Relative effects of increment and pedestal duration on the detection of intensity increments^{a)}

Daniel L. Valente,^{b)} Harisadhan Patra,^{c)} and Walt Jesteadt

Center for Hearing Research, Boys Town National Research Hospital, 555 North 30th Street, Omaha, Nebraska 68131

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The detection of a brief increment in the intensity of a longer duration pedestal is commonly used as a measure of intensity-resolution. Increment detection is known to improve with increasing duration of the increment and also with increasing duration of the pedestal, but the relative effects of these two parameters have not been explored in the same study. In several past studies of the effects of increment duration, pedestal duration was increased as increment duration increased. In the present study, increment and pedestal duration were independently manipulated. Increment-detection thresholds were determined for four subjects with normal-hearing using a 500- or 4000-Hz pedestal presented at 60 dB sound pressure level (SPL). Increment durations were 10, 20, 40, 80, 160, and 320 ms. Pedestal durations were 20, 40, 80, 160, and 320 ms. Each increment duration was combined with all pedestals of equal or greater duration. Multiple-regression analyses indicate that increment detection under these conditions is determined primarily by pedestal duration. Follow-up experiments ruled out effects of off-frequency listening or overshoot. The results suggest that effects of increment duration have been confounded by effects of pedestal duration in studies that co-varied increment and pedestal duration. Implications for models of temporal integration are discussed.

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I. INTRODUCTION

The detection of a brief increment in the intensity of a longer duration pedestal tone is commonly used as a measure of intensity-resolution and is known as increment detection. The purpose of this study was to compare increment-detection thresholds for conditions where the duration of the pedestal and increment were varied independently. It is well established that thresholds for detection of a brief increment in a continuous tone are lower than those obtained when the increment and the pedestal are equal in duration (Campbell and Lasky, 1967; Carlyon and Moore, 1986; Green, 1969; Green *et al.*, 1979; Turner *et al.*, 1989; Viemeister and Bacon, 1988). The threshold for detection of an increment in a continuous tone has been found to decrease with increasing duration of the increment (Dai *et al.*, 2001; Green *et al.*, 1979; Harris, 1963; Leshowitz and Raab, 1967; Moore and Peters, 1997), much as it does for detection of a tone in quiet (e.g., Plomp and Bouman 1959; Viemeister and Wakefield 1991; Watson and Gengel, 1969). Many later studies of increment detection have used gated pedestals,¹ where the standard tone or pedestal was shortened to the duration of the observation interval (e.g., Gallun and Hafter, 2006; Jesteadt *et al.*, 2009; Moore and Peters, 1997; Moore *et al.*, 1999; Oxenham, 1997, 1998). The use of gated pedestals has become more common with increased use of digital signal generation, where gating func-

tions are easily implemented, but creation of continuous tones is difficult. Several studies have examined the effect of increment duration using finite duration pedestals, but little attention has been paid to the effect of pedestal duration. The influence of these two parameters on increment-detection threshold has implications for models of increment detection and temporal integration.

Most models of increment detection assume that detection improves with increment duration for the same reasons that detection of a tone in quiet or in noise improves with duration, because the longer signal has more energy, results in an improved signal-to-noise ratio, or increases the number of multiple looks. An alternative class of models assumes that detection is based on detection of change at the increment onset (Bonnel and Hafter, 1998; Laming, 1986; Macmillan, 1971, 1973) on detection of energy splatter associated with rapid onset (Leshowitz and Wightman, 1971) or on detection of amplitude modulation (Dau *et al.*, 1997a,b; Gallun and Hafter, 2006; Oxenham, 1998). Detection threshold is predicted to be independent of increment duration in change-detection models or when off-frequency energy is used as a cue. Modulation models predict a range of rates of improvement in threshold with increasing duration but have typically focused on the duration of the increment while ignoring the duration of the pedestal.

Green *et al.* (1979) reported an improvement in increment detection as pedestal duration increased, extending to the longest pedestal duration of 1600 ms. Moore and Peters (1997) observed a small improvement when pedestals were increased from 30–40 ms to 410–420 ms. Moore *et al.* (1999) summarized the results of increment-duration effects observed in 11 studies, eight of which included data for conditions where the pedestal was longer than the increment (de Boer, 1986; Dai *et al.*, 2001; Green *et al.*, 1979; Harris,

^{a)}A portion of this work was presented at the 2010 Annual Midwinter Meeting of the Association of Research in Otolaryngology.

^{b)}Author to whom correspondence should be addressed. Electronic mail: daniel.valente@boystown.org

^{c)}Present address: Department of Audiology and Speech Pathology, Bloomsburg University, Bloomsburg, PA 17815.

1963; Leshowitz and Raab, 1967; Moore and Peters, 1997; Moore *et al.*, 1999; Oxenham, 1997). Additional data have been reported by Oxenham (1998), Gallun and Hafter (2006), Shepherd *et al.* (2008), and Jesteadt *et al.* (2009). Penner (1978), Formby *et al.* (1994), and Heinz and Formby (1999) have reported data for broadband noise. As Moore *et al.* (1999) noted, it is difficult to compare results across studies due to the number of experimental parameters that may have an effect on increment-detection thresholds. These include the frequency and level of the pedestal, pedestal and increment gating, and presence or absence of a background noise masker.

