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## **5aPP2. The Relative Contribution of Adaptation and Temporal Integration in Forward Masking**

**Naveen K. Nagaraj, Jeffrey J. DiGiovanni\* and Dennis T. Ries**

**\*Corresponding author's address: Communication Sciences and Disorders, Ohio University, W151a Grover Center, Athens, OH 45701, [digiovan@ohio.edu](mailto:digiovan@ohio.edu)**

The aim of this study was to demonstrate the relative contribution of adaptation and temporal integration on forward masking. In the first of two experiments, monaural gap-detection, thresholds were measured for broad-band noise markers having different levels on either side of the gap. In the second experiment, subjects matched the gap-duration within comparison noise markers to be perceptually equal to that of standard noise markers. Levels of standard noise markers and the first noise marker level of the comparison stimuli were set constant at 30 dB SL. Gap-duration matches were performed by decreasing the level of the second noise marker by 5 dB SL relative to the first noise marker in the comparison stimuli. The results indicated that gap-detection thresholds increased with a decrease in level of noise after the gap. Subjects required longer gaps in the gap-duration matching task with a decrease in level of the second noise marker. Both results are consistent with the notion that persistence of excitation is the dominate perceptual mechanism that results from forward masking.

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## Introduction

The process of forward masking has been studied extensively; however, the mechanism underlying forward masking is still being debated (see <sup>7</sup> for a brief review on this topic). Two main physiological mechanisms (persistence of excitation and adaptation) have been proposed to explain psychophysical forward masking. Researchers who support the persistence of excitation theory or temporal integration believe that forward masking is due to the persistence of neural activity in the auditory system even after the masker is turned off<sup>5, 4, 10, 12</sup>. On the other hand, adaptation in the auditory nerve following a masker, causing reduction in neural activity, has also been thought as a possible explanation of forward masking<sup>6, 13, 16, 17</sup>. Similarities between forward masking, observed in cochlear-implant users and normal-hearing listeners, suggest that forward masking occurs in the auditory system at a level higher than the auditory nerve<sup>15</sup>. Oxenham<sup>7</sup> investigated if forward masking can be explained using the temporal integration<sup>8, 11</sup> or adaptation model and concluded that both models provide similar results. Specifically, when either model is employed, it can reasonably account for forward masking data. To date, evidence accounting for the relative roles of these explanations is lacking.

Another similarly motivated study by Ewert et al.<sup>3</sup> compared forward masking simulation using the temporal-window model<sup>8</sup> and the adaptation-loop model<sup>2</sup>. They concluded that both models produced essentially similar results. In summary, it appears that forward masking data can be accounted for similarly by employing either persistence or an adaptation model, even though these constructs are conceptually very different. It is however difficult to separate the individual contribution of each mechanism using the forward masking detection task. It is possible that both mechanisms are contributing towards forward masking and we may need to use an alternative tool to identify the relative contribution of each.

The motivation for using gap-detection threshold and gap-duration matching task as a tool in this study is that it gives us an opportunity to measure how adaptation and/or persistence affects perception of gap in both tasks. Given that the results of forward masking detection data can be explained equally well using persistence or adaptation model<sup>3, 7</sup>, this study was designed to employ a method as an alternative to forward masking in order to better determine the dominant mechanism. We predicted that instead of using forward masking detection data, using a gap-duration matching task, a higher level task than simple signal detection, would provide us better insight about which mechanism dominates in the process of forward masking. In the duration-matching task, subjects were asked to adjust the gap within the symmetrical noise markers (levels of noise before and after the gap being the same) to be subjectively equal to that of the gap within the asymmetrical noise markers (i.e., the level of first noise marker being higher than that of the second noise marker). Data from a gap-detection experiment provides baseline information as to the minimum duration required to perceive a gap. These data can be used to establish minimum durations in a gap-duration matching experiment. Therefore, we hypothesized that if adaptation is the dominating mechanism, the subjects would require smaller gap in asymmetrical stimuli than symmetrical stimuli for it to be subjectively equal. This would occur as the response to the second noise marker would be adapted by the presence of the first, creating a perceptual gap, thereby reducing the gap required for matching. Alternatively, if persistence dominates, the second noise marker would be perceived as an extension of the first noise marker, increasing the gap in the asymmetrical stimuli for matching.

## Method

### Experiment 1: Gap Detection Threshold

#### *Subjects*

Four adult subjects with normal hearing (bilateral hearing thresholds of 15 dB HL or less across the octave frequencies between 250 to 8000 Hz) took part in this experiment. Informed consent was obtained and all subjects were compensated for their time.

