

The effects of varying signal intensity on the perceptual organization of rhythmic auditory patterns

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Cyclic repetitions of temporally structured sequences of sound bursts and gaps are perceived as rhythmic patterns. Some are perceptually unambiguous—the pattern organization is unique; others are perceptually ambiguous—the organization changes. Previous research suggests that the pattern of neuronal adaptation and recovery from adaptation associated with these stimuli determines how listeners perceptually organize the sequences. It follows that variations in the intensity of specific sound elements, which should produce specific changes in the underlying patterns of neuronal activation, should produce predictable changes in the perceptual organization of the sequences. The present study tested this hypothesis by observing the perceptual responses of listeners while varying the intensity of critical elements of unambiguous and ambiguous sequences. The results support the hypothesis in that an unambiguous sequence was made ambiguous and an ambiguous sequence was made less ambiguous. However, the unambiguous sequence did not completely reverse its perceptual organization, nor did the ambiguous sequence become completely unambiguous. The outcome is discussed focusing on the range of intensity increments tested, the type of stimuli used, and the possibility that neurosensory factors may interact with other organizing factors in determining the perceptual organization of rhythmic auditory sequences. © 1998 Acoustical Society of America. [S0001-4966(98)01210-7]

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INTRODUCTION

In the past decade there has been a concerted effort to understand complex sound perception in humans (e.g., Bregman, 1990; Handel, 1993). Included in this effort have been studies exploring the heuristic rules that lead to the organization of sounds into perceptual patterns. Within the broad area of auditory pattern perception, investigators have attempted to delineate organizational principles that are constrained by the temporal or rhythmic properties of stimuli (e.g., Essens, 1986, 1995; Essens and Povel, 1985; Handel, 1973, 1974; Handel and Osinsky, 1981; Longuet-Higgins and Lee, 1982; Povel, 1981, 1984; Povel and Essens, 1985; Royer and Robin, 1986). A clear depiction of the temporal parameters that drive auditory pattern perception has an impact on the understanding of normal and impaired processing of both speech and music (e.g., Bregman, 1990; Deutsch, 1980, 1981; Efron, 1963; Gfeller *et al.*, 1997; Longuet-Higgins and Lee, 1984; Martin, 1972; Massaro, 1975; Pisoni and Swausch, 1975; Povel and Essens, 1985; Robin *et al.*, 1990b).

One set of auditory stimuli that has received close scrutiny involves the repetition of sequences of sounds over regular temporal intervals. When cyclic repetitions of sound sequences are presented to listeners with normal hearing abilities, they can identify rhythmic patterns in which a given sequence has a beginning point and an ending point, even though the sounds repeat continuously and there is no unique beginning or ending based on the physical structure of the stimuli (e.g., Garner and Gottwald, 1968; Handel, 1973, 1974; Royer and Garner, 1966, 1970; Royer and Robin,

1986). The perceived organization depends, among other things, on the temporal structure of the sequence, which includes the sounds and silent intervals (gaps) between the sounds that make up the sequence. The type of processing underlying the perception of rhythmic patterns depends on the rate of presentation of the sequence. With presentation rates of less than two sounds per second, pattern perception depends on an active learning process. The perceived beginning of the pattern is strongly influenced by the first sound element of the sequence that is presented. With faster presentation rates, pattern perception is holistic and automatic. The perceived beginning of the pattern is determined by the structure of the elements comprising the sequence, independent of the physical starting point (Garner and Gottwald, 1968). With very fast presentation rates, pattern perception breaks down and unitization occurs; the perception is of a repeating packet of sounds that includes the entire sequence. Although individual sounds can still be heard, the temporal structure of the sequence—the pattern—cannot be identified. With extremely fast presentation rates, only a continuous sound—an “auditory texture”—is heard (Royer and Robin, 1986). The present study focused on the condition in which the presentation rates produced an automatic, integrated perception of a repetitive rhythmic pattern.

An extensive literature has been devoted to studying the perceptual organization of rhythmic auditory patterns (see Robin *et al.*, 1987, for a review). In brief, given an auditory sequence in which a sound element is represented by an “X” (a sound burst of some duration followed by a silent interval of the same duration) and a gap is represented by a

“-” (a silent interval of the same duration as X), one can define perceptually unambiguous and perceptually ambiguous patterns that emerge based on the temporal structure of the stimuli. Two of the organizing principles that have been proposed to guide the perception of rhythmic auditory patterns are the *run* and *gap principles* (Garner, 1974; Garner and Gottwald, 1968; Preusser *et al.*, 1970). The run principle states that the longest run of sound elements will mark the perceived beginning of an auditory pattern, and the gap principle states that the longest gap will mark the perceived ending. Sequences in which runs and gaps predict the same organization are perceptually unambiguous; the rhythmic pattern has a unique perceptual organization. Sequences in which runs and gaps temporally conflict are perceptually ambiguous; the rhythmic pattern has multiple perceptual organizations. For example, the sequence XXX-X--- is unambiguous because the longest run and the longest gap are in accord and predict the same beginning (underlined) and ending of the pattern. When listeners are given the opportunity to describe their perceptions by tapping the pattern, or by written or vocal description, they almost always report hearing the pattern as beginning with the first sound element of the longest run, even though there are multiple possible starting points (e.g., Garner and Gottwald, 1968; Preusser *et al.*, 1970; Royer and Garner, 1966). In contrast, the sequence XX-X-XX- is ambiguous because there are two runs of equal length and three gaps of equal duration. Listeners describe the pattern as beginning with one of three sound elements (underlined), even though other organizations are possible. Ambiguous auditory patterns can change organization both during and between presentations, much like the visual Necker cube.