When comparing the effect of a tenfold increase in increment duration on increment-detection threshold where threshold is defined as the value of $10 \log (\Delta I/I)$ required for $d' = 1$, Moore *et al.* (1999) noted that the effect of increasing increment duration was more substantial as well as less varied at a lower test frequency (250 Hz) than a higher tested frequency (4000 Hz) and noted that there were differences in duration results obtained with gated and continuous pedestals. A 5–6 dB improvement per tenfold increase in duration has been reported in experiments using a 250-Hz test frequency (Moore *et al.*, 1999; Moore and Peters, 1997). Studies which used a continuous pedestal (Moore and Peters, 1997; Dai *et al.*, 2001) at 4000 Hz have reported a larger improvement in threshold as a function of increment duration (4–5 dB) than studies which used a gated pedestal (Moore and Peters, 1997; Oxenham, 1997; Dai *et al.* 2001) where the effect was more modest (2 dB or less).

In studies more recent than Moore's summary, Oxenham (1998) used a 6000 Hz, 500-ms pedestal and increments of 2, 7, 20, 80, and 300 ms and found threshold improvement of 2.7 dB per decade increase in increment duration (1.5 dB for the decade from 2 to 20 ms). Gallun and Hafter (2006) used a 477-Hz, 1000-ms pedestal and short-duration increments (20, 50, and 85 ms with 10-ms $\cos^2$ ramps) and found an improvement of 3.9 dB. Shepherd *et al.* (2008) used a 1000-Hz, 500-ms pedestal and increments of 10, 50, 100, and 200 ms, with 5-ms $\cos^2$ ramps, and found an improvement of 0.9 dB. Jesteadt *et al.* (2009) used a 4000-Hz, 370-ms pedestal and increments of 10, 20, 40, and 60 ms, with 5-ms $\cos^2$ ramps, and reported an improvement of approximately 5 dB per decade when the data were averaged across pedestal level. At the two highest levels, 40 and 80 dB sensation level (SL), however, the improvement was only 0.7 dB per decade. In general, the effects of increment duration are less at higher frequencies than lower frequencies and less when the pedestal is not much longer than the longest increment. The difference in results obtained with continuous and pedestals has also been observed for broadband noise stimuli, where Penner (1978) found 6.9 dB per decade using a continuous pedestal while Formby *et al.* (1994) and Heinz and Formby (1999) found 3.0 and 1.4 dB, respectively, using pedestals of 480 and 500 ms.

Despite the number of studies, the relative contributions of pedestal and increment duration to thresholds of increment detection are unclear. Studies by de Boer (1986), Moore and Peters (1997), and Moore *et al.* (1999) used pedestal durations that were tied to the increment durations. The other studies used a single pedestal duration per study.

To obtain a more complete picture of the relative effects of increment and pedestal duration on increment detection, thresholds for increment detection were obtained at a number of different combinations of increment and pedestal duration in three experiments where the increment was always in the temporal center of the pedestal. In a fourth experiment, the temporal position of a fixed-duration increment was varied to assess the possible influence of overshoot (Zwicker, 1965) in the results of the three prior experiments.

II. EXPERIMENT 1: EFFECTS OF PEDESTAL AND INCREMENT DURATION ON INCREMENT DETECTION AT 500 HZ

A. Subjects

Four normal-hearing, paid volunteers (one males, three females) aged 20–32 yr participated. All had previous experience in psychoacoustics tasks. Hearing had been screened at 0.5, 1, 2, and 4 kHz within the past year using a two-interval-forced-choice (2IFC) adaptive procedure and standard laboratory equipment. Thresholds were ≤ 15 dB sound pressure level (SPL) for all test frequencies bilaterally for all subjects. The appropriate informed consent procedures were approved by the Institutional Review Board (IRB) at the Boys Town National Research Hospital.

B. Apparatus

Stimuli were generated digitally in MATLAB at a sampling rate of 44.1 kHz and were presented to subjects via 24-bit digital-to-analog convertors (DAC) (CardDeluxe, Digital Audio Labs, Chanhassen, MN). A remote passive attenuator coupled the outputs of the DAC with (Sennhesier Electronic Corporation, Oly Lyme, CT) HD250 Linear II headphones. Stimuli were delivered to the left ear of the subject in a double-walled sound-attenuated booth. The same equipment was used in all experiments presented in this study.

