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The effect of masker level uncertainty on intensity discrimination

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Abstract

Thresholds were measured for detection of an increment in level of a 60-dB SPL target tone at 1 kHz, either in quiet or in the presence of maskers at 0.5 and 2 kHz. Interval-by-interval level rove applied independently to remote masker tones substantially elevated thresholds compared to intensity discrimination in quiet, an effect on the order of 10+ dB [$10\log(\Delta I/I)$]. Asynchronous onset and stimulus envelope mismatches across frequency reduced but did not eliminate masking. A pre-interval cue to signal frequency had no effect, but cuing masker frequency reduced thresholds, whether or not masker level was also cued. About 1–2 dB of threshold elevation in these conditions can be attributed to energetic masking. Decreasing the overall presentation level and increasing masker separation essentially eliminates energetic masking; under these conditions masker level rove elevates thresholds by approximately 7 dB when the target and masker tones are gated synchronously. This masking persists even when the flanking masker tones are presented contralateral to the target. Results suggest that observers tend to listen synthetically, even in conditions when this strategy reduces sensitivity to the intensity increment.

I. INTRODUCTION

The term *masking* can be used to describe any elevation in signal threshold due to the presence of a masker. Masking is said to be *energetic* when the peripheral response to the masker interferes with response to the signal; this occurs when the auditory channel or channels best representing the signal are also excited or suppressed by concurrent masker energy. Psychophysical thresholds are not determined solely by energy in the channel associated with the signal frequency however. Across-channel effects have been shown to introduce masking under some conditions, such as comodulation-detection difference (Cohen and Schubert, 1987; McFadden, 1987) and across-channel masking (Moore *et al.*, 1990). Under other stimulus conditions, across-channel effects are thought to improve sensitivity, as demonstrated in the paradigms of profile analysis (Green, 1988) and comodulation masking release (Hall *et al.*, 1984). These across-channel effects are often discussed in terms of central auditory processing cues, including those thought to underlie grouping (Hall and Grose, 1990), but could also involve peripheral mechanisms, such as suppression (e.g., Oxenham and Plack, 1998; Moore and Borrill, 2002). Threshold elevation that cannot be attributed to *energetic* masking is sometimes described as *informational* masking. Informational masking is typically assumed to occur central to the cochlea and is thought to be due to stimulus uncertainty and/or perceptual similarities between masker and signal (for a review, see Durlach *et al.*, 2003).

The experiments described here examine an effect reported by Fantini and Moore (1994). That study compared the conditions under which different classes of across-channel cues improve thresholds. In one control condition, observers were asked to detect a level increment in one tone in the presence of remote masker tones for which level was roved. An optimal listening strategy in this task would be to monitor a narrow frequency region around the signal frequency

and to ignore auditory channels associated with the masker tones. However, the presence of roved masker tones elevated thresholds by approximately 4 dB [$10\log(\Delta I/I)$] despite the fact that energetic masking was argued to be negligible for the conditions tested. Fantini and Moore called this effect *across channel interference* (ACI), and while they did not describe it in this way, ACI can be thought of as a form of informational masking associated with masker level uncertainty.

The literature on informational masking has traditionally focused on the detrimental effects of frequency uncertainty. In one common paradigm, pure tone detection for a signal at a fixed frequency is estimated in the presence of a masker composed of pure tones with randomly selected frequencies, excluding a protected region around the signal frequency. Thresholds under these conditions can be elevated by 40 dB or more relative to fixed masker frequency conditions (Kidd *et al.*, 1994; Neff and Dethlefs, 1995). Using a frequency uncertainty paradigm, Neff and Callaghan (1988) assessed the effects of roving masker frequency and/or amplitude. While frequency rove elevated detection thresholds substantially, amplitude rove had little or no effect, suggesting that amplitude uncertainty was not associated with informational masking for these stimuli. Later modeling work by Oh and Lutfi (1998) bolstered the conclusion that masker amplitude rove does not introduce informational masking for tone detection. On the face of it this conclusion may seem at odds with the ACI result of Fantini and Moore (1994), which can be described as significant masking in the face of masker amplitude (but not frequency) uncertainty. The key difference between the paradigms used in these studies may be the task used to quantify masking; amplitude rove may have very different effects for tone detection and intensity discrimination, with substantial informational masking in the latter case.

Results of several recent studies are consistent with the conclusion that there is substantial informational masking for intensity discrimination in the presence of masker level rove. Both Doherty and Lutfi (1999) and Stellmack *et al.* (1997) estimated spectral weights for intensity discrimination of one tone in the presence of remote masker tones; applying level rove introduced substantial across-channel masking. While these results are broadly consistent with the previous ACI data, it is difficult to compare them in detail. Notably, in these studies level rove was applied to both the masker and the target tones, and task difficulty was manipulated by adjusting the variance of the associated rove distributions. The fact that the level of the target itself is uncertain in this paradigm could increase task complexity, perhaps by way of preventing the observer from forming an accurate template of the standard (no-signal) interval.

The effect of masker uncertainty on the processing of intensity information at the target frequency has also been studied in the context of the profile analysis paradigm (Green, 1988). Whereas masker level is unrelated to the presence of a signal in the ACI and informational masking paradigms discussed above, masker level is incorporated into the optimal strategy for detecting an increment in target level for a typical profile analysis task. Because both target and masker tones are roved together in this paradigm, synthetic listening incorporating stimulus components across frequency can improve thresholds. Introduction of stimulus uncertainty into a profile analysis paradigm interferes with the regular relationship between target and masker stimuli, and this in turn elevates threshold. This effect has been demonstrated for both frequency uncertainty (Richards *et al.*, 1989; Gockel and Colonius, 1997) and amplitude uncertainty (Kidd *et al.*, 1986; Lentz and Richards, 1998). Independently roving profile components in either level or frequency elevates thresholds more than predicted based on optimal use of the information provided to the observer (Kidd *et al.*, 1986; Kidd *et al.*, 1988; Lentz and Richards, 1998; Richards and Zeng, 2001). This finding is consistent with the ACI result and with the informational masking studies discussed above: it demonstrates that observers tend to incorporate level information across frequency regardless of whether or not this is an optimal strategy.