In an attempt to provide a neurophysiologic explanation of the run and gap principles, Robin *et al.* (1990a) reasoned that neuronal adaptation and recovery from adaptation might underlie the perceived rhythmic organization. They argued that because adaptation results in changes in the response of a neuron following repeated stimulation, the run and gap principles emerged as a result of the repetitive, cyclic nature of the auditory stimulus. They further argued that because the spacing among elements in the stimulus varied, the degree of adaptation would vary as well. Specifically, they hypothesized that the first element of a run receives psychological stress because it is associated with the greatest neuronal response (i.e., with the least adaptation). Moreover, the element after the longest gap also receives psychological stress because the greatest recovery from adaptation occurs during the longest pause in stimulation. Listeners appear to mark the beginning of patterns where psychological stress is greatest, that is, at the start of the longest run or following the longest gap. When there is a uniquely longest run preceded by a longest gap, one element in the sequence receives the greatest stress, and the emergent rhythmic organization is unambiguous. When there are multiple runs or gaps of equal length, or when the runs and gaps temporally conflict, there may be stress placed on more than one element of the sequence and the emergent rhythmic organization is ambiguous.

To provide support for this hypothesis, Robin *et al.*

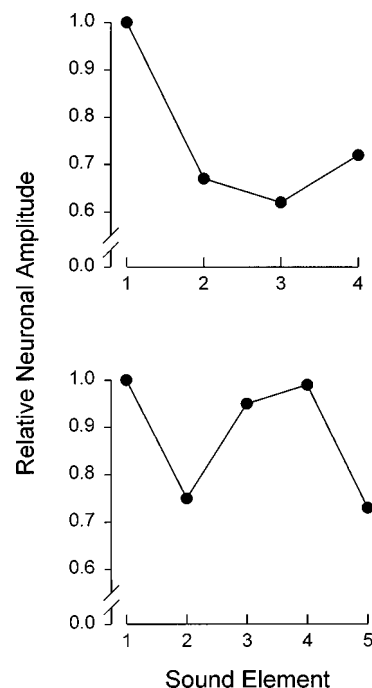


FIG. 1. Schematic representation of the normalized neuronal amplitude data reported by Robin *et al.* (1990a). The top graph represents data from the unambiguous sequence (XXX-X---), and the bottom graph represents data from the ambiguous sequence (XX-X-XX-).

(1990a) examined adaptation in the eighth nerve, brain stem, and auditory cortex of cats. They used an unambiguous (XXX-X---) and an ambiguous (XX-X-XX-) sequence. For the unambiguous sequence, it was predicted that the amplitude of the neuronal response would be greatest for the first sound element of the longest run (XXX), and that responses to each of the successive two elements would be progressively reduced in amplitude due to adaptation. There would then be a brief but incomplete recovery of the neuronal response amplitude following the first gap (-), and a greater degree of recovery following the longest gap (---). The results supported this prediction as can be seen in the upper plot of Fig. 1, which depicts the pattern of neuronal responses reported by Robin *et al.* for the unambiguous sequence. The prediction for the ambiguous sequence was that the amplitude of the neuronal response would be equal for the first sound element of each of the two-element runs (XX), but higher than that for each of the immediately successive sound elements. The neuronal response amplitude associated with the single sound element (X) was predicted to be relatively high as well because there should be some recovery from adaptation after the pause (-). Overall, the pattern of neuronal response amplitude across the five sound elements of the ambiguous sequence was predicted to reflect the three possible perceptual organizations reported by human listeners. As before, the results supported this prediction as can be seen in the lower plot of Fig. 1, which depicts the pattern of neuronal responses reported by Robin *et al.* for the ambiguous sequence. It should also be noted that although there were differences in the absolute magnitude of the neuronal responses across the three recording sites (eighth nerve, brain stem, and auditory cortex), the patterns of neuronal

response amplitude were found to be the same regardless of the recording site.

If Robin *et al.*'s hypothesis is strictly true (i.e., it represents a strong form of the prediction), then a logical extension of it is that changes in the intensity of the sound elements within the cyclic patterns should result in predictable changes in listeners' perceptions. Changes in signal intensity will have a direct effect on the amplitude of the neuronal response. That is, increases in the intensity of specific sound elements will lead to a greater neuronal response amplitude for those elements. Thus if the strong form of Robin *et al.*'s hypothesis is true, changing the intensity of a given sound element in an unambiguous sequence should result in making the emergent pattern perceptually ambiguous. Moreover, if the intensity is sufficiently increased, it should be possible to systematically move from an unambiguous to an ambiguous pattern and, with further increases in intensity, to an unambiguous but new organization. Likewise, altering the intensity of a specific sound element of an ambiguous sequence should result in a perceptually unambiguous organization.