C. Procedure

Adaptive thresholds were estimated using a 2IFC task in which one interval included an increment presented in phase with the pedestal. The level of the increment started well above threshold, decreased after two correct responses, and increased after one incorrect response to estimate the level required for 71% correct (Levitt, 1971). Step sizes of 4 dB were used until the fourth reversal, at which point a 2-dB step was used. The threshold for each block of trials was calculated from the average of the level of the reversal points after the fourth reversal. Responses were collected with a serial response box with a liquid crystal display (LCD) which instructed subjects of the warning interval, interval 1, interval 2, and answer interval, then provided feedback regarding the correct answer. The warning interval duration was 300 ms, followed by two 420-ms observation intervals separated by 500 ms. After the subject answered, the correct answer was displayed for 100 ms.

D. Stimuli and conditions

The pedestal was a 500-Hz tone presented at 60 dB SPL. The pedestal was 20, 40, 80, 160, or 320 ms with 5-ms

TABLE I. The combinations of pedestal and increment durations used in the study. The “*” symbol denotes conditions of intensity discrimination (equal duration pedestal and increment).

Increment duration (ms)	Pedestal duration (ms)				
	20	40	80	160	320
10	X	X	X	X	X
20	X*	X	X	X	X
40		X*	X	X	X
80			X*	X	X
160				X*	X
320					X*

$\cos^2$ ramps. The increment was 10, 20, 40, 80, 160, or 320 ms, also with 5-ms $\cos^2$ ramps. The pedestal and increment had a variable duration of silence directly before and after to make a complete duration of 420 ms. Pedestals and increments were presented at the temporal center of the complete observation interval. The complete set of pedestal durations was combined with all increment durations less than or equal to the pedestal duration. This created 15 increment-detection conditions, where the pedestal was longer than the increment and five intensity-discrimination conditions where the increment and pedestal were equal in duration (Table I). Eight 50-trial-blocks were completed for each of the 20 conditions in a counterbalanced order.

E. Results and discussion

Threshold increment levels were converted to ΔL [$10 \log(1 + \Delta I/I)$] and geometric mean values of ΔL were computed across replications and subjects. In an independent analysis, the 400 trials for each condition were pooled and fitted with psychometric functions (PFs) following procedures described by Dai (1995)² to estimate the parameters α and β in the equation

$$d' = \left(\frac{\Delta L}{\alpha} \right)^\beta. \quad (1)$$

The correlation between α , the value for ΔL required for $d' = 1$, and the mean value of ΔL required for 71% correct was 0.98. Only values of α , rather than the ΔL required for 71% correct will be presented. In addition, the PF slope, β , will be presented for some of the experiments. Figure 1 shows values of α for all combinations of increment and pedestal duration, plotted as function of those two variables. Because temporal integration data are often presented in units of $10 \log \Delta I/I$, those units are shown on the right axis. The filled symbols in the figure denote intensity-discrimination conditions. They are plotted at the same points in both panels because there is no distinction between pedestal and increment duration. Thresholds in these conditions improve (when recomputed in units of $10 \log \Delta I/I$) by 5.3 dB per tenfold increase in duration. The increment-detection conditions improve at about the same rate (5.1 dB per tenfold increase) when the data are plotted as a function of pedestal duration (panel B of Fig. 1), but the improvement is less pronounced

FIG. 1. Intensity-resolution data for a 500-Hz, 60-dB SPL pedestal (experiment 1). Filled symbols are for intensity-discrimination conditions with equal-duration increments and pedestals. When they are excluded from the analysis, the remaining increment-detection conditions (open symbols) show little effect of increment duration, but a strong effect of pedestal duration.

as a function of increment duration (panel A of Fig. 1). The independent contributions of pedestal and increment durations were estimated for the 15 increment-detection conditions using the multiple-regression equation

$$\text{Log}(\alpha) = b_0 + b_{\text{inc}} \cdot \text{Log}(\text{Inc}) + b_{\text{ped}} \cdot \text{Log}(\text{Ped}) + \varepsilon_i, \quad (2)$$

where in Eq. (2), α is the value of ΔL required for $d' = 1$, b_{inc} is the change in $\log(\alpha)$ as a function of increment duration, b_{ped} is the change in $\log(\alpha)$ as a function of pedestal duration, b_0 is the intercept, and ε_i is the error term of the prediction. The overall test of the model shows a good fit to the data ($F_{(2,12)} = 54.05$, $p < 0.001$). The effect of pedestal duration is highly significant in affecting the increment-detection threshold ($F_{(1,12)} = 76.85$, $p < 0.001$). The effect of increment duration was not, however, found to be significant ($F_{(1,12)} = 0.21$, $p = 0.65$). The results of this analysis show a 4.2 dB improvement in increment-detection threshold per tenfold increase in pedestal duration [when estimated values of $\alpha = \Delta L$ are recomputed in units of $10 \log(\Delta I/I)$] over and above the increase due to increment duration. The increment duration does not make a significant contribution to the increment-detection threshold over and above the pedestal duration. The five intensity-discrimination conditions were not included in this analysis as the difference in the task produces large differences in both the α and β values in the resulting PF as has been previously described by Green *et al.* (1979). There is, of course, no way to partial out the relative effects of pedestal and increment duration in these conditions. Moore and Peters (1997) reported an effect of stimulus duration on intensity-resolution thresholds but co-varied the increment and pedestal durations. They did not report the duration effect found in this experiment, perhaps because the number of conditions in their study was more limited and the conditions with equal duration (intensity discrimination) were included in their analyses.