The present series of experiments was designed to provide information about the conditions under which ACI occurs. One major motivation was to evaluate the hypothesis that ACI is largely driven by the operation of a synthetic mode of listening, wherein across-channel cues are combined. This was assessed via manipulation of stimulus parameters intended to modulate the degree of synthetic listening. Experiment 1 uses two stimulus segregation cues, onset asynchrony and envelope mismatches across frequency, to test the hypothesis that segregation cues which reduce synthetic listening can also reduce the magnitude of ACI. Experiment 2 introduces pre-interval cues; this manipulation may be used to promote analytic listening by cuing observers to particular aspects of a stimulus. In addition to exploring aspects of ACI related to synthetic listening, another goal of this research was to explore the extent to which ACI may be influenced by energetic masking. Therefore, the third experiment estimates the contribution of energetic masking to previous ACI results.

II. EXPERIMENT 1: Across-channel interference and release from interference

Fantini and Moore (1994) asked observers to detect an increment in level of a 60-dB SPL, 2-kHz pure tone. Thresholds rose by approximately 4 dB with inclusion of a set of roved-level maskers, defined as tones at 1.02, 1.43, 2.80 and 3.29 kHz, with masker levels randomly assigned without replacement from the set of 0, -7, -14 and -21 dB re: 60 dB SPL. Those authors noted that when the maskers were present, the dominant percept in the face of random changes in the masker amplitude was a change in overall pitch or timbre. This observation suggests that observers were not able to focus attention at the signal frequency to the exclusion of the masker. Therefore, it was hypothesized here that manipulations promoting analytic listening, such as onset asynchrony and incoherence of amplitude modulation across frequency, could improve intensity discrimination thresholds in the presence of remote maskers.

Asynchronous onset has been shown to reduce informational masking (Neff, 1995), and to reduce across-channel effects, both those which elevate thresholds and those which reduce thresholds (e.g., Hall and Grose, 1991; Green and Dai, 1992; Grose and Hall, 1993). While there are fewer data on the grouping effects of AM coherence as such in informational masking, it has been argued to play a significant role in stream segregation (Bregman, 1978) and in comodulation masking release (Grose and Hall, 1993).

A. Methods

1. Observers—Observers were six adults, ranging in age from 23 to 42 years (mean of 29.7 years). All had thresholds of 20 dB HL or less at octave frequencies 250–8000 Hz (ANSI, 1996), and none reported a history of chronic ear disease. All observers were practiced in psychoacoustical tasks at the outset of the experiment, having participated in at least one prior experiment unrelated to the current research.

2. Stimuli—Stimuli were made up of a target and two maskers. The target was centered at 1000 Hz and was either a pure tone (*steady*) or tone that had been amplitude modulated (AM). In a no-signal interval, the target was 60 dB SPL, and in a signal-present interval that level was elevated from baseline. The target was always 500-ms in duration, with 20-ms $\cos^2$ onset and offset ramps. Maskers were pairs of tones or AM tones at 500 and 2000 Hz. These tones were nominally 60 dB SPL, with a rove of ± 10 dB (drawn from a uniform distribution) applied on an interval-by-interval basis and determined independently for the two maskers. In synchronous gating conditions, maskers were gated on and off with the target, for a total duration of 500 ms, including 20-ms $\cos^2$ ramps. In the asynchronous gating conditions, maskers were gated on 500-ms prior to the target and gated off synchronously with the target, for a total duration of 1 sec. Amplitude modulation of target and/or masker tones was achieved via multiplication with a raised 10-Hz sinusoid, with phase set to $-\pi/2$ at the beginning of

stimulus onset. As such, all components receiving AM were coherently modulated, beginning in a modulation minimum, with 100% modulation depth. Conditions in which both target and masker components shared the same temporal envelope (either *steady* or *AM*) will be referred to as *matched* and those with different temporal envelopes as *unmatched*.

In a pair of supplemental conditions, maskers were always assigned a level of 70 dB (+10 dB re: 60-dB SPL standard level), the highest level possible in the roved condition. This *no-rove* manipulation was designed to eliminate effects due to amplitude uncertainty, with level set at the top of the rove range to measure fixed-level performance in the ‘worst case’ of energetic masking. Envelopes were matched and gating was synchronous across target and masker components in the *no-rove* conditions.

All stimuli were generated in software (RPvds; TDT), played out of one channel of a DAC (RP2; TDT), routed through a headphone buffer (HB7; TDT) and presented to the left ear with circumaural headphones (Sennheiser, HD 265).

3. Procedures—Stimuli were presented in a 2-alternative forced-choice procedure. In one interval the target component was 60 dB SPL, and in the other (randomly chosen) interval its level was greater than 60 dB SPL. Observers responded via a hand-held response box and received visual feedback indicating the correct response. The ‘signal-present’ interval was generated by in-phase addition of a 1000-Hz pure tone or AM tone to the 60-dB target. The level of this added tone was adjusted according to a 3-down, 1-up tracking rule, estimating the signal level associated with 79% correct (Levitt, 1971). Initial signal level adjustments were made in steps of 8 dB, reduced to 4 dB after the second reversal, and reduced to 2 dB after the fourth reversal. Each track continued until ten reversals were obtained. Threshold estimates were computed as the average level at each track reversal after the first four. Between three and five replications were run in each condition. Thresholds improved by more than 10 dB in two out of 36 cases (6 observers $\times$ 6 conditions); in those cases the poor thresholds were omitted, leaving only the last three estimates. Thresholds were averaged to produce a final estimate. Data were obtained in blocks, completed in quasi-random order.

B. Results

Thresholds are reported in units of $10\log(\Delta I/I)$. While there were individual differences in sensitivity, both in masked and unmasked conditions, the trends discussed below were evident in all observers’ data. Figure 1 shows mean thresholds, with signal condition indicated on the abscissa and masker condition indicated with symbols. Error bars indicate standard error of the mean associated with each estimate.