The purpose of the present study was to test these hypotheses. This was accomplished by varying the intensity of the fourth sound element of the unambiguous sequence (XXX-X---) and the intensity of the first, third, and fourth sound elements of the ambiguous sequence (XX-X-XX-) and observing the perceptual responses of human listeners to cyclic repetitions of the altered stimuli. It was predicted that the unambiguous sequence, which is typically organized as XXX-X---, would become perceptually ambiguous under certain intensity manipulations, and under the greatest increase in intensity it would reorganize as X---XXX-, a new unambiguous pattern. It was also predicted that the ambiguous sequence, which is equally often organized as XX-X-XX-, X-XX-XX-, or XX-XX-X-, would become perceptually unambiguous under the greatest increase in intensity. It was expected that the particular perceptual reorganization of the ambiguous sequence would depend on the element being manipulated. When the intensity of the first sound element was increased, the pattern XX-X-XX- should predominate; when the intensity of the third sound element was increased, the pattern X-XX-XX- should predominate; when the intensity of the fourth sound element was increased, the pattern XX-XX-X- should predominate.

I. EXPERIMENT 1

A. Hypothesis

This experiment tested the hypothesis that variations in the intensity of the fourth sound element of the unambiguous sequence (XXX-X---) would produce changes in the perceptual organization of the auditory pattern. The perceptual responses of human listeners were recorded in five intensity conditions. In the baseline condition, each sound element had the same intensity. This condition was similar to that of previous experiments (e.g., Garner and Gottwald, 1968; Preusser *et al.*, 1970; Royer and Garner, 1966; Royer and Robin, 1986), so it was expected that listeners would report hearing the conventional unambiguous pattern (XXX-

X---) on most of the trials. There were three conditions in which the intensity was greater than baseline. It was expected that as intensity increased, listeners would report hearing the conventional pattern on fewer trials and would report hearing the alternate organization (X---XXX-) with increasing frequency. In the final condition, the fourth sound element was of a lower intensity than baseline. This condition was included to examine the possibility that changes in the frequency of hearing the alternate organization may be due simply to the presence of an altered sound element within the sequence, rather than to the direct effects of increased intensity on the magnitude of the neuronal response. If this possibility is correct, then the frequency of hearing the alternate pattern organization should increase under the condition of decreased intensity as well as under the condition(s) of increased intensity. On the other hand, if increased amplitude of neuronal response is the determining factor underlying changes in the perceived pattern organization, then the frequency of hearing the conventional pattern organization should not differ between the condition in which signal intensity of the fourth sound element was decreased and the baseline condition.

B. Method

1. Participants

Ten individuals from the University of Iowa community (seven females, three males) between the ages of 20 to 39 (mean age=25.6 years) volunteered to participate. All were naive regarding the aims of the study. Each participant was found to have hearing abilities within normal limits as determined by a pure-tone audiometric screening test. Participants were screened at each octave from 125 Hz to 8000 Hz at a constant intensity level of 20 dB. Each participant received monetary compensation. All of the participants in this study were treated in accordance with the guidelines established by the American Psychological Association (1992).

2. Stimuli and apparatus

The auditory stimulus consisted of 15 repetitions of an 8-element sequence. The sequence was composed of four computer-generated pulses of a 250-Hz tone and four gaps in which there was no tone. Each sound element had an on-duration and an off-duration of 44 ms; each gap was 88 ms. The temporal parameters of a single sequence are shown in Fig. 2. The digital output of the computer was converted to an analog voltage that was low-pass filtered, amplified, and used to drive an audio speaker. The intensity of the fourth sound element of the sequence was varied in five intensity conditions (see Fig. 2). In the baseline condition, each sound element had an intensity of 74 dB. Three of the conditions involved increases in the intensity of the fourth sound element of 3, 6, and 9 dB from the baseline intensity. The remaining condition involved a decrease in intensity of 9 dB from baseline. Thus while the intensity of the first, second, and third sound elements was always 74 dB, the intensity of the fourth sound element could be 65, 74, 77, 80, or 83 dB. Sound intensity was measured by placing a sound-level meter at the approximate position of the listener's head.

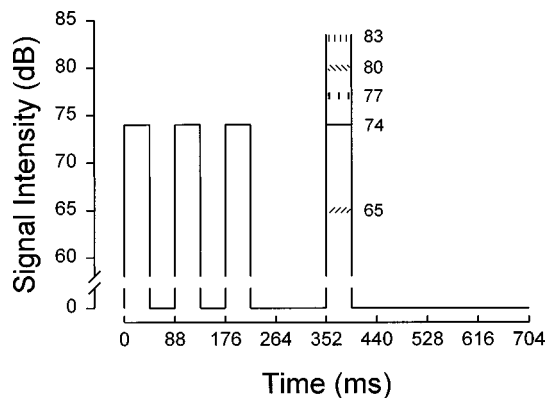


FIG. 2. Temporal structure of the unambiguous sequence (XXX-X---) used in experiment 1. Each sound element consisted of a 250-Hz tone. The intensity of the first, second, and third sound elements was 74 dB. The intensity of the fourth sound element could be 65, 74, 77, 80, or 83 dB.

