Discrimination of restrictions upon auditory sequentially encoded information: Block parity

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Finite-state sequences were generated by a digital computer, converted to interval-coded pulse sequences, and transduced to sound by means of earphones. Within each block of B successive intervals, $(B - 1)$ intervals were randomly selected and the B th interval was selected to achieve a fixed parity sum over the block. Discriminability among the sequences—as measured by interstate interval thresholds—reflects both the specific form and the extent of the sequential restrictions introduced by parity. Parity restrictions upon interval-coded sequences may be discriminable through modification of distributions of runs.

The present paper represents a further examination of the discriminability of restrictions in sequentially encoded information, when such information is encoded in the form of interval-coded auditory pulse trains (cf. Pollack, 1968, 1969, 0000). We seek here to determine if a listener can serve as a detector of parity restrictions within such displays. Parity checking is a powerful tool for combating noise within communication circuits, but human sensitivity to parity restrictions has been largely untested.

Following Garner (1962), it is convenient to distinguish between the *extent* and the specific *form* of sequential restrictions imposed by any operation. For example, with binary sequences odd parity and even parity restrict the information of the generated sequences to the same extent. The form of the restriction, however, may be substantially different with respect to other sequential features, e.g., distribution of runs.

The aim of the study was to identify the variables associated with the discriminability of parity restrictions of interval-coded auditory pulse trains and to relate the discriminability to the extent and to the form of the imposed restrictions.

GENERAL METHOD

Restriction of Sequences

Parity restriction over a block of B units is reflected in the following operations: Each of $(B - 1)$ units is randomly chosen from among m equally likely states; the

B th unit is assigned so that the sum over the B units (in modulo M arithmetic) is equal to a constant aimed-for sum, S . For example, with $m = 2$, $B = 3$, and odd parity, if random selection yielded 11 as the first two units of the block, the third unit would be assigned as 1 ($1 + 1 + 1 = \text{odd}$); similarly, if 00, 01, and 10 were yielded by random selection, the third unit would be 1 ($0 + 0 + 1 = \text{odd}$), 0 ($0 + 1 + 0 = \text{odd}$), and 0 ($1 + 0 + 0 = \text{odd}$), respectively.

Binary, or two-state, sequences were constructed with even parity, with odd parity, and with random parity. In the latter case, the B th unit of each block was randomly selected without regard for parity.

A message of N units consisted of N/B independently generated blocks of B units in length. Within each block, $(B - 1)$ independent random selections were made among m equally likely states. The B th unit was determined by the aimed-for sum,

S . For example, with $N = 600$, $B = 3$, and odd parity, two random selections and one constrained selection were made within each block of three units, and the entire process was replicated 200 times to form a sequence of 600 units.

It is noted that certain aimed-for sums have greater consequences for long runs than do other aimed-for sums. As illustrated in Table 1 for the case of $B = 2$, binary states, and odd parity, each block consists of sequences of either 01 or 10. The longest possible run is two units, as in 01, 10. (The commas mark the blocks for the reader. They were not represented in the tests.) The entire run-length distribution for this restriction is $p(r = 1) = 2/3$, $p(r = 2) = 1/3$. For the same conditions with even parity, extremely long runs are possible, as in 00, 00, 00, 11, 11, The run-length distribution for this restriction is $p(2r) = (0.5)^r$.

The zero aimed-for sum leads to long runs for any combination of an even block size and an even number of states, as shown in Table 1 for $m = 4$, $B = 2$. And, as also shown in Table 1, when $m = B$, an aimed-for sum of 0 includes all run sequences of Length B over a block of B units.

Procedure

A PDP-8 digital computer (Digital Equipment Corporation) constructed sequences with defined block parity restrictions and converted the sequences to interval-coded electrical pulse trains. The electrical pulse trains were converted to auditory pulse trains by means of earphones (Koss PRO-4).

The listener heard four pulse trains: three with one parity restriction, one with

Table 1

BLOCK PARITY RESTRICTIONS

BINARY

	B = 2	B = 3
Even	00 11	000 011 101 110
Odd	10 01	111 001 010 100
Random	00 11 01 10	000 111 001 010 011 100 101 110

MULTISTATE

Sum = 0	00 12 21	000 111 222 (+ 6 others)
m = 3	1 22 01 10	001 112 220 "
2	11 02 20	002 110 221 "
Sum = 0	00 22 13 31	000 013 022 (+ 13 others)
1	01 10 23 32	333 010 023 "
m = 4	2 11 33 02 20	222 011 020 "
3	03 12 21 30	111 012 021 "