Thresholds in the absence of masker tones (filled squares) were similar for both the steady and the 10-Hz AM targets, with mean values of -5.4 and -4.4 dB, respectively. This is in good agreement with pure tone intensity discrimination thresholds for a 60-dB SPL standard reported in the literature, which span -5 to 0 dB in units of $10\log(\Delta I/I)$ (Viemeister, 1972; Penner *et al.*, 1974; Neff and Jesteadt, 1996). Thresholds rose with the introduction of synchronously gated roved-level maskers, as indicated by the filled symbols. The largest elevations in threshold were obtained for conditions where the target and maskers had matched envelopes (filled circles), with masking of 17.6 and 16.1 dB, respectively. Introduction of maskers with unmatched stimulus envelopes elevated thresholds more modestly, with masking of 13.9 dB for a steady signal and 11.9 dB for an AM signal (filled triangles). A similar pattern of thresholds was obtained for conditions in which the target and maskers were asynchronously gated, but with approximately 10-dB improved sensitivity overall, as indicated by open symbols. In the matched conditions, masking was 7.5 dB for the steady signal and 4.5 dB for the AM signal (open circles). Masking was reduced by 1 to 1.5 dB for the unmatched target/masker envelope condition (open triangles). These results suggest that manipulations designed

to facilitate analytic listening improved performance, with larger effects of gating asynchrony (>10 dB) than envelope mismatch (~5 dB).

These observations were evaluated by a repeated measures ANOVA, with 2 levels of SIGNAL (steady, AM), 2 levels of MATCH (matched, unmatched across target/masker envelope) and 2 levels of gating (synchronous, asynchronous). This analysis resulted in a main effect of MATCH ($F_{1,5}=17.5$, $p<0.01$) and a main effect of GATING ($F_{1,5}=136.4$, $p<0.0001$). There was no main effect of SIGNAL ($F_{1,5}=4.1$, $p=0.10$), and none of the interactions approached significance ($p>=0.25$). To assess the elevation in threshold under conditions of combined segregation cues, two paired t-tests were performed comparing each no-masker threshold with the associated masked threshold under conditions of envelope and gating segregation cues (i.e., the unmatched/asynchronous onset condition). Thresholds for the steady signal were significantly higher with asynchronously gated, AM maskers than in the absence of maskers ($t_5=6.89$, $p<0.001$ one-tailed). Likewise, thresholds for the AM signal were significantly higher with asynchronously gated, steady maskers than in the absence of maskers ($t_5=2.27$, $p<0.05$ one-tailed).

Results of the supplemental *no-rove* conditions employing the maximum value of rove on every trial are shown with filled diamonds in Figure 1. Thresholds in these conditions were 0.56 dB and 0.15 dB for the matched steady and the matched AM stimuli, respectively. These thresholds are reduced relative to the associated roved-masker conditions by 11.7 dB ($t_5=10.3$, $p<0.0001$, two-tailed) and 11.5 dB ($t_5=24.6$, $p<0.0001$, two-tailed). However, they are also significantly different from the associated no-masker conditions by 5.9 dB ($t_5=3.83$, $p<0.05$, two-tailed) and 4.6 dB ($t_5=4.19$, $p<0.01$, two-tailed). This result suggests that masker amplitude uncertainty likely plays a dominant role in threshold elevation, but does not entirely account for the effects observed.

C. Discussion

The basic finding of ACI reported by Fantini and Moore (1994) was broadly replicated in Experiment 1. That is, inclusion of masker tones with independently roved level interfered with intensity discrimination at the target frequency even though these maskers were well removed from the signal in frequency. This effect was on the order of 15 dB, larger than the 4-dB effect noted by Fantini and Moore, but comparable to previous data on the effects of random amplitude perturbation in profile analysis (e.g., Lentz and Richards, 1998). The largest threshold elevation due to the presence of maskers was observed when the target and maskers were all steady pure tones or AM tones. This effect was reduced by approximately 4 to 5.5 dB when the target and maskers had unmatched envelopes. The introduction of target/masker onset asynchrony had a larger effect, reducing the ACI effect by approximately 10 dB. The effects of these manipulations combined reduced ACI by 13 to 14.5 dB but did not eliminate it, leaving 3 to 6.5 dB of masking. Both asynchronous onset and introduction of envelope mismatches across frequency are often discussed in the literature as facilitating sound source determination and analytic listening. The results obtained here are consistent with the interpretation that analytic processing reduces the ACI masking effect.

Thresholds in the supplemental conditions, with masker level consistently assigned as the maximum possible in roved conditions (70 dB SPL) were similar to those in the asynchronous gating conditions. This is consistent with the hypothesis that stimulus uncertainty played a large role in threshold elevation in the roved-level, synchronous onset conditions, and that asynchronous gating largely counteracted those effects. Spiegel *et al.* (1981) showed poorer intensity discrimination with the inclusion of fixed-level tonal maskers, a finding that is consistent with the current result. In contrast, Fantini and Moore (1994) report that thresholds improved slightly with the inclusion of fixed-level maskers. Significant differences across studies exist, but it is unclear which factors are responsible for the different results. The fact

that the thresholds were elevated in the *no-rove* condition relative to the no-masker baseline in the present study suggests that amplitude uncertainty may not be the sole source of masking in these conditions.

