the NoSo threshold with flanking bands present was not significantly different from that of the baseline condition. This result is consistent with an interpretation that the flanking bands were so far removed from the signal frequency that they caused a negligible increase in the energy at the output of the auditory filter centered on 500 Hz.

2) For correlated envelopes, the NoSo threshold with flanking bands present was substantially better than that for the baseline condition. This result can be regarded as a CMR (across-frequency analysis of waveform envelope).

3) For uncorrelated envelopes, the NoSπ threshold with flanking bands present was worse than that for the baseline condition. This agrees with the classical finding that NoSπ detection is affected deleteriously by masking energy relatively remote from the signal frequency.

4) For the case of correlated envelopes, the NoSπ threshold with flanking bands present was again better than that of the baseline condition.

5) When the flanking bands were replaced by equal-energy pure tones, the NoSπ thresholds did not differ much from the baseline threshold. This shows that when the remote energy has a flat amplitude envelope, the NoSπ detection is affected neither negatively (as for uncorrelated envelopes) nor positively (as for correlated envelopes). This result suggests further that the effect of remote energy on the MLD is related strongly to the relation between the amplitude envelope at the signal frequency and the amplitude envelope at the remote frequencies.

6) When the flanking bands were comodulated among themselves, but independently from the 500-Hz band, the deleterious effects of the independent flanking bands on NoSπ detection was reduced. The interpretation was that the coherently modulating flanking bands could be perceptually segregated from the independently-modulating 500-Hz band, thus reducing their disruptive effects.

In summary, these results are consistent with an interpretation that across-frequency comparison processes similar to those contributing to monaural CMR may also contribute to NoSπ detection.

Hall, J.W. and Grose, J.H (1992). "Masker envelope fluctuations and binaural masking release," in Auditory Physiology and Perception (Y. Cazals, L. Demany, and K. Horner, eds) (in press).

H. Gap detection in multiple narrow bands of noise as a function of spectral configuration:

This study sought to differentiate between the effect of stimulus bandwidth and the effect of number of activated auditory channels on gap detection in narrow bands of noise. The aim was to clarify the role of across-frequency analysis in temporal processing. Experiment 1 established that when total noise bandwidth is held constant at 100 Hz, gap detection improves as stimulus energy is distributed to both lower and higher frequencies. Experiment 2a showed that the effect was smaller, or was absent, when the cumulative stimulus bandwidth was increased from 100 Hz to 200 Hz. Experiment 2b confirmed that the benefit of spectral dispersion for the narrower cumulative bandwidth also held for a higher frequency region. The results suggested that in conditions where the cumulative stimulus bandwidth is relatively narrow and, concomitantly, gap detection is relatively poor, there is an advantage in dispersing the stimulus across a number of auditory channels. The advantage for the distribution of energy across a range of auditory channels may be offset when the spectral spacing of bands exceeds a critical value.

Grose, J.H. (**1991**). "Gap detection in multiple narrow bands of noise as a function of spectral configuration," Journal of the Acoustical Society of America **90**, 3061-3068.

I. Gap detection and modulation masking. CMR suggests that the auditory system is sensitive to across-frequency differences in modulation pattern. This raises the question of whether it is as sensitive to modulation differences due to the absence of activity (a silent interval) as it is to the presence of additional of activity (a signal). If so, gap detection in a narrow-band noise would be expected to be better in the presence of a comodulated flanking band than in the presence of a noncomodulated flanking band. In contrast, an auditory grouping hypothesis would predict that the presence of a comodulated flanking band would result in a fused auditory image of the two bands, rendering a momentary silent interval in one of the bands less noticeable. The present study was designed to test between these divergent hypotheses. Gap detection was measured in a 25-Hz-wide narrow-band noise centered at either 0.5, 1.0 or 1.5 kHz. A second 25-Hz band of noise, centered between 0.5 and 1.5 kHz, was then added which was either comodulated or noncomodulated with the target band. The most striking result was that gap detection deteriorated markedly with the addition of a second noise band, irrespective of its modulation pattern. Further testing suggested that this deterioration was due to a process of modulation masking. The variable data prevented a firm conclusion being drawn regarding the relative effect of a comodulated versus a noncomodulated flanking band.

Grose, J.H. and Hall, J.W. (**1993**). Gap detection in a narrow band of noise in the presence of a flanking band of noise, Journal of the Acoustical Society of America (in press).

Publications resulting from project

Hall, J.W. and Grose, J.H. (**1990**). "Comodulation masking release and auditory grouping," Journal of the Acoustical Society of America **88**, 119-125.

Wilson, A.S., Hall, J.W. and Grose, J.H. (**1990**). "Detection of frequency modulation (FM) in the presence of a second FM tone," Journal of the Acoustical Society of America 88, 1333-1338.

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Grose, J.H. and Hall, J.W. (**1990**). "The effect of coherence of modulation on signal detection in frequency modulated noise bands," Journal of the Acoustical Society of America **88**, 703-710.

Hall, J.W. and Grose, J.H. (**1991**). "Relative contributions of envelope maxima and minima to comodulation masking release," Quarterly Journal of Experimental Psychology, **43A**, 349-372.

Hall, J. W. and Grose, J. H. (**1991**). "Some effects of auditory grouping factors on modulation detection interference (MDI)," Journal of the Acoustical Society of America **90**, 3028-3035.

Hall, J.W. and Grose, J.H. (**1992**). "Masker envelope fluctuations and binaural masking release," in Auditory Physiology and Perception (Y. Cazals, L. Demany, and K. Horner, eds) (in press).

Grose, J.H. (**1991**). "Gap detection in multiple narrow bands of noise as a function of spectral configuration," Journal of the Acoustical Society of America **90**, 3061-3068.

Grose, J.H. and Hall, J.W. (**1993**). Gap detection in a narrow band of noise in the presence of a flanking band of noise, Journal of the Acoustical Society of America (in press).