Studies of the effects of increment duration on threshold have used single pedestal duration or have co-varied pedestal and increment duration. Studies of the effects of pedestal duration have generally compared thresholds obtained in intensity discrimination, when the pedestal duration is equal to

the increment duration, to those obtained in increment detection, when the pedestal is longer than the increment (e.g., Campbell and Lasky, 1967; Formby *et al.*, 1994; Green, 1969; Green *et al.*, 1979; Shepherd *et al.*, 2008; Turner *et al.*, 1989; Viemeister and Bacon, 1988). As noted in the Introduction, lower thresholds have been reported for increment detection in almost all cases. In most of these comparisons, a continuous pedestal was used in the increment-detection conditions. One study (Green *et al.*, 1979) contains an anecdotal report that thresholds in conditions where the pedestal is continuous are lower than those where the pedestal is as long as 1600 ms. Given these comparisons, the open symbols in the left panel of Fig. 1 would be expected to fall below the filled symbols. The conditions where they fail to do so are typically for increments half as long as the pedestal. These were the increment-detection conditions with the longest increments for any given pedestal duration. Duration ratios between 0.5 and 1 might represent a transition region between increment detection and intensity discrimination.

When comparing values of β , or slope of the PF, across conditions, results are also clearest when considered in terms of the relative durations of the increment and the pedestal. For each of the 20 conditions, Fig. 2 shows the slope or exponent of the PF on the ordinate, plotted with pedestal duration as the parameter. The abscissa shows the ratio of increment duration to pedestal duration. A multiple-regression model which predicts the β of the PF as a function of the ratio of the increment duration to the pedestal duration is significant ($F_{(1,18)} = 75.06$, $p < 0.001$). The β of the PF for increment-detection decreases as the ratio of increment to pedestal duration approaches 1 (conditions of intensity discrimination). Based on similar results, Shepherd *et al.* (2008) argued that increment detection became more like intensity discrimination as increment duration approached pedestal duration.

FIG. 2. PF slopes for 500-Hz intensity-resolution data (experiment 1). The slope is shallow for intensity-discrimination conditions (filled symbols) where the increment and pedestal are equal in duration. For increment-detection conditions (open symbols), the slope is determined by the ratio of the two durations.

An alternative interpretation of these data is that subjects show no effect of increment duration because they are listening off-frequency (Leshowitz and Wightman, 1971) to additional cues afforded by spectral splatter. To further test that hypothesis, the set of conditions was repeated with a new group of subjects using 4000-Hz pedestals and increments, where spectral splatter due to gating the stimuli would be minimized.

III. EXPERIMENT 2: EFFECTS OF PEDESTAL AND INCREMENT DURATION ON INCREMENT DETECTION AT 4000 Hz

A. Methods

The methods were identical to those used in experiment 1 except that the pedestal and increment were 4000-Hz tones. The 10-ms increment-duration conditions were excluded from the set of conditions run for this experiment, as they were highly variable at 500 Hz.

B. Subjects

A new set of four normal-hearing paid volunteers (one males, three females), aged 28–31 yr participated in experiment 2. All four had previous experience in psychoacoustics tasks, but none participated in experiment 1. Hearing had been screened at 0.5, 1, 2, and 4 kHz within the past year using a 2IFC adaptive procedure and standard laboratory equipment. Thresholds were ≤ 15 dB SPL for all test frequencies bilaterally for all subjects.

C. Results and discussion

The data were analyzed as in experiment 1. Figure 3 shows values of α for all combinations of increment and pedestal duration, plotted as function of those two variables. Intensity-discrimination thresholds (filled symbols in Fig. 3) improve by 2.8 dB per tenfold increase in duration. This is less than the effect observed in experiment 1, consistent with previous studies showing a smaller effect of increment and/or pedestal duration at higher frequencies (Carlyon and Moore, 1984; Dai *et al.*, 2001; Henning, 1970; Moore *et al.*, 1999; Moore and Peters, 1997). Thresholds in the increment-detection conditions also showed a smaller effect of

FIG. 3. Intensity-resolution data for a 4000-Hz, 60-dB SPL pedestal, in the format used for 500-Hz data in Fig. 1. The filled symbols are for intensity-discrimination conditions with equal-duration increments and pedestals. When they are excluded from the analysis, the remaining increment-detection conditions (open symbols) show little effect of increment duration. The effect of pedestal duration is reduced in magnitude at 4000 Hz compared to 500 Hz, but still significant.

duration, but the effect was again less pronounced as a function of increment duration (panel A of Fig. 3), as opposed to pedestal duration (panel B of Fig. 3).

