Interval patterning and auditory gap detection¹

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Pattern effects associated with the perception of the temporal microstructure of auditory signals were examined. Temporal changes, or gaps, were introduced into auditory interval patterns produced by a sequence of pulses. Discrimination thresholds for positive, and for negative, gaps were obtained as a function of the surrounding pattern of intervals. Gap thresholds increase with the slope of the surrounding interval pattern. Gap thresholds are smaller when the gap interval represents an extension, rather than a reversal, of the surrounding pattern. The results are in agreement with Heise and Miller's thresholds of tonal isolation from repeated melodies, and with Mangelsdorf's visual extrapolation thresholds of point-of-collision. The agreement of results from diverse test situations suggests a non-specific, general patterning effect upon discontinuity thresholds.

The effect of the "shape" of an auditory melodic pattern has previously been examined by Heise and Miller (1951). They played a repeated sequence of 11 tones to listeners who adjusted the frequency of the sixth tone until it appeared "isolated" from the rest of the sequence. They found that the threshold for isolation of the variable tone was determined by the shape of the pattern of tones surrounding the variable tone (on a frequency vs time plot), and by the slope of the surrounding pattern of tones.

In the Heise and Miller study, the duration of each tone of the melodic pattern was 1/8 sec in duration. Their listeners heard a sequence of individual notes which alternately increased and decreased in pitch. The present study examines the role of auditory interval patterns in terms of their temporal microstructure, rather than in terms of individually perceived elements of the sequence. Specifically, temporal patterning effects in the microsecond (μ sec) region were introduced between successive pulses of auditory pulse trains. The task of the listeners was to detect the presence of a temporal gap (Uttal & Krissoff, 1966) in the pattern of interpulse intervals. The gap was manifested to the listener in terms of the relative roughness of a short buzz tone, rather than in terms of individually perceived elements.

GENERAL APPROACH

Pulse trains were constructed by a PDP-8 computer. The parameters of the pulse trains are described in Table 1 and are schematically illustrated in Fig. 1.

Two forms of representation are illustrated in Fig. 1 for each of four interval patterns. The left-hand diagram is a two-dimensional plot of the interpulse intervals against the ordinal scale of successive intervals. The reference signals, without a gap, are shown as open circles. For example, the circles for Pattern a represent a pattern in which successive intervals uniformly increase at 10 msec/interval, i.e., $DIPI_1 = DIPI_2 = DIPI_3 = 10$ msec. For the stated parameters, Pattern a is a train of seven interpulse intervals: 70, 80, 90, 100, 110, 120, and 130 msec for the

reference signal. With the addition of a positive gap of 20 msec in the middle position, signalled by 1/, the seven intervals become: 70, 80, 90, 120, 110, 120, 130 msec. With the addition of a negative gap of 20 msec, signalled by 2/, the seven intervals become 70, 80, 90, 80, 110, 120, 130 msec.

The corresponding one-dimensional time representation is given in the right-hand diagrams. Within each block, the middle line indicates the time diagram of the reference signal; the top line, the reference signal with an added positive gap; and, the bottom line, the signal with an added negative gap. Each mark represents the occurrence of a pulse. For Pattern a, pulses occur at: 0, 70, 150, 240, 340, 450, 570, and 700 msec. For the same reference signal with a positive gap of 20 msec, pulses occur at 0, 70, 150, 240, 360, 470, 590, and 720 msec. For the same reference signal with a negative gap of 20 msec, pulses occur at: 0, 70, 150, 240, 320, 430, 550, and 680 msec.

For interval Patterns a and b of Fig. 1, $DIPI_1 = DIPI_2 = \pm DIPI_3$. For interval Patterns c and d of Fig. 1, $DIPI_1 = \pm DIPI_2 = 0$. In all tests, $DIPI_1 = \pm DIPI_3$, unless specified otherwise.

Fig. 1. Schematic representation of gap thresholds within interval patterns. The left side presents a two-dimensional representation in which the duration of successive interpulse intervals is plotted relative to the temporal ordering of the intervals. The right side represents the equivalent time diagram of successive pulses for the positive gap (top line within each triplet), for the reference signal without a gap (middle line), and for a negative gap (bottom line within each triplet).