It is frequently assumed that maskers an octave removed from the signal introduce essentially no energetic masking to the processing of that signal. Glasberg *et al.* (1984), for example, measured pure tone detection thresholds (as opposed to intensity discrimination) in the presence of pairs of masker tones up to 400 Hz above and below a 1-kHz signal. Auditory filters fitted to these data suggest that excitation associated with a masker tone at 500 Hz is attenuated by 40 dB in the auditory filter centered on 1-kHz. Based on these results, energetic masking would be negligible for the 60-dB, 1-kHz target, even at the highest masker level used in the current experiment: a 500-Hz masker tone at 70 dB SPL would change excitation at 1-kHz by approximately -30 dB in units of $10\log(\Delta I/I)$, and the change associated with a 2-kHz masker tone would be even less. These effects are well below thresholds measured experimentally. This line of reasoning does not rule out energetic masking for intensity discrimination, however. It is widely believed that intensity discrimination for a tone is based on cues distributed across the spectral range encompassing spread of excitation of that tone (e.g., Florentine and Buus, 1981). If some of those cues originate near the region of significant masker excitation, then even remote maskers could elevate thresholds via energetic masking. In contrast to this energetic masking explanation, it is also possible that fixed-level maskers may be associated with informational masking based on stimulus similarity attributes, as opposed to stimulus uncertainty attributes. There is some precedent for this hypothesis in the literature. Leibold and her colleagues (Leibold *et al.*, 2005; Leibold and Neff, 2007) report evidence of informational masking even in conditions of little or no external stimulus uncertainty. Experiment 3 will evaluate these two hypotheses regarding the small threshold elevation in the presence of fixed-level maskers. The next experiment focuses on the relatively large threshold elevation in the presence of roved-maskers, which is susceptible to masking release based on segregation cues, and so is likely to be informational rather than energetic.

III. EXPERIMENT 2: ACI and pre-interval cues

Data collected in Experiment 1 demonstrated that remote masker tones significantly elevate thresholds for detecting an increment in target tone intensity, particularly in the presence of level rove and in the absence of target/masker segregation cues. The exact mechanism for the masker rove effect is unclear, however. One possibility is that masker variability draws attention away from the (less variable) target stimulus. Another possibility is that masker variability produces a changing overall stimulus timbre or pitch, a factor that would interfere with performance if the increment detection cue were based on an obligatory synthesis of the target and masker tones.

Experiment 2 attempted to identify the mechanism of masking in ACI by presenting pre-interval cues designed to reduce the possible sources of masking. For example, loss of focus on the target frequency with masker onset might be ameliorated by a cue to signal frequency, while masker level uncertainty should be greatly reduced by a pre-interval cue indicating the masker tone levels associated with the subsequent interval. A similar cue-based approach was used by Richards and Neff (2004). In that study the task was to detect a tone in the presence of a multi-tone masker, with frequencies randomly assigned to each tone on each interval or on each trial. Informational masking was reduced by pre-interval masker frequency cues, a result that can be interpreted in terms of reduced stimulus uncertainty in the listening interval. In some cases thresholds were also reduced by signal-frequency cues, even in the absence of signal frequency rove. This effect cannot be attributed to reduction in stimulus uncertainty, but may relate to allocation of attention to frequency-specific cues. The utility of different pre-interval cues in ACI may shed light on the mechanisms of masking at work in the uncued case.

A. Methods

1. Observers—Nine observers completed this experiment, ranging in age from 24 to 50 years (mean of 33.7 years). All had thresholds of 20 dB HL or less at octave frequencies 250–8000 Hz (ANSI, 1996) in the test ear, and none reported a history of chronic ear disease. All had previously participated in a study of ACI, including Observers 1–5 from Experiment 1. Observers 7–10 had previously participated in ACI protocols not reported here.

2. Stimuli—Stimuli were identical to those used in Experiment 1 with the exception of the inclusion of pre-interval cues. A cue interval was presented prior to each of the two listening intervals. Stimuli in both the cue and the listening interval were 500-ms in duration, including 20-ms $\cos^2$ onset and offset ramps. The cue/interval pairs were separated by a 300-ms delay, and there was a 500-ms delay between stimulus pairs.

There were five conditions. The first condition presented a cue interval consisting of a 500-ms silence, and so is referred to as the *no-cues* condition. In the *signal-standard* condition the cue was a 60-dB standard target tone, identical to that presented in no-signal intervals. In the *masker-freq* condition the cue consisted of the two masker tones played at their median level of 60-dB SPL. In the *masker-freq&lev* condition the cue consisted of the two masker tones played at the levels associated with rove values chosen for the subsequent listening interval. Finally, in the *full-standard* condition the cue was the sum of the 60-dB target tone and the pair of masker tones, with masker levels corresponding to the subsequent listening interval. In this condition, stimuli in the cue and listening intervals differ only when there is an intensity increment (i.e., on a signal-present interval) and are identical for no-signal intervals.

3. Procedures—Observers completed the *no-cue* condition first; the four remaining conditions were then completed in random order, with all thresholds completed in blocks by condition. As in Experiment 1, thresholds were obtained in a 2-alternative forced-choice, 3-down 1-up track. Other procedures were likewise identical, with the following exception. Because of variability in these data, additional steps were taken to obtain stable and reliable threshold estimates. Observers completed up to six replications in each condition, depending on the volatility of estimates and observer availability. In cases where more than four data points were available, the lowest and the highest estimates were omitted from mean data. This procedure reduced the across-observer variance but did not change the overall pattern of mean data across conditions.

B. Results

Figure 2 shows thresholds plotted as a function of cue condition for each of the nine observers. Open symbols indicate each individual observer's data, and filled circles show the mean across observers. These data were subjected to a repeated measures ANOVA, with 5 levels of CUE, as indicated on the abscissa of Figure 2. This analysis resulted in a significant effect of CUE ($F_{4,32}=16.15$, $p<0.0001$). Mean threshold in the *signal-standard* cue condition was nearly identical to that in the *no-cues* condition, differing by just 0.1 dB ($t_8=0.11$, $p=0.91$). Planned comparisons for the series of masker cues indicate that each of the masker cue conditions aided performance compared to the no-cue baseline. Mean threshold improved by 3.5 dB with the introduction of masker tones in the *masker-freq* condition, dropped an additional 0.4 dB with introduction of masker level information in the *masker-freq&lev* condition and improved by a further 3.0 dB in the *full-standard* condition. Each of these conditions was incrementally better than the last with a one-tailed t-test ($\alpha=0.05$) with the exception of introducing masker level information: thresholds in the *masker-freq&lev* condition were not significantly different from those in the *masker-freq* condition. Data of Observer 10 were somewhat different from the mean. This observer appeared to benefit from all four of the cues to a similar extent, including

the *signal-standard* cue. Repeating the ANOVA without data from Observer 10 did not change the pattern of significance reported above.