Testing was conducted in a dark, sound-treated booth. During testing, the participants were required to stay positioned in a chin rest to ensure that a consistent distance was maintained from the audio speaker located in the testing booth. A trial started with a visual ready message presented for 700 ms on a computer monitor visible through a plexiglass window in the testing booth. After a 300-ms delay, the auditory stimulus was presented, and then a visual response screen appeared on the monitor which displayed two patterns, XXX-X--- and X---XXX-, one on the left and one on the right. The position of the patterns on the response screen (left, right) varied and was counterbalanced over each of the intensity conditions. The response screen remained visible until a response was made. A response box with three response keys was situated in front of the participant. Responses were made by pressing either the left or right key to indicate which pattern best characterized the perceptual pattern of the sequence during the trial. There was an inter-trial interval of 2 s.

3. Procedures

Each participant was tested in one session that lasted about 1.25 h. The participant was first led through a demonstration block of three trials of the baseline intensity condition to become familiar with the experimental setup. This block could be repeated at the participant's request. It was followed by a 20-trial practice block consisting of 4 trials of each of the 5 intensity conditions. This block could be repeated once if the participant requested it. Finally, there was one 150-trial experimental block consisting of 30 trials of each intensity condition. There was a 2-min rest interval after trials 50, 90, and 120. This block was not repeated. For both practice and experimental blocks, the order of the intensity conditions was random, and for each trial, the starting element of the eight-element sequence was selected randomly.

C. Results and discussion

For each intensity condition, the proportion of trials in which the conventional unambiguous pattern (XXX-X---) was reported was calculated for each participant. The means

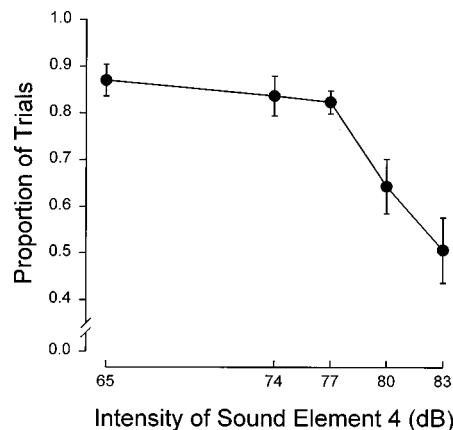


FIG. 3. Mean proportion of trials in which the standard unambiguous pattern (XXX-X---) was reported as a function of the intensity of the fourth sound element. Data are from experiment 1. Bars = ± 1 SEM.

are presented in Fig. 3. A logarithmic transformation of the proportion scores was calculated (Kirk, 1982) after adding a constant of 1/60 (1 divided by twice the number of trials of each intensity condition). The constant was added to eliminate empty cells which could have occurred in cases in which the participant did not report perceiving the conventional unambiguous pattern. The log-transformed values were analyzed by a one-way repeated-measures analysis of variance (ANOVA). The main effect of intensity was significant [$F(4,36) = 7.96, p < 0.001$]. A Tukey pairwise comparison ($\alpha = 0.05$) of the mean log scores indicated that performance in the 83-dB intensity condition was significantly different from performance in the 65-, 74-, and 77-dB levels. No other pairwise comparisons were significant.

The results generally support the predictions. In the baseline condition the conventional pattern was reported on the majority of trials—84% (see Fig. 3). This outcome was expected and replicates the results of previous studies (e.g., Garner and Gottwald, 1968; Preusser *et al.*, 1970; Royer and Garner, 1966; Royer and Robin, 1986). When the intensity of the fourth sound element was increased by 3 dB, the conventional pattern was reported on 82% of the trials—about the same as in the baseline condition. With further increases of 6 and 9 dB from baseline, the conventional pattern was reported less frequently—64% and 51%, respectively. The change in the perceived pattern organization from baseline was significant in the condition with the greatest (9 dB) intensity increment. This outcome supports the hypothesis that increasing the intensity of the fourth sound element of the unambiguous sequence would reduce the frequency of perceiving the conventional unambiguous pattern and, conversely, increase the frequency of perceiving the alternate pattern organization.

When the intensity of the fourth sound element was decreased by 9 dB, the conventional pattern was reported on 87% of the trials—about the same as in the baseline condition. This finding rules against the possibility that increases in the frequency of hearing the alternate pattern organization were due to an alteration in the intensity of the fourth sound element per se. Rather, the changes appear to be specific to increments in intensity.

II. EXPERIMENT 2

A. Hypothesis

The results of experiment 1 provide some support for Robin *et al.*'s (1990a) hypothesis. However, the hypothesis predicts that with a sufficient intensity increment of the fourth sound element, the emergent pattern should perceptually reorganize to a new unambiguous pattern beginning with the altered element (X---XXX-). This outcome was not obtained, but it may be that the intensity increment was not sufficient to produce the expected reorganization. The purpose of this experiment was to test the hypothesis that an intensity increment of greater than 9 dB would produce a perceptual reorganization of the unambiguous pattern into a new unambiguous pattern beginning with the altered sound element.

B. Method

1. Participants

Ten individuals from the University of Iowa community (nine females, one male) between the ages of 21 to 34 (mean age=23.9 years) volunteered. They were naive regarding the aims of the study. Each participant passed a pure tone audiometric screening test as in experiment 1. Each participant received monetary compensation.

2. Stimuli and apparatus

The stimuli and apparatus were identical to those used in experiment 1 with the exception of the intensity conditions. The intensity of the fourth sound element of the sequence (see Fig. 2) was varied in three, rather than five, conditions. In the baseline condition, each sound element was 65 dB rather than 74 dB. The other two conditions involved increments of 9 and 18 dB above baseline to 74 and 83 dB, respectively.