Table 1
Parameters of Auditory Pulse Trains for Glissando Asynchrony Tests

n_1	number of interpulse intervals in the pre-gap region.
$DIPI_1$	difference in duration between successive interpulse intervals in the pre-gap region.
n_2	number of interpulse intervals in the gap region.
$DIPI_2$	difference between successive interpulse intervals in the gap region.
n_3	number of interpulse intervals after the gap region.
$DIPI_3$	difference between successive interpulse intervals in the post-gap region.
IPI_c	center interpulse interval of the gap region.
P	number of successive presentations of the entire sequence of n_1, n_2, n_3 intervals.

Four pulse trains were presented to the listener: three reference trains and one train with an added gap. The task of the listener was to identify whether the first, the second, the third, or the fourth pulse train differed from the other three. The program varied the magnitude of the gap by an adaptive stimulus programming procedure—the PEST procedure described by Taylor and Creelman, 1967—so that PEST converged upon 50% correct response within a four-interval forced-choice (4IFC) test.

The pulses were brief (10 μ sec) before being smoothed by the earphones (Koss PRO-4), and the pulse trains were presented at a comfortable binaural listening level. Most of the Ss were advanced music students who had extensive previous experience in auditory gap tests (Pollack, 1967b, 1967a).

RESULTS

The insert in Fig. 2 represents four interval patterns into which positive and negative gaps were introduced. With both positive and negative gaps, these four patterns give eight experimental configurations. The abscissa of Fig. 2 is the slope of the reference signal. The ordinate is the magnitude of the gap threshold.

Three results relate to the configuration of the patterns.

(1) For all pattern shapes, gap thresholds increase with the steepness of slope of the reference signal.

(2) Except at the steepest slope, there is a consistent rank-ordering, i.e., Conditions 3 and 8 yield the lowest thresholds, Conditions 4 and 7 the highest thresholds, and the other conditions intermediate thresholds.

(3) Among the intermediate conditions with a one-directional interval change (Conditions 1, 2, 5, and 6), threshold gaps in the same direction as the reference slope tend to be greater than gaps in the opposite direction. Specifically, Condition 1 with a positive gap gives larger gap thresholds than Condition 2 among the patterns with a positive slope (6 out of 7 DIPIs). And, Condition 6

Fig. 2. Gap increment and gap decrement thresholds as a function of the slope of the pattern of intervals surrounding the gap. The numerals represent the eight patterns illustrated at the upper left. Pattern shapes yielding the largest effects are connected. At 0 DIPI, the odd pattern is associated with a positive gap, the even pattern with a negative gap. Each point in Figs. 2, 6, 7, and 8 represents 1-4 thresholds (median: 2) by each of 10 or 11 listeners.

Fig. 3. Gap increment and decrement thresholds as a function of the shape of the pattern. The parameter is the number of intervals in the gap region. The inset shows the shape of the interval pattern on which positive gaps and negative gaps were introduced. Positive gaps are indicated by odd numbers; negative gaps by even numbers. Each point in Figs. 3, 5, and 9 represents 2 or 3 (median: 2.5) thresholds by each of six listeners.

with a negative gap gives larger gap thresholds than Condition 5 (5 out of 7 DIPIs) among the patterns with negative slope.

Figure 3 examines the effect of pattern shape for patterns with a flat-topped gap region, i.e., $DIPI_2 = 0$. For a single gap interval, $n_2 = 1$, the rank-ordering is the same in Fig. 3 as in Fig. 2. Specifically, the gap threshold is highest for Patterns 4 and 7, lowest for Patterns 3 and 8, and intermediate for the other conditions. As the number of n_2 , or gap, intervals is increased, gap detection thresholds become lower, and the effect of pattern shape becomes smaller. With a large number of intervals in the gap region, the gap threshold is independent of its surrounding intervals. Here the task apparently becomes more of an interval discrimination task than a comparison between the gap interval and its immediate neighbors.