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Fig. 1. Interstate discriminability thresholds, DIPI, as a function of the average interpulse presentation interval for discrimination between pairs of binary parity restrictions. The lower section represents a block length of two units. Different pairs of parity restrictions are represented as the parameter. The upper section represents a block length of three units. The extent of filling of the points reflects the proportion of terminated trials (see text).

a different parity restriction. His task was to identify which one of the four pulse trains sounded different from the other three. An adaptive stimulus programming procedure of variable step size (Taylor & Creelman, 1967) varied the interstate interval difference, DIPI, to converge upon 50% correct response within the four-interval forced-choice (4IFC) procedure. When a correct observation was made, DIPI was increased; when an incorrect observation was made, DIPI was decreased. When the sought-for level of DIPI exceeded $2(IPI_c - .148) \text{ msec}/(m - 1)$, an observation was provided at the limiting condition. An incorrect response at the limiting condition terminated the trial. Conditions with 10% or fewer terminated trials use the geometric means of two thresholds of each of 15 experienced listeners and are plotted as open points. Conditions with >10% terminated trials use the median threshold, including the terminated trials. Half-filled points represent 10%-20% terminated trials; filled points represent >20% terminated trials. Listeners completed 77 and 58 experimental conditions for binary and multistate parity discrimination, respectively.

Unless otherwise specified, the average interval, $IPI_c = 0.5 \text{ msec}$, or 2,000 samples per second; $m = 2$; $N = 625$.

RESULTS

Binary Sequences

The tests of Fig. 1 sought to determine if the average sampling rate—or alternatively, the average interpulse interval—modified the interstate threshold difference. The pulse train duration was constant at 1.05 sec, or limited to 2,100

Fig. 2. Interstate discriminability thresholds as a function of sequence length (abscissa) and block length (parameter) for discrimination between pairs of binary parity restrictions. The three sections represent three different pairs of binary parity restrictions.

interpulse intervals. For a block length of 2 (lower section), a wide range of scores—almost a two-decade range—is associated with even vs random parity. A smaller range of threshold scores is obtained for odd vs even or odd vs random parity. Maximal sensitivity is associated with an average interpulse interval of about 0.5 msec. For a block length of 3 (upper section), there is a large jump in thresholds, and there is little effect of the average interpulse interval.

Figure 2 presents interstate discrimination thresholds as a function of the total number of intervals (abscissa) and as a function of block length (parameter). In the left section of Fig. 2, odd parity sequences are pitted against sequences of random parity. In the center section of Fig. 2, odd parity is pitted against even parity. In the right section of Fig. 2, even parity is pitted against random parity. All tests were carried out at a sample presentation rate of 2,000 samples per second.

Although differing in detail, each parity combination shows increasing thresholds with larger block lengths (parameter) and with shorter pulse trains (abscissa). The degree of shading of the points reflects the proportion of terminated trials that exceeded the limits of the program. Long sequences of block length 3 are discriminable under all conditions of parity, but shorter sequences and most sequences of block lengths 5 and 6 were not discriminated consistently. Best discrimination, i.e., lowest thresholds, is obtained with odd parity vs even parity; poorer discrimination is obtained with binary sequences of odd vs random parity and with sequences of even vs random parity. For extremely long sequences, poorest discrimination is obtained with sequences of odd vs random parity.

Multistate Sequences

Figure 3 presents interstate discrimination thresholds as a function of the number of possible states (abscissa). The lower section represents a block length of 2; the upper section represents a block length of 3. Within each session, several parity relationships are contrasted. The dashed line represents the expected shape of the empirical functions if the interstate interval threshold was determined by the range of intervals subtended by the lowest and highest states, $DIPI_R$. This relation between the two measures is: $DIPI_R = (m - 1)DIPI$.

Consider first the results with a block length of 2 (lower section). As in Fig. 2, with long binary sequences, $m = 2$, discrimination is best with sequences of odd vs even parity and poorest with

Fig. 3. Interstate discriminability thresholds as a function of the number of possible states for multistate parity restrictions. The lower and upper sections represent block lengths of 2 and 3, respectively. The dashed line represents the shape of the expected relation if the total range of interpulse intervals was constant with the number of possible states.

sequences of odd vs random parity. Differences among conditions are smaller with a larger number of states. At least with a zero aimed-for sum, the change in thresholds tends to reflect a nearly constant range of interpulse intervals for $3 \leq m \leq 8$. By contrast, with a nonzero aimed-for sum, there is little change in the threshold interpulse interval difference as a function of m .