3. Procedures

For each participant, testing was conducted during one session that lasted about 50 min. The testing procedures were identical to those in experiment 1 with the following exceptions. Each practice block consisted of 24 trials, rather than 20, and there were 8 trials of each of the 3 intensity conditions. The experimental block consisted of 90 trials, rather than 150, with 30 trials of each intensity condition. There was only one 2-min rest interval which occurred after trial 50.

C. Results and discussion

For each intensity condition, the proportion of trials in which the conventional unambiguous pattern was reported was calculated for each individual. The means are presented in Fig. 4. A constant of 1/60 was added to the proportion scores, and the log-transformed values were analyzed by a one-way repeated-measures ANOVA. The main effect of intensity was significant [$F(2,18) = 5.46$, $p < 0.02$]. A Tukey pairwise comparison ($\alpha = 0.05$) of the mean log scores indi-

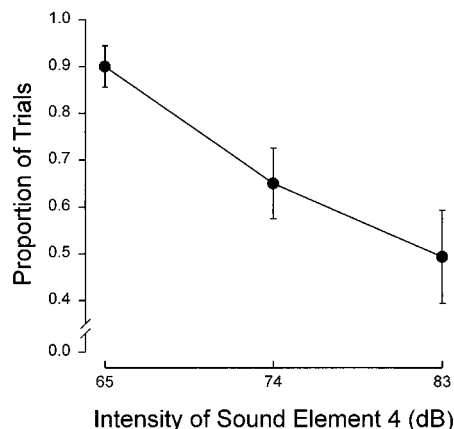


FIG. 4. Mean proportion of trials in which the standard unambiguous pattern (XXX-X---) was reported as a function of the intensity of the fourth sound element. Data are from experiment 2. Bars = ± 1 SEM.

cated that performance in the 83-dB condition was significantly different from that in the baseline condition. No other pairwise comparisons were significant.

These results replicate those of experiment 1. In the baseline condition the conventional pattern was reported on 90% of the trials (see Fig. 4). When the intensity of the fourth sound element was increased by 9 and 18 dB, the conventional unambiguous pattern was reported less frequently—65% and 50%, respectively. The change in performance from baseline was significant with the greatest (18 dB) intensity increment. However, the results do not support the hypothesis that an intensity increment greater than 9 dB would produce a perceptual reorganization of the auditory sequence to a new unambiguous pattern beginning with the altered sound element. Although the intensity increment was increased by 9 dB in this experiment compared to experiment 1, the same outcome was obtained.

III. EXPERIMENT 3

A. Hypothesis

This experiment tested the hypothesis that variations in the intensity of the first, third, or fourth sound element of the ambiguous sequence (XX-X-XX-) would produce changes in the perceptual organization of the auditory pattern. The perceptual responses of listeners were recorded in five intensity conditions for each of the three sound-element manipulations. In the baseline condition, each of the sound elements had the same intensity. This condition was similar to previous studies (e.g., Garner and Gottwald, 1968; Preusser *et al.*, 1970; Royer and Garner, 1966; Royer and Robin, 1986), so it was expected that listeners would report hearing each of the three different patterns (pattern 1: XX-X-XX-; pattern 2: X-XX-XX-; pattern 3: XX-XX-X-) with about equal frequency. There were three conditions in which the intensity of the manipulated sound element was greater than baseline. It was expected that as intensity increased, listeners would report hearing the pattern as beginning with the manipulated sound element more often than in the baseline condition, and they would report hearing the two

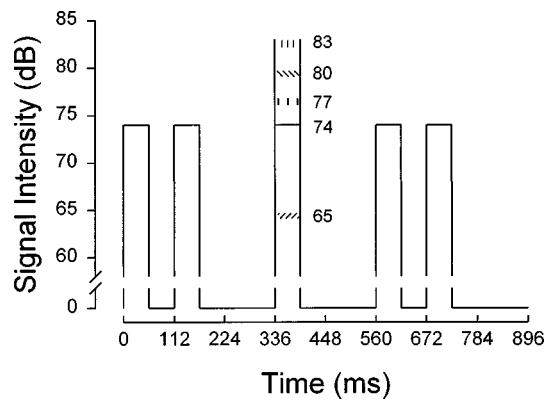


FIG. 5. Temporal structure of the ambiguous sequence (XX-X-XX-) used in experiment 3. Each sound element consisted of a 250-Hz tone. Depicted in the figure is the sound-element 3 manipulation. In this condition, the intensity of the third sound element could be 65, 74, 77, 80, or 83 dB. The other four sound elements had an intensity of 74 dB. For the sound-element 1 manipulation (not shown), the structure of the sequence was the same as depicted except the intensity of the first sound element varied. For the sound-element 4 manipulation (not shown), the intensity of the fourth sound element varied.

alternate organizations less often. There was also a condition in which the intensity of the manipulated sound element was less than baseline, as in experiment 1.

B. Method

1. Participants

Eighteen individuals from the University of Iowa community (nine females, nine males) between the ages of 16 to 33 (mean age=20.2 years) volunteered. They were all naive regarding the aims of the study. Each individual was screened for hearing impairments using a pure-tone audiometric screening test as in experiment 1. Each participant received monetary compensation.