DISCUSSION

The effects of patterns of auditory intervals will be discussed in terms of: (1) their equivalent visual representation, (2) an arithmetic analysis of the intervals in the gap region, (3) comparison with the auditory melodic patterns of Heise and Miller (1951), and (4) comparison with visual dot patterns in a collision prediction task of Mangelsdorf (1955).

Consider first the auditory interval patterns in terms of their equivalent visual representation. Gap thresholds are lower for a pattern extension (Patterns 3 and 8) than for a pattern inversion (Patterns 4 and 7). Is the Gestalt concept of "goodness" of pattern applicable in this case?

Consider next an arithmetic analysis of the intervals of the gap region. We first assume that gap detectability is related to the size of the differences in the gap region. A positive gap introduces a larger arithmetic difference upon an inverted-V pattern than a negative gap of the same magnitude. Specifically, gap of +1 msec added to the pattern of 3, 5, and 3 msec, results in the sequence 3, 6, 3 msec, whereas a gap of -1 msec results in the sequence 3, 4, 3 msec. The reverse situation holds for V patterns. A gap of -1 msec added to the pattern of 5, 3, and 5 msec results in the sequence 5, 2, 5 msec, whereas a gap of +1 msec results in the sequence 5, 4, 5 msec. Therefore, with the stated assumption, positive gaps should be more readily detected in inverted-V sequences (Pattern 3) than negative gaps (Pattern 4). And, negative gaps should be more

Fig. 4. Relative gap increment (+) and decrement (-) thresholds for 3-segment interval patterns. The conditions associated with the upper two lines and with the lower two lines are indicated at the left. Each entry represents 2-4 thresholds (median: 2) by each of nine listeners. The superscript numbers indicate the number of listeners, out of nine, who required a larger gap threshold for the associated condition than for its paired condition.

readily detected in V sequences (Pattern 8) than positive gaps (Pattern 7). These predictions are consistent with the results of Figs. 2 and 3.

The arithmetical analysis can be extended to patterns with a uniform slope if we further assume that post-gap differences are more significant for discrimination than pre-gap differences. A positive gap introduces a larger arithmetic post-gap difference upon descending patterns than a negative gap of the same magnitude. Specifically, a gap of +1 msec added to the pattern 7, 5, and 3 msec results in the sequence 7, 6, 3 msec, whereas a gap of -1 msec results in the sequence 7, 4, 3 msec. The reverse situation holds for ascending patterns. A gap of -1 msec added to the pattern 3, 5, and 7 msec results in the sequence 3, 4, 7 msec, whereas a gap of +1 msec results in the sequence 3, 6, 7 msec. Therefore, with the stated assumptions, positive gaps should be more readily detected in descending sequences (Pattern 5) than negative gaps (Pattern 6). Negative gaps should be more readily detected in ascending sequences (Pattern 2) than positive gaps (Pattern 1). These predictions are consistent with Fig. 2.

Consider next a comparison with the melodic patterns of Heise and Miller (1951). They employed tonal segments of 1/8 sec duration at 2050 Hz for initially ascending segments and at 1454 Hz for initially descending segments. They were thus dealing with

critical segments of 256 and 182 periods. The number of gap intervals in the present study was substantially smaller. Nevertheless, the results agree on several points.

(1) Thresholds for tonal isolation increase with the slope of the initial segment, whether the slope is increasing or decreasing (Heise & Miller, Figs. 1 and 2). This result is consistent with the gap tests of Fig. 2.

(2) Threshold differences for tonal isolation are substantially smaller for extensions of V-shaped and inverted V-shaped patterns than for changes in the opposite direction. In terms of the patterns in Fig. 2, Heise and Miller's (1951, Figs. 1 and 2) listeners required smaller frequency differences for Patterns 3 and 8 than for the corresponding Patterns 4 and 7. This result is consistent with the gap tests of Figs. 2 and 3.

(3) Threshold differences for tonal isolation are greater for changes in the same direction as that of a consistently changing sequence than for changes in the opposite direction. In terms of the patterns in the insert of Fig. 2, Heise and Miller's (1951, Figs. 1 and 2) listeners required a larger frequency difference for Patterns 1 and 6 than for the corresponding Patterns 2 and 5. This result is consistent with the gap tests of Fig. 2.