#### *Stimuli*

Broad-band noise markers (low-pass filtered at 8000 Hz) were used for the gap-detection threshold measurements. Gap-detection thresholds were measured by keeping the level of the noise marker before the gap constant at 30 dB SL, and the level of noise marker after the gap was varied at 30, 25, 20 or 15 dB SL. The duration of the noise marker was set to approximately 400 ms. The duration of the noise marker in each observation interval was varied randomly over the range of  $\pm 40$  ms to control for an overall duration cue, and to eliminate the duration of the second noise pulse as a cue for gap-detection<sup>10</sup>.

All the stimuli were generated digitally at a sampling rate of 24,414 Hz, using the digital signal processor (Tucker-Davis Technologies, RP 2.1) interfaced with a computer (Dell Dimension, Dim 4550). Stimuli were then passed through a programmable attenuator (Tucker-Davis Technologies, PA5) and a headphone driver (Tucker-Davis Technologies, HB7) before being presented to the right ear of each listener via an insert earphone (ER-2A, Etymotic Research). The experiments were conducted in a double walled sound-treated booth (IAC Model 1204-A, Industrial Acoustics Corp.). Stimulus presentation and response collection were automated using custom written Matlab programs (The MathWorks, Inc).

#### *Procedure*

Threshold for the white noise of 400 ms was obtained using the two-interval, two-alternative forced choice (2I-2AFC) adaptive procedure with a step size of 1 dB. These thresholds were then used to set the desired sensation level in the gap-detection and gap-duration matching experiments. The 2I-2AFC adaptive method with the two-down one-up tracking procedure were used to estimate 70.7% correct gap-detection (Levitt, 1971). In one interval, noise markers were presented without a gap; in the other interval, noise markers were presented with a gap. The gap size was increased or decreased by a factor of 1.2 using a two-down, one-up rule. Visual feedback for the correct response was given after each observation interval. Threshold was calculated from the final 10 of 12 twelve reversals. Inter-stimulus interval was fixed at 400 ms. Thresholds measured from three blocks per conditions were geometrically averaged to determine the final threshold.

## Results of experiment 1:

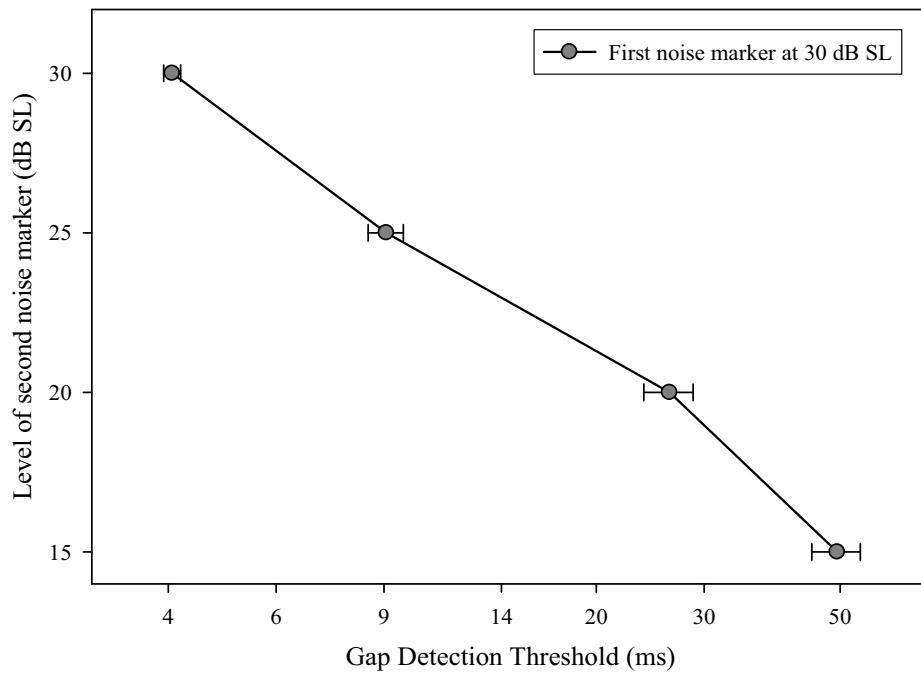


FIG.1. Mean gap-detection threshold measured as a function of level of second noise marker. Corresponding standard error bars are shown.