A multiple-regression analysis was performed using the same predictors as described in experiment 1. The overall test of the model shows a good fit to the data ($F_{(2,7)} = 39.51$, $p < 0.01$). The effect of pedestal duration is highly significant in affecting the increment-detection threshold ($F_{(1,7)} = 42.12$, $p < 0.01$). Similar to the results of the 500-Hz conditions, the effect of increment duration was not found to be significant ($F_{(1,7)} = 4.08$, $p = 0.08$). The results of this analysis show a 1.8 dB improvement in increment-detection threshold per ten-fold increase in pedestal duration [when estimated values of $\alpha = \Delta L$ are recomputed in units of $10 \log (\Delta I/I)$ over and above the increase due to increment duration. Increment duration does not make a significant contribution to the increment-detection threshold over and above the pedestal duration.

It is problematic that thresholds are lower for intensity discrimination than for increment detection in the left panel of Fig. 3. As noted in the discussion of experiment 1, the literature would predict lower thresholds in increment-detection conditions. A comparison of Figs. 1 and 3 suggests that this group of subjects had thresholds that were similar to the first group for increment detection, but that were lower for intensity discrimination. We cannot account for this difference.

Figure 4 shows the slope or exponent of the PF, for each of the 15 tested conditions on the ordinate, plotted with pedestal duration as the parameter. The abscissa shows the ratio of increment duration to pedestal duration. A linear regression model which predicts the β of the PF as a function of the ratio of the increment duration to the pedestal duration is significant ($F_{(1,13)} = 42.27$, $p < 0.001$). The slope of PF is the steepest in increment-detection conditions where the pedestal duration is long compared to the increment duration. Similar to the results reported in experiment 1, the slope of the PF

for increment detection decreases as the ratio of increment to pedestal duration approaches 1. Unlike experiment 1, values for β in the intensity-discrimination conditions are variable and have a geometric mean of approximately 1, in agreement with Buus and Florentine (1991).

The purpose of experiment 2 was to test the hypothesis that the lack of an independent effect of increment duration was due to the use of spectral splatter. Although the results at 4000 Hz, where spectral splatter associated with 5-ms $\cos^2$ ramps is assumed to be well within the critical band centered on the signal frequency, replicated those obtained at 500 Hz, the smaller size of the duration effects makes the results more difficult to interpret. An alternative test of the hypothesis would be to hold the signal frequency constant at 500 Hz and increase the ramp duration from 5 to 10 ms, the value used by Gallun and Hafter (2006).³ That test was conducted in experiment 3.

IV. EXPERIMENT 3: EFFECTS OF PEDESTAL AND INCREMENT DURATION ON INCREMENT DETECTION AT 500 Hz, USING 10-ms RAMPS

A. Methods

The methods were identical to those used in experiment 1 except that the pedestal and increment stimuli were created using 10-ms $\cos^2$ ramps. The 10-ms increment duration conditions were excluded due to the increased ramp duration. Conditions with equal duration pedestal and increment (intensity-discrimination) were excluded because the goal was to assess the effect of the increased ramp duration in increment-detection conditions. The maximum pedestal duration was extended to 640 ms.

B. Subjects

The three subjects who participated in experiment 3 had also participated in experiment 2. This made it possible to verify that the effect of pedestal duration observed in experiment 1 could be repeated in a different set of subjects and that the difference in results between experiments 1 and 2 was due to the test frequency (as summarized by Moore *et al.* 1999) and not to spectral cues available at the lower frequency or to the use of different subjects.

C. Results and discussion

The data were analyzed as in experiment 1. Figure 5 shows values of α for all combinations of increment and pedestal duration, plotted as function of pedestal duration with increment duration as the parameter. Compared to the results of experiments 1 and 2, there is a limited difference between increment-detection thresholds as a function of increment duration, and an even stronger effect of pedestal duration on the increment-detection threshold. The overall test of the model described by Eq. (2) shows a good fit to the data ($F_{(2,12)} = 38.95$, $p < 0.001$). The effect of pedestal duration is highly significant in predicting the increment-detection threshold ($F_{(1,12)} = 52.56$, $p < 0.001$). Similar to the results of the 4000-Hz conditions with 5-ms ramps for this set of subjects, the effect of increment duration was not significant

FIG. 4. PF slopes for 4000-Hz intensity-resolution data (experiment 2). The slope is shallow for intensity-discrimination conditions (filled symbols) where the increment and pedestal are equal in duration. For increment-detection conditions (open symbols), the slope is determined by the ratio of the two durations.

FIG. 5. Intensity-resolution data for a 4000-Hz, 60-dB SPL pedestal where stimuli were created using 10-ms $\cos^2$ ramps (experiment 3). These data show a strong effect of pedestal duration and limited effect of increment duration consistent with the findings presented in experiment 1.

($F_{(1,12)} = 0.53$, $p = 0.48$). The results of this analysis show a 3.7 dB improvement in increment-detection threshold per tenfold increase in pedestal duration over and above the increase due to increment duration. Increment duration does not make a significant contribution to the increment-detection threshold over and above pedestal duration.