The maximal informational masking (*no-cues*) condition was associated with a mean threshold of 9.3 dB, somewhat lower than the 12.2 dB threshold obtained under analogous conditions in Experiment 1. It is unclear whether to attribute this difference to individual differences, practice effects, or the longer inter-stimulus interval (from 500-ms in Exp 1 to 800-ms in the current paradigm), but in any case this value provides substantial masking to compare against pre-interval cue masking release conditions. The best-cued thresholds (*full-standard*) were on average 2.3 dB (with a 1.8 dB standard deviation). As such, these thresholds are still significantly greater than those expected in the absence of maskers (approx -5.3 dB, based on results of Experiment 1) and comparable to those obtained with pure tone signal and maskers with asynchronous onset (2.1 dB).

C. Discussion

It was hypothesized prior to this experiment that if masker tones deflected attention from the signal frequency, then presenting the standard target prior to the listening interval could help focus attention on the signal frequency to the exclusion of remote masker tones. This was not borne out in the data, where no masking release was associated with the *signal-standard* condition, with the possible exception of Observer 10. While unexpected, this result is not without precedent in the literature; Richards and Neff (2004) reported a wide range of signal cue results across observers and across paradigms, including additional masking with inclusion of a signal cue in some cases.

Masker cues were predicted to improve performance to the extent that they reduced stimulus uncertainty in the listening interval. That is, cues to masker level were predicted to reduce masking, but cues comprised of masker tones presented at the median (60-dB) level were not predicted to impact performance. Again, this expectation was not borne out in the data, where both the *masker-freq* and *masker-freq&lev* conditions were associated with similar reductions in masking. This finding merits further investigation, but one possible explanation for this result is that presenting the maskers prior to the listening interval highlights the target as the 'new' aspect of the stimulus. This idea is similar to the basis of the CoRE model (Lutfi, 1993), where the perception of a stimulus is dominated by stimulus features with the largest trial-to-trial variance. This result could also be related to auditory streaming (Bregman and Pinker, 1978).

While all masker-based cues significantly improved thresholds, the *full-standard* cue was the most effective cue. From an information theoretic perspective this is an odd result; the *full-standard* and *masker-freq&lev* conditions differ only in the inclusion of the 60-dB tone at 1-kz, a stimulus feature that is constant across all trials and so does not add information. Better sensitivity in the *full-standard* condition suggests that observers may be unable to listen to the target analytically, basing their decision instead on the combination of target and masker tones. This might be the case if the percept associated with the three-tone complex were akin to a chord. In this case information about the masker tones alone would not convey information about the interaction of target and masker tones, and so might not be predictive of the overall percept. This hypothesis is consistent with the observation that the target tone alone was not an effective cue (*signal-standard*), but that the combination of the target and masker tones significantly improved performance over the case of masker tones alone (*masker-freq&lev* vs. *full-standard*).

IV. EXPERIMENT 3: effects of energetic masking in ACI

Experiments 1 and 2 showed that intensity discrimination for a 60-dB tone at 1 kHz can be significantly impaired by the presence of roved-level masker tones an octave above and an octave below that target, elevating thresholds as much as 15 dB relative to threshold for the same task in the absence of maskers. This masking can be significantly reduced by inclusion of segregation cues (Exp 1) or by pre-interval cues that foreshadow features of the masker or target/masker complex (Exp 2). Thresholds in these conditions are not reduced to the baseline (no-masker) condition, however. Even in the presence of the most effective segregation cues or pre-interval cues, thresholds are elevated by approximately 3 dB or more with respect to the baseline condition, similar to the masking obtained in the no-rove conditions of Experiment 1. One possible source of this masking is energetic. Intensity discrimination is widely believed to rely on off-frequency changes in excitation pattern (Florentine and Buus, 1981), including excitation an octave removed from the signal frequency (Viemeister, 1971); cues from these off-frequency regions could be energetically masked in the present paradigm.

Data from Moore and Raab (1974) lend credence to the idea that intensity discrimination at 1 kHz could be affected by energetic masking for tones an octave removed. Masking effects in that study were on the order of 5 dB, similar to the *no-rove* effect seen for steady tones in Experiment 1; however, a higher target standard level was used in the Moore and Raab study, and greater spread of excitation at high than low stimulus levels would be associated with a wider distribution of cues across-frequency. The purpose of Experiment 3 was to assess the role of energetic masking in the ACI effect reported above. Three strategies were used to estimate the role of energetic masking independent of informational masking. First, intensity discrimination thresholds were measured at three fixed masker levels: the bottom, middle and top of the rove range. It was hypothesized that if thresholds with the fixed-level masker in Experiment 1 were due to energetic masking, then those thresholds should be sensitive to increases in masker level. Second, thresholds were also measured in the presence of a pair of 400-Hz wide noise bands configured to produce energetic masking comparable to that of the tonal maskers. If intensity discrimination in the presence of fixed-level tonal maskers is due to similarity-based informational masking, then introducing a qualitative mismatch across target and maskers (tone vs. noise band) should reduce masking. Third, stimulus onset synchrony was manipulated to either discourage or facilitate analytic listening. Supplemental conditions also explored the effects of contralateral masker presentation, where no energetic masking would occur.

A. Methods

1. Observers—Observers were eight adults, ages 18–54 years (mean 32 years). All had thresholds of 20 dB HL or less at octave frequencies 250–8000 Hz (ANSI, 1996), and none reported a history of chronic ear disease. All observers were practiced in psychoacoustical tasks at the outset of the experiment, having participated in at least one prior experiment unrelated to the current research. In addition, Observer 1 had previously completed both Experiments 1 and 2, Observer 7 had completed just Experiment 2, and a third observer had previously completed another ACI protocol.