All four subjects showed a similar pattern of results for gap-detection thresholds. Therefore, only mean data were plotted as a function of log of duration (see Figure 1). The effect of level of second noise marker on gap-detection thresholds were analyzed using a repeated-measures ANOVA. There was a significant main effect of second noise marker level of gap-detection threshold [ $F(3, 48) = 44.39, p < 0.05$ ]. All possible *post hoc* comparisons were evaluated using Fisher's protected least significant difference (LSD) multiple comparisons test with an alpha level of 0.05. The gap-detection threshold for each level of second noise marker was statistically significant from the others, except for second noise level at 30 dB SL and 25 dB SL.

It is apparent from the figure that gap detection threshold increased with decrease in level of second noise marker in a log-linear fashion, which is consistent with literature<sup>10, 12</sup>. The aim of this experiment was to establish a minimum gap for the gap-duration matching task. The minimum duration of the gap in the standard stimuli was set based on the results of the gap-detection threshold experiment, such that the standard gaps in the gap-duration matching task were clearly perceivable. It was important for the subjects to perceive the gap within the standard stimuli in order to perform gap-duration matching task, hence the minimum gap within the standard stimuli were set at least larger than one standard deviation from the gap detection thresholds for each condition.

## Experiment 2: Gap Duration Matching

### *Subjects*

Twenty adult subjects with normal hearing (bilateral hearing thresholds of 15 dB HL or less across the octave frequencies between 250 to 8000 Hz) were selected for this experiment. Informed consent was obtained and all subjects were compensated for their time. All subjects were trained at least for an hour before collecting the data.

### *Stimuli*

Band-limited broad-band noise markers (low pass filtered at 8000 Hz) similar to those used in experiment 1 were used in a subjective, gap-duration matching task.

### *Procedure*

Method of adjustment procedure was used for the gap-duration matching task. In this task, subjects adjusted the gap between the variable stimuli to be subjectively equal to that of the standard stimuli. The duration of the gap in the standard stimuli was set based on the results of experiment 1, such that the standard gaps were clearly perceivable and larger than the subject's gap-detection threshold.

Gap-duration matches were measured in four conditions. In all the conditions, the levels of the standard noise markers and the first noise marker of the comparison stimuli were set constant at 30 dB SL. The first condition was the control condition, in which the level of the first and second comparison noise markers were 30 dB SL (hereafter called 30-30 dB SL) with matching performed for standard gaps of 10, 20, 30, 40, and 60 ms. The second condition was 30-25 dB SL with standard gaps of 15, 20, 25, 30, 40, and 60 ms. The third condition was 30-20 dB SL with standard gaps of 35, 40, 45, 50, and 60 ms. The final condition was 30-15 dB SL with standard gaps of 70 and 90 ms.

The duration of the noise markers in each observation interval were varied randomly over the range of  $\pm 40$  ms to eliminate the overall duration cue and the duration of the second noise pulse as a cue for gap detection. The duration between the standard and variable stimuli were kept constant at 400 ms. Subjects used the dial on a computer screen to adjust the gap-duration in the variable stimuli. They were instructed to bracket the gap of subjective equality by first positioning the slider such that the variable stimuli gap was clearly longer and shorter than the standard stimuli. Second, they were asked to position the dial such that the gap-duration in the standard and variable were perceived to be equal. Finally, once the matching was done, they pressed the button on the screen to store the response. Subjects were allowed to listen to the stimulus pair as many times as they desired. Each subject completed 20 matches for each condition. A total of 360 matches per subject were obtained. The starting gap-duration and the number of dial rotations before the hard stop were randomized for each adjustment sequence.

## Results of Experiment 2

Figure 2 shows the mean data for gap-duration matching task for all four conditions as a function of standard gap duration. The abscissa is the difference between matched gap within comparison noise markers and gap within standard noise markers. Positive values indicate that subjects required longer than standard gap for matching. In condition 1, where levels of noise

markers in both standard and comparison stimuli were constant, we expected that the subjective match would be equal to the standard gap. We noticed a bias in the results; that is for smaller standard gaps, subjects required a slightly larger gap than standard gap for subjective equality. This was probably due to bias in the presentation of the stimuli; we always presented comparison noise markers followed by standard noise markers which might have led to such a result.