(4) Threshold differences for tonal isolation in patterns with initially ascending segments yield the following rank-orders for

Fig. 5. Gap increment thresholds for two patterns as a function of the number of intervals in the gap region. The patterns differ primarily with respect to $DIPI_2$.

Fig. 6. Gap increment thresholds as a function of the interval pattern. The parameter is the number of intervals surrounding the gap. Conditions in which $n_1 = n_3 = 1$ are connected by the thin line.

Fig. 7. Gap increment thresholds as a function of the slope of the interval pattern. The parameter is the number of intervals in the gap region.

Heise and Miller's listeners in terms of the patterns in Fig. 2: $1 > 3$ and $4 > 2$ (Heise & Miller, 1951, Fig. 3). For the corresponding descending segments, $6 > 8$ and $7 > 5$ (Heise & Miller, 1951, Fig. 4). The same rank-orders obtain for the discrimination of temporal gaps in Fig. 2.

And finally, consider a comparison with the visual thresholds obtained in a collision prediction task. Mangelsdorf (1955, Fig. 8) instructed observers to predict the extrapolated point of collision of two simulated aircraft trails. Mangelsdorf's Figs. 10 and 11 show that the error of extrapolation increased as the angle

between the two trails increased. This result may be compared to the result of Fig. 2, where gap thresholds increase with the slope of the interval pattern for Patterns 3, 4, 7 and 8.

In summary, the temporal gap thresholds of the present study are related to (1) the "goodness" of pattern configuration of the visual representation of the patterns; (2) to pattern effects upon thresholds for tonal isolation obtained by Heise and Miller; and (3) to pattern effects upon visual extrapolation thresholds obtained by Mangelsdorf. Are we, perhaps, dealing with a generalized feature of sensory patterning upon discontinuity thresholds that is not tied to a specific task-environment?

APPENDIX

The major effects of stimulus patterning of Figs. 2 and 3 were extended and qualified in additional tests. The Appendix briefly considers these tests.

A. Further Effects of Pattern Shape

Figure 4 shows the effect of pattern shape for an even wider variety of interval patterns. Three-segment patterns are schematically illustrated along the top of Fig. 4. Positive (+) and negative (-) interval changes were introduced in the n_2 , or gap region. In the two upper lines, the gap region is 16 intervals; in the lower two lines, the gap region is 96 intervals. As noted in Fig. 3, the effect of pattern on gap detection tends to be reduced with a large number of intervals in the gap region. Nevertheless, there is some consistency in the differences between positive and negative gap thresholds. On the basis of the qualitative predictions discussed in connection with Fig. 2, the positive and negative gaps of the upper two lines in Fig. 4 result in seven correct and four incorrect predictions and one tie; the lower two lines result in eight correct and four incorrect predictions.

The differences between "smooth" ($DIPI_1 = DIPI_2 = DIPI_3$) and "broken" ($DIPI_2 = 0$) patterns of Fig. 4 are clarified in Fig. 5. Little difference is observed between smooth and broken patterns until the number of gap intervals is sufficiently large: for the conditions of Fig. 5, four or more intervals are required to differentiate between the patterns in terms of the gap threshold.

B. Further Effects of Slope of Auditory Interval Pattern

Figures 6-8 present the results of additional tests on the effect of the slope of the auditory interval pattern. In Figs. 6 and 7, an unbroken ascending interval pattern, i.e., $DIPI_1 = DIPI_2 = DIPI_3$, was employed. The gap threshold increases with the slope of the pattern in Figs. 6 and 7. The parameter in Fig. 6 is the number of pre-gap intervals, n_1 , and the number of post-gap intervals, n_3 . Filled points represent $n_1 = n_3 \geq 16$; open points represent $n_1 = n_3 \leq 8$. Gap thresholds are relatively independent of n_1 or n_3 , except that lower gap thresholds are obtained with large n_1 at low DIPI and with small n_1 at large DIPI. The parameter in Fig. 7 is the number of gap intervals, n_2 . Slope effects are obtained over a wide range of gap intervals. As in Fig. 3, gap thresholds decrease with the number of gap intervals.