2. Stimuli and apparatus

The auditory stimulus consisted of 15 repetitions of an 8-element sequence that was composed of 5 computer-generated pulses of a 250-Hz tone and 3 gaps. The on-duration and the off-duration of each sound element was 56 ms, and each gap was 112 ms. The temporal parameters of a single sequence are shown in Fig. 5. There were three sound-element manipulation conditions corresponding to manipulating the intensity of the first, the third, or the fourth sound element. For each of these conditions, the intensity of the manipulated element was varied in five conditions (see Fig. 5). These were the same as in experiment 1—65, 74, 77, 80, and 83 dB.

Testing was conducted in the same manner as before, and the structure of a trial was the same with the following exception. The response screen displayed the three patterns, XX-X-XX-, X-XX-XX-, and XX-XX-X-, one in the upper left, one in the center, and one in the lower right of the video monitor. Each of the three positions on the response screen corresponded to one of the three response keys on the response box. The participants responded by pressing the key that matched the position of the pattern that best characterized the perceptual pattern of the sequence during the trial.

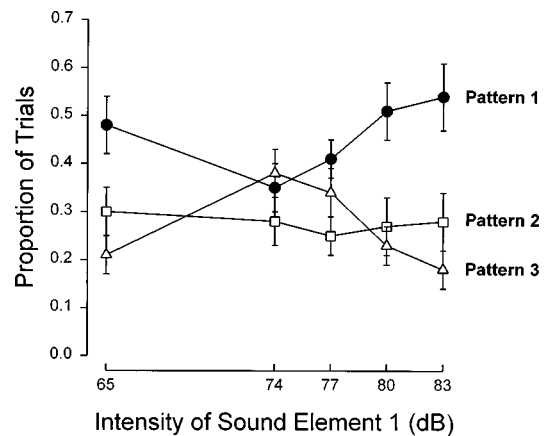


FIG. 6. Mean proportion of trials in which pattern 1 (XX-X-XX-; circles), pattern 2 (X-XX-XX-; squares), and pattern 3 (XX-XX-X-; triangles) were reported as a function of the intensity of the first sound element. Data are from experiment 3, sound-element 1 manipulation. Bars = ± 1 SEM. Filled symbols indicate the pattern beginning with the manipulated sound element.

3. Procedures

All of the participants were tested in each of the experimental conditions. Testing was conducted in three separate sessions that took place on three days within a 1- to 2-week period. Each testing session lasted about 1.25 h. The sound-element manipulation condition was blocked by session. At the start of the experiment, the participant was led through a demonstration block of three trials of the baseline intensity condition. This block could be repeated if the participant requested it. For each testing session, there was a 30-trial practice block composed of 6 trials of each of the 5 intensities. This block was not repeated. It was followed by one experimental block of 150 trials—30 trials of each intensity. There was a 2-min rest interval after trials 50, 90, and 120. The session order (i.e., the presentation order of the sound-element manipulation conditions) was counterbalanced across the 18 participants. Within each block, the presentation order of the five intensity conditions was randomized, and the starting element of the eight-element sequence was selected at random on each trial.

C. Results and discussion

The three sound-element manipulation conditions were analyzed separately. For the five levels of stimulus intensity, the proportion of trials in which pattern 1 (XX-X-XX-), pattern 2 (X-XX-XX-), and pattern 3 (XX-XX-X-) were reported was calculated for each participant. The means are presented in Figs. 6, 7, and 8 for the sound-element 1, 3, and 4 manipulations, respectively. A constant of 1/60 was added to each proportion score, and the logarithms of these values were calculated. To examine the effects of the intensity manipulation on the participants' responses across the different patterns, three planned contrasts were conducted for each sound-element manipulation condition. Separate contrasts were used because the frequency of responding to the three different patterns was not independent for a given intensity condition. Differences between the log-transformed proportions were calculated and used in the analyses. Using differ-

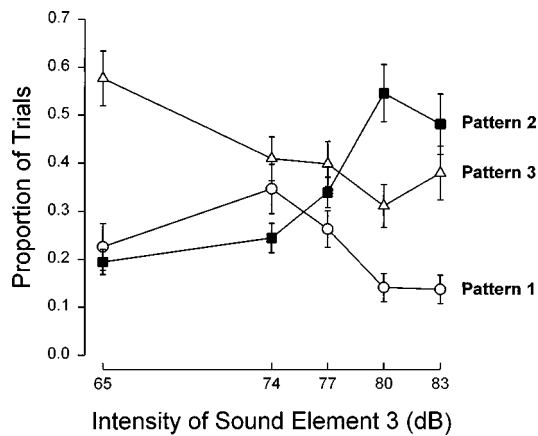


FIG. 7. Mean proportion of trials in which pattern 1 (XX-X-XX-; circles), pattern 2 (X-XX-XX-; squares), and pattern 3 (XX-XX-X-; triangles) were reported as a function of the intensity of the third sound element. Data are from experiment 3, sound-element 3 manipulation. Bars = ± 1 SEM. Filled symbols indicate the pattern beginning with the manipulated sound element.

ence scores provided a way to directly examine changes in the relative frequency with which any two patterns were chosen as a function of the intensity of the manipulated element, while taking into account that there were absolute differences in the response frequency between the patterns in the baseline condition (see Figs. 6, 7, and 8, 74-dB intensity condition). The three planned contrasts examined the effects of the intensity manipulation on the response differences between patterns 1 and 2, 1 and 3, and 2 and 3. This amounted to three one-way repeated-measures ANOVAs on the difference in log scores. Because there were three analyses for each sound-element manipulation, significance levels were set at $\alpha=0.017$ ($0.05/3$) to minimize the possibility of a type I error (Keppel, 1991).