2. Stimuli—Stimuli were based on those used in Experiment 1. The observer's task was to detect an increment in the level of a 1000-Hz tone above the 60-dB SPL standard level. This target was 500 ms in duration, including 20-ms $\cos^2$ ramps. In the tonal masker conditions, the masker was a pair of pure tones at 500 and 2000 Hz; masker levels were either fixed at 50, 60 or 70 dB SPL, or the level was roved independently on an interval-by-interval basis using a pair of uniform draws from a distribution 50–70 dB. In the narrowband noise masker conditions the masker was a pair of 400-Hz wide bands of noise centered on 400 and 2100 Hz; masker

levels were either fixed at 51, 61 or 71 dB SPL, or the level of each band was roved uniformly over this span. Excitation pattern simulations¹ suggested that these narrowband masker frequencies and levels produce comparable excitation in the region of the signal frequency as that associated with the tonal maskers. In gated conditions the two maskers were gated on and off with the target, and in the continuous conditions they played throughout a threshold estimation track. When the masker level was roved in the continuous presentation conditions it was adjusted in the inter-stimulus interval; the transition was smoothed via convolution with a 20-ms boxcar function.

3. Procedures—As in Experiment 1, thresholds were obtained in a 2-alternative forced-choice procedure, with a 500-ms duration inter-stimulus interval. Signal level was adjusted in a 3-down 1-up track, with track parameters identical to those described above. Observers completed three threshold estimates, with a fourth estimate taken in cases where prior estimates varied by 3 dB or more. Data reported below are the mean of all estimates obtained. Observers completed all narrowband noise conditions prior to beginning the tonal masker conditions. Additional data were collected at the end of the experiment to spot check for practice effects. In no case was there sufficient evidence of improvement to prompt replacement of data.

B. Results

The pattern of results was consistent across the eight observers, so only the mean data are shown. Figure 3 shows mean thresholds plotted as a function of condition for tonal masker conditions (left panel) and narrowband noise conditions (right panel). As in Figure 1, squares indicate baseline performance of intensity discrimination in the absence of maskers. Diamonds indicate performance with fixed-level maskers and circles show roved-masker data; in both cases synchronous gating data are shown with filled symbols, and continuous conditions are shown with open symbols. Error bars show standard error of the mean, and in some cases error bars are occluded by the symbols.

In the course of this experiment baseline performance for intensity discrimination in the absence of maskers was estimated twice, once at the beginning of the narrowband masker conditions and again prior to tonal masker conditions, with mean thresholds of -5.5 and -4.1 dB, respectively. These estimates were not significantly different ($t_7=2.0$, $p=0.08$), so the mean of -4.8 dB is plotted in both panels for comparison with the masked thresholds.

Data collected in the fixed masker conditions were submitted to a repeated measures ANOVA, with 2 levels of MASKER (tone, noise), 3 levels of LEVEL (low, mid, hi), and two levels of SYNCHRONY (gated, continuous). There was a main effect of LEVEL ($F_{2,14}=30.54$, $p<0.0001$) and a main effect of SYNCHRONY ($F_{1,7}=16.53$, $p<0.005$). There was no main effect of MASKER ($F_{1,7}=1.20$, $p=0.31$). None of the interactions with MASKER approached significance ($p>0.5$), but the interaction between LEVEL and SYNCHRONY approached significance ($F_{2,14}=2.70$, $p=0.10$). These results support the conclusion that masker level was positively related to threshold, as would be expected if masker tones introduced energetic masking. Playing the maskers continuously reduced threshold, and there was a non-significant trend for a larger gating effect at the high masker levels.

Comparisons between fixed-level and roved data are somewhat complicated by the effect of level within the fixed-level conditions. Using the maximum fixed-level threshold as a reference, however, provides a liberal estimate of the energetic masking present in the roved conditions. The difference in thresholds between fixed and roved level conditions is greater

¹Excitation patterns were based on Moore *et al.* (1997). Software for making these calculations (excite2005.exe) is available for download from: <http://hearing.psychol.cam.ac.uk/Demos/demos.html>

for the gated than the continuous presentation modes, with differences on the order of 4.5–7 and 1.5 dB, respectively. The roved level data were submitted to a repeated measures ANOVA, with two levels of MASKER (tone, noise) and two levels of SYNCHRONY (gated, continuous). There was a main effect of MASKER ($F_{1,7}=18.76$, $p<0.005$) and a main effect of SYNCHRONY ($F_{1,7}=186.34$, $p<0.0001$). The interaction fell short of significance ($F_{1,7}=3.45$, $p=0.11$).

These results suggest that energetic masking was likely small but significant for these stimuli; supplemental conditions were run to see if ACI could be demonstrated under conditions associated with no evidence of energetic masking. These conditions employed lower levels (50 dB, with rove range of ± 8 dB) and wider masker spacing (300 and 3000 Hz). The standard was a 948.7-Hz tone, geometrically centered between the two masker tones. Results of the supplemental conditions are shown in Figure 4. Baseline intensity discrimination in the absence of maskers for the 50-dB, 948.7-Hz standard was compared with the mean from the previous two conditions using a 60-dB, 1-kHz standard frequency (with means of -3.6 and -4.8 dB, respectively). This difference was significant ($t_7=3.28$, $p<0.05$), indicating slightly reduced sensitivity for increments to the 50-dB standard as compared to the 60-dB standard employed previously. A repeated measures ANOVA was performed for the fixed level maskers with three levels of LEVEL (low, mid, high) and two levels of SYNCHRONY (gated, continuous). There was a main effect of SYNCHRONY ($F_{1,7}=29.0$, $p<0.001$), but no effect of LEVEL ($F_{2,14}=0.86$, $p=0.44$) and no interaction ($F_{2,14}=0.43$, $p=0.65$). Because there was no significant effect of level, thresholds for the continuous presentation were averaged across the three fixed-level conditions. That mean (-2.8 dB) was not significantly different from the no-masker baseline ($t_7=1.09$; $p=0.31$), but it was significantly lower than the associated roved condition ($t_7=2.47$, $p<0.05$), an effect of only 0.9 dB. The comparable comparison in gated conditions resulted in a 3.6 dB effect of introducing fixed-level maskers ($t_7=3.70$, $p<0.01$) and a further 7.5 dB effect of introducing masker level rove ($t_7=8.27$, $p<0.001$).