Fig. 8. Gap increment thresholds for a 3-segment pattern as a function of the slope of the terminal segment. Each point represents the results of an individual listener. Thin lines and open points connect the results of listeners at the extremes of sensitivity. The Xs are geometric means for the pattern shown in the insert. The filled triangles are geometric means for an initial segment with a slope of $-60 \mu\text{sec/interval}$.

Fig. 9. Relative gap thresholds as a function of the number of presentations of the entire n_1, n_2, n_3 pattern. The parameter is the number of intervals in the gap region.

Fig. 10. Relative thresholds as a function of the duration of the gap region. The parameter is the Doppler shift between successive interpulse intervals. The ordinate values for the three highest DIPI conditions (open points) were multiplied by 2 to facilitate the display of the results. Each point in Figs. 10 and 11 represents 2-5 thresholds (median: 2) by each of eight listeners.

Fig. 11. Gap increment thresholds as a function of the number of intervals surrounding the gap. The parameter is the duration of the gap region.

Fig. 12. Relative gap thresholds as a function of the pattern of intervals surrounding the gap. The numerical entries represent the patterns illustrated in the upper left corner of Fig. 2.

Figure 8 presents tests with three-segment patterns in which the slope of the terminal segment was varied. The points of Fig. 8 present individual gap thresholds. The light lines connect thresholds for selected listeners. The Xs and heavy smooth curve show the geometric mean gap threshold. The filled triangles give geometric means for the case where $DIPI_1$ was $-60 \mu\text{sec/interval}$. The minimum gap threshold for an ascending slope of $+60 \mu\text{sec/interval}$ occurs at about $DIPI_3 = -60 \mu\text{sec/interval}$, but the effect is not striking.

C. Further Effects of Number of Gap Intervals

Figure 9 considers the interaction between the number of gap intervals, n_2 , with the number of successive presentations, P , of the entire n_1, n_2, n_3 interval pattern. The number of successive presentations has little effect upon the gap threshold, although the gap threshold decreases sharply with the number of gap intervals, as noted in Figs. 3, 4, and 7.

D. Effect of Interpulse Interval

The previous tests were confined to gap intervals in the region of 4 msec, or 250 pulses per sec, pps. Might we expect sharply increased gap sensitivity at higher pulse frequencies?

Figure 10 presents gap thresholds for a wide range of pulse frequencies (8 to 4000 pps, or $IPI_c = 0.25$ to 128 msec). (The results for the three upper functions have been multiplied by a factor of 2, in order to permit visual differentiation among conditions.) The points are coded in terms of the percentage change between successive interpulse intervals, DIPI. A single function is drawn through the results for DIPI to 0.64% per interval. For these conditions, the relative gap threshold is nearly constant at 5% between 0.25 and 4 msec, and is nearly constant at about 25% for intervals of about 50 msec and greater. The intermediate transition region is not sharply defined by the tests. For larger values of DIPI, the minimum relative gap threshold is shifted toward shorter interpulse intervals.

The results of Fig. 11 cover a narrower interval range of interpulse intervals, 0.47 to 15 msec, with a varying number of intervals surrounding the gap. Gap thresholds are nearly independent of the number of intervals surrounding the gap for interpulse intervals of 2 msec and longer (solid figures). Gap thresholds are markedly dependent upon the number of gap intervals for interpulse intervals of about 1 msec and shorter (open figures). This result is consistent with the finding that a variety of discrimination thresholds are strikingly more dependent upon pulse number for high pulse frequencies than for low (Pollack, 1967a, 1968a, b).

Finally, Fig. 12 examines whether the pattern effects of Figs. 2 and 3 are maintained over a range of interpulse intervals. The numerical point-entries refer to the patterns of Fig. 2. Pattern effects are maintained over a wide range of interpulse intervals. For all interpulse intervals, gap thresholds among the conditions rank: $4 > 3$ and $7 > 8$, as in Fig. 2. Condition 2 is usually associated with intermediate thresholds. Therefore, the previously obtained pattern effects are observed over a wide range of interpulse intervals.

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NOTES

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