It was expected that the difference in log scores between the pattern beginning with the manipulated element and the other two patterns would increase with increasing intensity. No specific predictions were made regarding the differences between the two patterns that did not begin with the manipu-

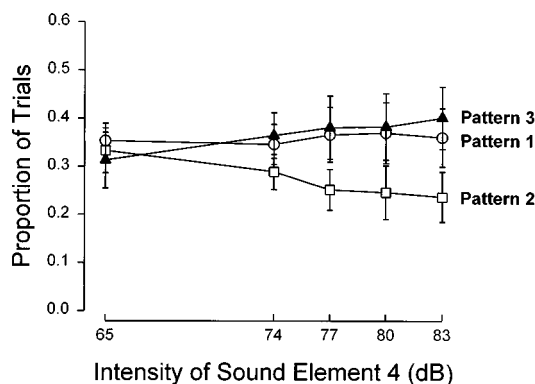


FIG. 8. Mean proportion of trials in which pattern 1 (XX-X-XX-; circles), pattern 2 (X-XX-XX-; squares), and pattern 3 (XX-XX-X-; triangles) were reported as a function of the intensity of the fourth sound element. Data are from experiment 3, sound-element 4 manipulation. Bars = ± 1 SEM. Filled symbols indicate the pattern beginning with the manipulated sound element.

lated element, and there were no specific predictions made about the differences in the conditions in which the intensity of the manipulated element was less than the baseline intensity.

1. Sound-element 1 manipulation

The statistical analyses did not reveal a significant effect of intensity on the differences between patterns 1 and 2 [$F(4,68)=0.65$, $p>0.62$]. However, there was a significant effect on the differences between patterns 1 and 3 [$F(4,68)=6.03$, $p<0.001$], and 2 and 3 [$F(4,68)=4.17$, $p<0.005$]. Tukey follow-up comparisons ($\alpha=0.05$) were conducted on the mean differences involved in the significant contrasts. For the contrast of patterns 1 and 3, there were significant differences between the 74-dB condition and the 83-, 80-, and 65-dB conditions, and also between the 77- and 83-dB conditions. For the contrast of patterns 2 and 3 there were significant differences between the 74-dB condition and the 83- and 65-dB conditions. There were no other significant pairwise comparisons.

It was expected that as the intensity of sound-element 1 (underlined) was incremented, the difference in response frequency between pattern 1 (XX-X-XX-) responses and both pattern 2 (X-XX-XX-) and pattern 3 (XX-XX-X-) responses would increase compared to baseline levels. This outcome was obtained for the comparison of patterns 1 and 3 with the two largest intensity increments. As shown in Fig. 6, the increased difference was due to an increase in the frequency of pattern 1 responses and a concurrent decrease in the frequency of pattern 3 responses. In addition, decreasing the intensity resulted in a significantly greater difference between these patterns, which was also due to an increase in the frequency of pattern 1 responses and a decrease in the frequency of pattern 3 responses. For the comparison of patterns 1 and 2, the expected outcome was not obtained; the difference in the frequency of pattern 1 and pattern 2 responses did not change significantly as a function of intensity. This outcome most likely resulted from the fact that the frequency of pattern 2 responses remained relatively stable across all intensity conditions (see Fig. 6). For the comparison of patterns 2 and 3, the difference was significant at the two intensity extremes—65 and 83 dB. Although pattern 3 was reported more often than pattern 2 in the baseline condition, pattern 2 was reported more often than pattern 3 when the intensity of sound-element 1 was increased or decreased by 9 dB.

2. Sound-element 3 manipulation

Analyses revealed a significant effect of intensity on the response differences between patterns 1 and 2 [$F(4,68)=8.5$, $p<0.001$], and 2 and 3 [$F(4,68)=11.84$, $p<0.001$], and a marginally significant effect of intensity between patterns 1 and 3 [$F(4,68)=3.23$, $p<0.018$]. For the contrast of patterns 1 and 2, the Tukey follow-up tests revealed that the 74-, 77-, and 65-dB conditions were all significantly different from both the 80- and 83-dB conditions. For the contrast between patterns 2 and 3, the 80- and 83-dB conditions were significantly different from the 74- and 65-dB conditions,

and the 77-dB condition was significantly different from the 65-dB condition. For the marginally significant contrast of patterns 1 and 3, there was a significant difference between the 74- and 65-dB conditions. No other pairwise differences were significant.