The pattern of results in experiment 3 with a different set of subjects mirrors those for experiment 1. Extending the ramp durations of the stimuli to 10-ms reduced the likelihood that off-frequency listening contributed to the lack of effect of increment duration and resulted in increments with properties similar to those used by Gallun and Hafter (2006). The appearance of an effect of increment duration when the pedestal duration was increased to 640 ms is consistent with the observation of increment-duration effects in conditions with continuous pedestals or long-duration gated pedestals. Gallun and Hafter found a strong effect of increment duration using a 1000-ms pedestal.

An alternative explanation for the strong effect of pedestal duration for any given increment duration is that the increase in pedestal duration increases the interval from the onset of the pedestal to the onset of the increment. Therefore, it is possible that overshoot (Zwicker, 1965; Zwicker and Fastl, 1972) could have contributed to the results of pedestal duration reported in experiments 1–3. To test this hypothesis, increment-detection thresholds were obtained for conditions where the increment and pedestal duration were fixed and the temporal position of the increment was varied.

V. EXPERIMENT 4: EFFECTS OF VARYING THE TEMPORAL POSITION OF THE INCREMENT

A. Methods

The methods were identical to those used in experiments 1–3. The pedestal was a 4000-Hz tone, with duration fixed at 320 ms. The increment duration was 20 ms, and both stimuli were created using 10-ms $\cos^2$ ramps. The delay between pedestal onset and increment onset was either 10, 30, 70, or 150 ms.

FIG. 6. Intensity-resolution data for a 500-Hz, 60-dB SPL 320 ms pedestal and 20 ms increment with varying offset created using 10-ms $\cos^2$ ramps (experiment 4). These data show no increase in increment-detection threshold as a function of offset indicating that overshoot was not a strong influence in threshold. The error bars represent ± 1 SE of the mean of three subjects.

The longest delay corresponded to an increment in the temporal center of the pedestal. If overshoot contributed to the effect of pedestal duration observed in experiments 1–3, thresholds would be expected to decrease with increasing delay.

B. Subjects

The same three subjects that participated in experiment 3 participated in experiment 4.

C. Results and discussion

Figure 6 shows values of α as a function of the delay between pedestal onset and increment onset. A linear regression model which predicts that threshold is influenced by the delay was not found to be statistically significant ($F_{(1,2)} = 7.01$, $p = 0.12$). Because overshoot has been shown in previous work to be most effective for detection of tones in noise and to be influenced by the presence of noise in a frequency region above the tone (McFadden, 1989; Schmidt and Zwicker, 1991; Bacon and Smith, 1991), the lack of an overshoot effect is not surprising.

VI. GENERAL DISCUSSION

Results of the four experiments indicate that: (1) pedestal duration is an important parameter in increment-detection tasks that employ relatively brief (< 1 s) pedestals; (2) the effects of pedestal duration on intensity-resolution are greater at lower frequencies; and (3) PF slopes are better described by a continuous function than by discrete categories of “steep” for increment detection and “shallow” for intensity discrimination. These conclusions have strong implications for models of increment detection.

The analyses of results from the first three experiments show that thresholds in increment-detection tasks are strongly influenced by the duration of the pedestal and are

TABLE II. Change in increment-detection threshold in units of $10 \log (\Delta I/I)$ as a function of increment duration, for studies in the literature. Data for [Dai et al. \(2001\)](#) are averaged across frequency as reported in their study. Pedestal level is given in decibels SPL and for noise studies in decibels SPL per hertz. Data for [Jesteadt et al. \(2009\)](#) and [Harris \(1963\)](#) have been transformed from decibels HL to decibels SPL for this summary. *NS (non-significant).

Study	Inc. duration (ms)	Ped. duration (ms)	Pedestal freq	Pedestal level	Change dB/decade
Present (Exp 1)	10–160	20–320	500	60	NS*
Present (Exp 2)	20–160	40–320	4000	60	NS*
Jesteadt et al. (2009)	10–60	370	4000	47.5, 87.5	–0.7
Oxenham (1997)	4–202	500	4000	55	–1.5
Oxenham (1998)	2–300	500	6000	40	–2.7
Shepherd et al. (2008)	2–200	500	1000	70	–0.9
Gallun and Hafter (2006)	20–85	1000	477	60	–3.9
Formby et al. (1994)	10–300	480	Noise	53	–3.0
Heinz and Formby (1999)	30–320	500	Noise	40	–1.4
Dai et al. (2001)	10–300	Continuous	250, 1 K, 4 K	65	–3.2
Green et al. (1979)	50–800	Continuous	500	25–85	–3
	10–100	Continuous	1000	35–75	–6
Harris (1963)	20–2000	Continuous	1000	12.5–87.5	–4.1
Leshowitz and Raab (1967)	10–500	Continuous	1000	51	–7
Moore and Peters (1997)	10–200	Continuous	250	70	–6
	10–200	Continuous	1000	70	–3.2
	10–200	Continuous	4000	70	–5.3
Penner (1978)	1–100	Continuous	Noise	17	–6.9