In addition to the monaural stimulus presentation used up to this point, thresholds in supplemental conditions were also obtained in the presence of roved-level masker tones presented contralateral to the target tone. This condition was completed several weeks after the previously reported conditions, at which point one of the eight observers was no longer available for testing. Contralateral presentation tended to improve thresholds relative to the roved-level ipsilateral data presented above, with mean improvement of 1.3 dB in the gated condition and 0.5 dB in the continuous condition. Paired one-tailed t-tests comparing these thresholds with thresholds in the no-masker condition indicated significant contralateral masking for the gated ($t_6=2.73$, $p<0.05$) but not the continuous ($t_6=0.70$, $p=0.25$) masker presentation.

C. Discussion

At the outset of this experiment it was hypothesized that if fixed-level masking was energetic in nature, then thresholds should increase with increasing masker level. Thresholds in the two conditions employing a 60-dB target were found to increase with increasing masker level, and there was some indication that this effect may be greater for gated than continuous masker presentation. It is sometimes argued that gating effects obtained with long duration signals reflect informational rather than just energetic masking (as in Neff, 1995). It has also been suggested that attention bands for the detection of a ~ 300 -ms tone are more sharply tuned in frequency when the masker is continuous than when it is gated (Dai and Buus, 1991; Wright and Dai, 1994). This effect has been described in terms of the masker onset capturing the observer's attention and introducing a bias to monitor a family of auditory filters rather than the just the optimal filter(s). If the masker onset in the current paradigm broadens or otherwise modifies spectral weighting of intensity cues, this could introduce threshold elevation independent of

energetic masking. As such, higher thresholds in gated as compared to continuous conditions could be interpreted as a form of informational masking.

Recently Jesteadt et al. (2007) reported that thresholds across a range of paradigms could be fitted using the excitation-based loudness model of Moore *et al.* (1997)ⁱⁱ. In one portion of that study, intensity discrimination thresholds of Viemeister (1972) were fitted using a criterion change in partial loudness of 4 phons. Predictions were quite accurate over a range of stimulus levels for a 950-Hz pure tone, gated with 160-ms duration, but thresholds were under-predicted in conditions incorporating highpass noise. Stimuli in the present no-masker and fixed-level conditions were submitted to this model. Using a 4-phon criterion, the predicted threshold in the no-masker condition is -7.4 dB, somewhat lower than the -4.8 dB obtained in the present study. Increasing the criterion change in partial loudness to 8 phons, as used in the modeling of Leibold and Jesteadt (2007), increases predicted threshold to -5.0 dB. Including fixed-level, 70-dB SPL masker tones increased thresholds by 1.7 dB, to -3.3 dB. The same prediction is made using the 71-dB SPL noise bands. This predicted masking is similar to the threshold elevation of 1.6 dB observed with narrowband noise maskers and is within the confidence interval (± 2 sem) of the 3.2 dB effect observed with tonal maskers. These results lend support to the hypothesis that threshold elevation in the fixed-masker, continuous conditions reflects energetic masking. Because this model does not make use of temporal cues it is not feasible to model the different gating conditions in the context of the model. One parsimonious explanation for the data, however, is that thresholds in the continuous condition represent the effects of energetic masking and those in the gated conditions reflect additional informational masking due to attentional capture associated with masker onset.

The partial loudness model also provides a framework for thinking about the detection process in roved-level conditions. In broad terms, this model is based on loudness as a function of frequency, similar to an excitation pattern. This function is computed for a masker alone and then again for a signal-plus-masker stimulus. The difference in loudness is computed and that difference is integrated across frequency. This process assumes that the observer has some internal representation of the masker alone stimulus that serves as a template. In the fixed-level conditions the masker alone is presented frequently – once in every 2AFC trial. In the roved-level conditions the masker alone reference is changing on every interval. When the masker is playing continuously and the target is gated on during the listening interval the observer can use the masker fringe, occurring after the change in level and before onset of the signal, as the basis for a masker alone template. Thresholds in these conditions are only slightly elevated relative to those in the fixed-level conditions, suggesting that information provided by the fringe is only slightly less helpful than fixing the masker level. In the gated conditions the observer is never presented with an example of the masker-alone stimulus associated with a particular listening interval. In this case, the only strategy remaining would be to use features of the full stimulus -- including maskers, target and possibly the signal -- to form a template. Theoretically all the information necessary to do this task at the limits of energetic masking are present; for example, knowing that the masker is always a pair of tones at 500 and 2000 Hz, a ‘perfect’ template could be computed based on the excitation at 500 and 2000 Hz. The fact that thresholds are more severely elevated in the gated roved-level conditions suggests that this is an error-prone and inaccurate process, which might be limited by memory or stimulus-driven attentional capture (Egeth and Yantis, 1997).

A simulation of the roved level, tonal masker conditions was undertaken to estimate thresholds from energetic masking alone for the primary roved-level conditions of Experiment 3, assuming that the observer is able to construct an accurate no-signal template as described

ⁱⁱIn that study loudness was calculated using the software partloud.exe, available for download from: <http://hearing.psychol.cam.ac.uk/Demos/demos.html>

above. The MATLAB script used to collect psychophysical thresholds was adapted to calculate 'responses' based on partial loudness. On each interval a single stimulus was generated, with independent values of rove selected for each masker tone. The partial loudness associated with addition of a signal tone was calculated. If that value exceeded the 8-phon criterion then the procedure correctly identified the signal-present interval, but if not then the procedure randomly selected either the signal-present or the no-signal interval. This process was repeated for 50 track reversals, and three such tracks were completed. This procedure predicts a mean masked threshold of approximately -4.0 dB and no-masker threshold -5.3 dB. This informal simulation suggests that energetic masking with the introduction of roved-level maskers may elevate thresholds by about 1–2 dB, substantially less than the 11 dB masking effect obtained psychophysically in the gated condition. By exclusion, the remaining ~ 10 dB can be categorized as informational masking.