The results with a block length of 3 are shown in the upper section. Discrimination was unreliable for larger block lengths for $m > 2$. Again, for a 0 aimed-for sum, thresholds tend to reflect a constant range of interpulse intervals.

DISCUSSION

A distinction may be made between the *extent* and the *specific form* of sequential restrictions imposed by block parity. The

extent of sequential restrictions imposed by parity was identified with the information of the generated sequences. Specifically, a nonrandom parity restriction is imposed upon only one of B units within each block, against $(B - 1)$ independently selected units. Informational restrictions associated with parity, therefore, become relatively weaker with larger block lengths. Paralleling the change in information restrictions is the most robust finding of this study: interstate thresholds increase dramatically with block length. The difference in information associated with any set of parity restrictions also grows with the number of successive blocks. Threshold discriminability improves with the number of successive blocks. Therefore, at least with respect to two main variables—block length and number of blocks—thresholds

are related to the differences in informational content of the sequences. The role of the number of possible states, m , is less clear. For a block length of 2, there may be a substantial change in thresholds as the number of possible states is increased from 2 to 3. Further threshold changes with the number of possible states tend to reflect a constant range of interpulse intervals which mark the separate states.

The specific form of sequential restriction, irrespective of informational properties, also determines interstate interval thresholds. This is most clearly seen in comparing the individual conditions of binary parity. In terms of differences in informational uncertainty with $B = 2$, odd vs even parity should be nondiscriminable, for it represents a zero difference in informational uncertainty; and, odd vs random and even vs random parity should be equally discriminable, for they both represent equal differences in uncertainty. Instead, lowest thresholds are obtained with odd vs even parity at high sampling rates, and unequal thresholds may be obtained with odd vs random and even vs random parity. Furthermore, since the informational constraints are independent of the mean interpulse interval, the large threshold differences obtained with interpulse interval in Fig. 1 further reflect independence of discriminability thresholds on the extent of informational restrictions.

It is therefore necessary to look beyond the overall informational properties in order to examine the effects of specific parity restrictions. Independent tests have shown that listeners can detect shifts in the distribution of runs for interval-coded auditory pulse trains (Pollack, 1969). Now, consider again the binary sequences of Table 1. For $B = 2$, the greatest difference

in run properties obtains for odd vs even parity. The random parity condition shares the run properties of both even and odd parity. These properties are reflected in the discriminability thresholds of Fig. 2. That is, at high presentation rates, lowest thresholds are obtained with odd vs even parity, and higher thresholds are obtained with random parity. On the basis of the run length alone, however, there should be no difference between random vs odd parity and random vs even parity. Differences between these parity pairs are suggested in Fig. 2 as a function of length of the sequences. For binary sequences, $B = 3$, the greatest difference in the specific form of the runs obtains with odd vs even parity. The random parity condition shares the specific run properties of both even and odd parity sequences. These properties are also reflected in the discriminability thresholds of Fig. 2. The tidy relation between threshold and run properties, however, is only partially maintained with multistate sequences. The zero aimed-for sum yields lower thresholds than do nonzero aimed-for sums, but the outstanding opportunity for long runs, $m = 3$, $B = 3$, does not lead to sharply lower thresholds.

Other results with multistate sequences cast doubt that the discriminability of specific parity combinations is due exclusively to run properties. The points in Fig. 3 represented average DIPI thresholds over several experimental conditions. In more detail, conditions with an aimed-for sum of $(m - 1)$ apparently yielded lower thresholds. In five comparisons with other aimed-for sums, DIPI thresholds with an aimed-for sum of $(m - 1)$ were 0.21, 0.27, 0.44, 0.46, and 0.72 times the corresponding thresholds for other sums. One feature of an aimed-for sum of $(m - 1)$ with a block length of 2 is that

differences between adjacent states are maximized. Specifically, with $m = 4$ an aimed-for sum of 3 yields the following possible blocks of two units: 03, 12, 21, and 03. The sum of the differences is 8 ($3 + 1 + 1 + 3$); all other aimed-for sums for this condition yield a sum of differences, e.g., an aimed-for sum of 0 yields the blocks 00, 13, 22, and 31, or differences of $(0 + 2 + 0 + 2)$. Thus, other specific features of the parity restrictions, beyond their information content and run properties, may influence discriminability thresholds.

In summary, threshold discriminability is reflected in the extent of the informational restrictions imposed by several variables associated with block parity. The effect of the specific form of parity restrictions, however, is more related to the specific properties of the sequential restrictions—such as run length or the composition of the run—than to the overall informational properties.

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