not influenced by the duration of the increment. This conclusion runs counter to all previous summaries of the increment-detection literature and all models of temporal integration and therefore requires additional consideration. The use of relatively brief pedestals may have played a role in this unusual result. The longest pedestal in the first two experiments was 320 ms and when the range was extended to 640 ms in the third experiment, an effect of increment duration was apparent. Table II provides a summary of pedestal durations used in increment-detection conditions in the studies reviewed in the introduction. Studies that used only pedestals in which pedestal duration varied systematically with increment duration (e.g., de Boer, 1986; [Moore et al., 1999](#)) have been excluded because the effects of increment and pedestal duration cannot be separated in those conditions. Studies with gated pedestals have found an average decrease in $10 \log (\Delta I/I)$ of 2.0 dB per tenfold increase in increment duration. The largest effect, 3.9 dB/decade, was observed by [Gallun and Hafter \(2006\)](#), who used the longest pedestal duration. Studies that used continuous pedestals have found an average decrease of 5.0 dB per tenfold increase in increment duration. Thresholds at any given increment duration are generally lower when pedestals are continuous rather than gated, even when the gated pedestal is longer than the increment (e.g., [Green et al., 1979](#)). Greater temporal integration may be observed in studies with continuous pedestals because thresholds in increment-detection studies with fixed-duration pedestals cease to decrease and may begin to increase as the increment duration approaches the pedestal duration (e.g., [Heinz and Formby, 1999](#)).

Of the studies summarized in Table II, only [Harris \(1963\)](#), [Green et al. \(1979\)](#), and [Jesteadt et al. \(2009\)](#) have reported data at different pedestal levels. [Green et al. \(1979\)](#)

did not report an increment-duration by pedestal-level interaction, but there is some indication of a larger effect of increment duration at low levels. There are large interactions in the data reported by [Harris \(1963, his Fig. 7\)](#) and [Jesteadt et al. \(2009, their Fig. 6\)](#). [Jesteadt et al.](#) found the interaction to be statistically significant, but reported a decrease in $10 \log (\Delta I/I)$ of 5.1 dB per tenfold increase in increment duration based on data averaged across all pedestal levels. At the two highest levels, 40 and 80 dB SL, the decrease was only 0.74 dB per decade. That value is shown in Table II.

The results of the regression analyses were also influenced by the exclusion of the intensity-discrimination conditions where the pedestal and increment were equal in duration. These conditions clearly show a strong effect of duration, but it is impossible to assign the effect to one of the two components. These conditions could also be excluded on the grounds that decision processes are different in intensity discrimination and increment detection ([Gallun and Hafter, 2006](#); [Heinz and Formby, 1999](#); [Laming, 1986](#); [Viemeister and Bacon, 1988](#); [Turner et al., 1989](#)). In any effort to include all conditions in the same framework, the pattern of results in Figs. 2 and 4 would lead to the conclusion that the effect of duration in the intensity-discrimination conditions is due to the pedestal rather than the increment. These results raise an interesting question about comparisons of thresholds for increment detection and intensity discrimination (e.g., [Viemeister and Bacon, 1988](#); [Turner et al., 1989](#)). The standard approach is to hold increment-duration constant and increase the duration of the pedestal in the increment-detection conditions so that the comparison is made across conditions where the signal energy is constant. The pattern of results in Figs. 2 and 4, however, would suggest an alternative approach where the intensity-discrimination conditions are run with longer

increment and pedestal durations and the increment duration is shortened to create an equivalent increment-detection condition. Implications of the threshold data for models of increment detection are discussed below.

The pattern of PF slopes also has implications for models of increment detection. It is noteworthy that the slopes are not an orderly function of the duration of either the increment or the pedestal alone, but of the ratio of the two durations. [Shepherd et al. \(2008\)](#) obtained PF slopes for a range of increment durations using a 500 ms pedestal and found a rapid decrease in slope as the increment duration increased from 10 to 200 ms. There was little change between their slopes for 200- and 500-ms increments. The duration ratios in Figs. 3 and 5 normalize for differences in pedestal duration, so their data for a 200-ms increment would represent a ratio of 0.4. Our results are similar to theirs, but show a marked difference between slopes for duration ratios of 0.5 and 1.

The specific values of the slopes are also of interest. Variations on Eq. (1) have been fitted to many sets of intensity-resolution data in an effort to identify the physical quantity, shown as ΔL in Eq. (1), that would allow all PFs to be fitted with a slope of 1 ([Buus and Florentine, 1991](#); [Moore et al., 1999](#); [Shepherd and Hautus, 2007](#)). Success in that effort would reduce PF fits to a single parameter and would identify a physical measure that was linear with d' . Unfortunately, the various exercises in curve fitting have failed to reach a consensus on the best measure. [Buus and Florentine \(1991\)](#) made a strong case for ΔL as the best measure and convinced many authors that it was appropriate to plot values of ΔL on a log scale, as in Figs. 1, 3, and 5. Using a similar approach, [Shepherd and Hautus \(2007\)](#) found that $\Delta p/p$ provided a better fit. For increment detection, [Moore et al. \(1999\)](#) found $\Delta I/I$ to have the best properties. We have opted to use ΔL in the analyses presented here, but agree with [Jeffress \(1975\)](#) that the best measure would be one that reflected the underlying processes, not physical units. The PF slopes for intensity discrimination in Fig. 2 (i.e., a duration ratio of 1) are less than the slope of 1 found by [Buus and Florentine \(1991\)](#), but those in Fig. 4 have a mean of about 1, with greater variability around that mean.