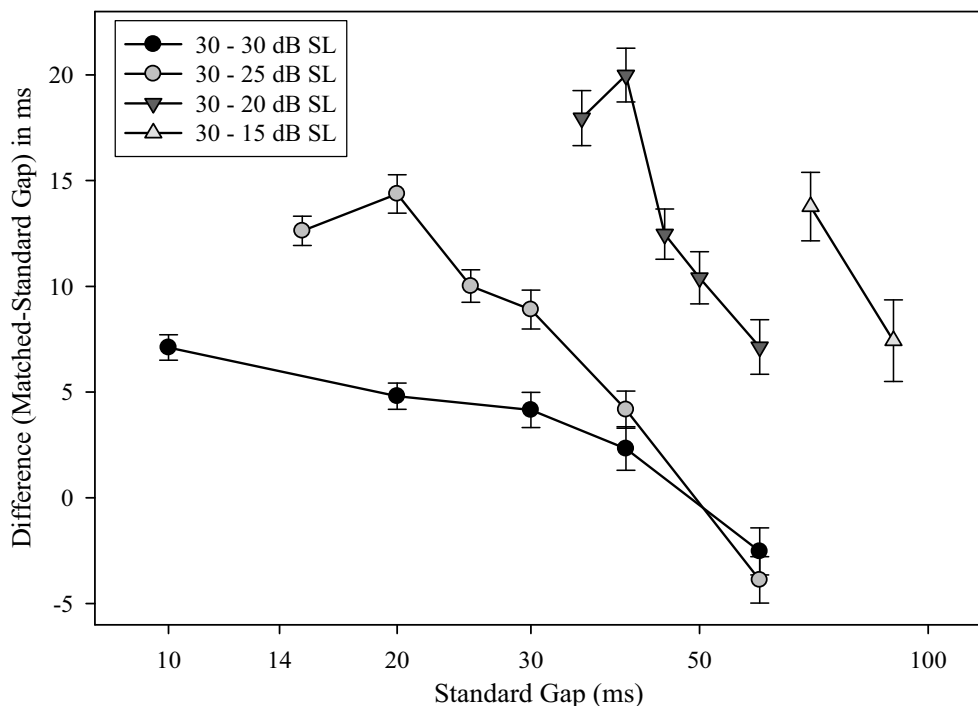


FIG. 2. Difference between matched gap in comparison and standard stimuli as a function of standard gap in gap-duration matching task. Corresponding mean and standard error bars are shown.

The difference between matched gaps and standard gaps were analyzed using repeated measure analysis of variance (ANOVA) with condition and standard gap under each condition as factors. There was a significant main effect of condition [ $F(3, 4032) = 13.73, p < 0.05$ ] and standard gap under each condition [ $F(17, 4032) = 11.30, p < 0.05$ ], with the Geisser-Greenhouse adjustment. As the omnibus ANOVA was significant, all possible *post hoc* comparisons were evaluated using Fisher's protected least significant difference (LSD) multiple comparisons test with an alpha level of 0.05. The results for each condition were statistically significant from the others. For standard gaps less than 30 ms, the control condition was different from the 30-25 dB SL condition. Standard gaps for condition 30-20 dB SL were different from (a) control, (b) 30-20 dB SL condition, and (c) 30-15 dB SL condition. Standard gaps in the 30-15 dB SL condition differed significantly from all other conditions.

## Discussion

The results of gap-detection and gap-duration matching experiments were consistent with one of our hypotheses. That is, if persistence is the dominating mechanism, subjects would require a longer gap in the matching procedure. Higher gap-detection thresholds with a decrease in level of the second noise marker and longer gaps in the gap-duration matching task were consistent with persistence of excitation theory. The results of this study, however, do not rule out the possibility that adaptation contributes to forward masking. The outcomes do support the notion that persistence of excitation is the dominate mechanism in forward masking.

Even though existing literature is not conclusive about where in the auditory system persistence manifests physiologically, our data are in agreement with the concept that auditory sensation invoked by sound continues after the stimulus offset. The concept of persistence has been well demonstrated by various psychophysical experiments and has been successfully used to model perceptual data of subjective duration<sup>4</sup>. Recently Schlauch et al.<sup>14</sup> studied subjective duration of ramped and damped stimuli and found that ramped sounds are perceived to be longer than damped sounds which support the findings of Fastl<sup>4</sup>. It is possible to explain simple detection of tones in forward masking experiments using adaptation in the auditory nerve<sup>13</sup> or adaptation at the level of inferior colliculus<sup>6</sup>. However, perception of subjective duration of signal<sup>4, 14</sup> and duration matching, as used in the present study, presumably are determined at a much higher level in the auditory system. These outcomes cannot easily be explained based on physiological measurements of adaptation.

## Conclusion

Based on the following findings:

1. gap-detection thresholds increase as the level of the second noise marker decrease, and
2. subjects require longer gaps in a gap-duration matching task as the level of second noise marker decreases

Overall, it appears that persistence of excitation is the dominate perceptual mechanism that results from forward masking.

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