The supplemental data collected with a 50-dB standard and more widely spaced tonal maskers (at 300 and 3000 Hz) resembled those in the primary conditions, but thresholds in the fixed-level conditions did not increase with increases in masker level. The partial loudness model predicts no energetic masking in these conditions; threshold is predicted to be constant across the no-masker and all three fixed-masker conditions. While the mean fixed-masker thresholds are 0.8 dB higher than those in the no-masker condition, this difference is small and non-significant, suggesting that energetic masking does not have an appreciable effect in these conditions. As in the previous data, gating the fixed-level stimuli elevated thresholds by 2.2 to 3.5 dB, and roving level elevated thresholds substantially, particularly in the gated condition. These results demonstrate that gating and roved-level effects occur even in the absence of energetic masking. The finding of ACI for gated maskers presented contralateral to the target tone further confirms that energetic masking is not a precondition for demonstrating this effect. Similar findings were reported by Shub *et al.* (2005), who argued that their results could be modeled in terms of a binaural intensity summation model.

V. GENERAL CONCLUSIONS

The results of Experiment 1 showed that the masking effect of across-channel interference (ACI) reported by Fantini and Moore (1994) can be reliably obtained with either steady or amplitude modulated tones. Intensity discrimination thresholds for a 1000 Hz, 60-dB SPL standard were increased substantially with inclusion of masker tones at 500 and 2000 Hz, played at 60-dB SPL ± 10 dB. Conditions incorporating unmatched envelope patterns across frequency were associated with a reduction in the ACI effect. Asynchronous target/masker onset reduced thresholds to a greater extent, and the combination of envelope and onset manipulations was associated with a combined release from masking. These results are consistent with the hypothesis that ACI is reduced under stimulus conditions facilitating analytic listening. Thresholds in conditions of onset asynchrony were comparable to those with synchronous onset and masker level set consistently at the top of the rove range. Eliminating masker level uncertainty did not eliminate masking, leaving approximately 6 dB of masking in the tonal masker conditions that cannot be accounted for by masker level uncertainty.

Experiment 2 showed that pre-interval cues to signal frequency and standard level were ineffective at lowering threshold, suggesting that memory for the target frequency does not limit performance in the presence of masker tones. Pre-interval cues incorporating the masker tones were effective in reducing threshold, even when the cue consisted of tones at 60-dB SPL rather than the random levels of the subsequent listening interval. The most effective cue incorporated both masker and target tones, foreshadowing the subsequent stimulus in all respects other than the presence of an intensity increment at the target frequency associated with a signal interval. Even in these conditions there was some evidence of residual masking:

average thresholds were on average 7 dB above those measured in Experiment 1 in the absence of masker tones.

Experiment 3 was designed to assess the possible contribution of energetic masking in the ACI effect, particularly that portion of the effect that cannot be eliminated with stimulus features promoting analytic listening or with cuing. Results of this study are consistent with the conclusion that energetic masking is responsible for approximately 1–2 dB of masking for the stimuli used in Experiments 1 and 2. Tonal roved-level maskers were slightly more effective than matched bandpass noise maskers, suggesting that similarity-based informational masking may play some role in ACI. Additional conditions using a lower stimulus level and wider masker spacing resulted in essentially no evidence of energetic masking, but significant threshold elevation of 7.5 dB under roved-level, gated masker conditions. This effect persisted even when the masker tones were presented contralateral to the target tone. These results suggest that the ACI effect does not depend on energetic masking.

Taken together, the results presented here suggest that observers have difficulty ignoring roved level maskers under conditions favoring synthetic listening, such as when stimulus components share a common onset and coherent temporal envelope. Spiegel et al. (1981) interpreted analogous findings under conditions of masker frequency uncertainty as suggesting that observers attend to the profile of intensity as a function of frequency. This tendency to judge the intensity of a target relative to adjacent masker tones is quite beneficial under some listening conditions (Green, 1988). This beneficial effect can be reduced or eliminated with stimulus manipulations promoting analytic listening, such as introduction of envelope mismatches across frequency (Green and Nguyen, 1988) or asynchronous onset (Green and Dai, 1992). The ACI effects described in the current study may reflect the same processes, but under conditions where such processes are not advantageous.

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Figure 1.

Mean thresholds are plotted in units of $10\log(\Delta I/I)$ as a function of signal type, as indicated on the abscissa. Symbols specify the masker condition, as indicated in the legend. Error bars show one standard error of the mean across the six observers' data.

Figure 2. Mean thresholds in the presence of a pre-interval cue are plotted in units of $10\log(\Delta I/I)$ as a function of cue condition. Open symbols show mean thresholds for individual observers, and solid circles indicate the mean across observers.

Figure 3.

Mean thresholds are plotted in units of $10\log(\Delta I/I)$ as a function of masker level condition. Symbols specify masker gating, and error bars indicate one standard error of the mean across the eight observers' data. In all cases the standard target stimulus was a 60-dB tone at 1000 Hz. In the left panel the masker was a pair of tones at 500 and 2000 Hz, and in the right panel maskers were a pair of 400-Hz wide bands of noise centered on 400 and 2100 Hz.

Figure 4.

Mean thresholds are plotted in units of $10\log(\Delta I/I)$ as a function of masker level condition for the supplemental conditions using reduced masker level and wider masker spacing. Plotting conventions follow those of Figure 3. The standard target was a 50-dB SPL tone at 948.7 Hz, and the masker was a pair of tones at 300 and 3000 Hz.