The lack of a clear effect of increment duration on threshold in these conditions provides additional evidence against energy detection as a model for increment detection. Although there are numerous other arguments against energy detection (e.g., [Formby et al., 1994](#); [Jesteadt et al., 2005](#)), the model continues to be applied in the literature whenever increment durations are equated in increment-detection and intensity-discrimination tasks. As noted above, it may be worth considering additional control conditions equated for pedestal duration rather than increment duration.

The importance of pedestal duration in determining both the increment-detection threshold and the PF slope presents problems for change detector models of the type proposed by [Laming \(1986\)](#) or older accounts based on off-frequency listening ([Leshowitz and Wightman, 1971](#)). More recent models based on use of a modulation filter bank (MFB) or template matching (e.g., [Dau et al., 1997a,b](#); [Moore et al., 1999](#)) have features in common with change detectors and may be better equipped to account for a more complex pattern of duration effects. The MFB model that has been used to account for

increment-detection data obtained with longer duration pedestals ([Gallun and Hafter, 2006](#)) will not account for the current results because it uses an analysis window centered on the increment and is not sensitive to changes in pedestal duration. A modification of the Gallun and Hafter model proposed by [Patra et al. \(2009\)](#) holds greater promise because it uses the pedestal duration to establish the analysis window. A longer window would result in increased resolution, with the potential to account for the observed threshold reduction. The model assumes use of a combination of level or energy cues and modulation cues, allowing it to predict an effect of increment duration in conditions where long-duration pedestals result in relatively constant modulation cues. Because changes in increment level contribute to both level and modulation cues in increment-detection conditions, the model predicts steeper PFs in increment detection. The model will be described in greater detail in a later paper.

Given that the effect of increment duration on increment-detection thresholds nearly reached significance in experiment 2 ($p = 0.08$) and that intensity-discrimination thresholds were lower than those for increment detection in some conditions, these conditions should be repeated in a larger number of subjects. In addition to increasing sample size, longer increment and pedestal durations should be used in order to more completely compare results with those of previous literature that have reported a marked effect of increment duration when using longer duration pedestals (> 1 s). Use of increment durations that were more than half the pedestal duration but less than the full pedestal duration might provide a more complete description of the transition from increment detection to intensity discrimination. Finally, it would be of interest to collect data at a greater number of pedestal levels to explore the impact of overall level on the results presented in the current study.

VII. CONCLUSIONS

- (1) The duration of the pedestal in an increment-detection experiment is an important factor in determining threshold.
- (2) Previous studies that varied pedestal duration with increment duration may have overestimated the effect of increment duration.
- (3) The effect of pedestal duration is more pronounced at lower frequencies (500 Hz) as opposed to higher frequencies (4000 Hz) for increment-detection conditions which used a gated pedestal. This is consistent with duration effects summarized by [Moore et al. \(1999\)](#).
- (4) Studies of PF slopes report steeper slopes for increment detection than for intensity discrimination. Figures 2 and 4 (see also [Shepherd et al., 2008](#)) show that the duration of the increment relative to the pedestal is an important factor.
- (5) The pattern of results demonstrated in these experiments cannot be accounted for by off-frequency listening, overshoot or standard models of temporal integration.
- (6) The pattern of results provides support for a model of intensity-resolution proposed by [Patra et al. \(2009\)](#) that is based on both level and modulation cues.

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¹The use of the term “gated” has been used in other contexts to refer to conditions where the signal and masker onsets are simultaneous. We use it here to distinguish pedestals that have onsets and offsets in each observation interval from pedestals that are continuous for an entire block of trials. The special case of gated pedestals that have onsets and offsets simultaneous with the increment is referred to here as intensity discrimination.

²An increase to a ramp duration greater than 10 ms would have been a stronger test but would have reduced the available range of increment durations. Use of 10-ms ramps was viewed as an adequate test because Gallun and Hafter (2006) observed a significant effect of increment duration using low-frequency stimuli with 10-ms ramps, suggesting that off-frequency listening was not a major factor under these conditions.

³Briefly, trials were sorted by increment level and the percent correct at levels with 30 or more trials were compared to the percent correct predicted by a given pair of values of α and β using Eq. (1). Values of α and β that minimized the squared differences between observed and predicted percents correct, weighted by the binomial variance of the predicted percents correct, were determined though an iterative procedure. Complete details are given by Dai (1995).

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