It was expected that as the intensity of sound-element 3 (underlined) increased, the difference in response frequency between pattern 2 (X-XX-XX-) responses and both pattern 1 (XX-X-XX-) and pattern 3 (XX-XX-X-) responses would increase compared to baseline levels. This outcome was obtained. For the comparison of patterns 1 and 2, the difference in response frequency was significantly greater than baseline levels for the two largest intensity increments. This was due to an increase in the frequency of pattern 2 responses with a concurrent decrease in pattern 1 responses (see Fig. 7). For patterns 2 and 3, the differences were also significantly greater than baseline levels for the two largest intensity increments. As Fig. 7 indicates, the frequency of pattern 3 responses remained relatively stable across the 74-, 77-, 80-, and 83-dB intensity conditions, but the frequency of pattern 2 responses increased with increasing intensity. As a result, although pattern 3 was reported significantly more often than pattern 2 in the baseline condition, pattern 2 was reported more often than pattern 3 in the 80- and 83-dB conditions. Also, decreasing the intensity of the third sound element resulted in a significantly greater difference in the frequency of both pattern 2 responses and pattern 1 responses compared to pattern 3 responses. The frequency of pattern 3 responses increased with decreasing intensity of the manipulated sound element, whereas the frequency of both pattern 1 and pattern 2 responses remained about the same as baseline (see Fig. 7).

3. Sound-element 4 manipulation

The analyses did not reveal a significant effect of intensity on the response differences between patterns 1 and 2 [$F(4,68)=0.35, p>0.84$], 1 and 3 [$F(4,68)=1.02, p>0.4$], or 2 and 3 [$F(4,68)=2.46, p>0.05$]. It was expected that as the intensity of sound-element 4 (underlined) increased, the difference in response frequency between pattern 3 (XX-XX-X-) responses and both pattern 1 (XX-X-XX-) and pattern 2 (X-XX-XX-) responses would increase compared to baseline levels. This outcome was not obtained. As Fig. 8 indicates, the pattern of responding was relatively stable across the five intensity conditions, although the frequency of pattern 2 responses tended to decrease slightly with increasing intensity of the fourth sound element, while the frequency of pattern 1 and pattern 3 responses tended to increase slightly.

4. Baseline conditions

A final analysis was conducted to test for overall differences in the frequency of responses to patterns 1, 2, and 3 in the baseline condition. For each participant, the proportion of trials on which pattern 1, pattern 2, and pattern 3 were reported was averaged over the three sound-element manipulation conditions. A constant of 1/60 was added to the average proportions, and the logarithms were calculated. The

log-transformed values were analyzed by a one-way repeated-measures ANOVA, which did not reveal a significant effect of pattern [$F(2,34)=1.09, p>0.34$]. This outcome supports the expectation that listeners would report the three patterns about equally often in the baseline condition. The averages across sound-element manipulation conditions were 35% (SE= $\pm 4\%$) for pattern 1, 27% (SE= $\pm 3\%$) for pattern 2, and 38% (SE= $\pm 4\%$) for pattern 3.

IV. DISCUSSION

The results of this study generally support Robin *et al.*'s (1990a) hypothesis that the amplitude of the neuronal response influences the perceptual organization of rhythmic auditory patterns. In experiments 1 and 2, increasing the intensity of the fourth sound element of the perceptually unambiguous sequence (XXX-X---) resulted in a perceptually ambiguous pattern organization; overall, listeners reported perceiving both of the alternative pattern organizations about equally often with the greatest intensity increments. Likewise, in experiment 3 it was found that increasing the intensity of either the first or third sound element of the perceptually ambiguous sequence (XX-X-XX-) biased the perceptual organization in favor of the pattern beginning with the altered sound element. Thus by manipulating the signal intensity of specific sound elements in the auditory sequences, which should have a direct effect on the underlying pattern of neuronal response amplitude, it was possible to produce predictable changes in the perceived pattern organizations.

Additional support for the hypothesis emerges in considering the results of experiment 3 when the intensity of either the first or third sound element of the ambiguous sequence was decreased. Under these conditions, the altered sound element appears to have taken on some of the qualities of a gap which then biased the perceptual organization of the sequence in specific ways. For example, when the intensity of sound element 3 was decreased (e.g., XX-x-XX-), the perceptual organization of the sequence was biased in favor of pattern 3 responses (e.g., XX-XX-x-). The reduced amplitude of the sound element effectively increased the size of the gap and, by increasing the degree of neuronal recovery from adaptation, produced an increase in the neuronal response amplitude associated with the fourth sound element. Thus listeners most often perceived the pattern as beginning with the sound element associated with the greatest neuronal response amplitude (i.e., pattern 3), as Robin *et al.*'s hypothesis predicts. When the intensity of sound-element 1 was decreased (e.g., xX-X-XX-), the perceptual organization of the sequence was biased in favor of pattern 1 responses (e.g., xX-X-XX-). In this case, the amplitude of the neuronal response associated with the second sound element would have been effectively increased, biasing perception of the pattern in favor of one beginning with the second sound element (e.g., X-X-XX-x). However, this pattern was not one of the response alternatives available to the listeners. Of the three available response alternatives, pattern 1 (XX-X-XX-) most closely resembles what listeners may have perceived, that is, a pattern containing a single sound

element in the middle position and ending with two consecutive sound elements.

The same logic can be applied to experiment 1 when the intensity of sound-element 4 was decreased (e.g., XXX-x---). In this case, the reduced intensity effectively increased the degree of recovery from neuronal adaptation during the gap, thereby increasing the amplitude of the neuronal response associated with the first sound element. However, because the frequency of responses to the standard unambiguous pattern was already high in the baseline condition (see Fig. 3), it would have been difficult to detect a significant increase in the frequency of responses in this condition. It is unlikely that when the intensity of the fourth sound element was increased, the listeners perceived a pattern organization other than the two available response alternatives.

There are some aspects of this study that are equivocal regarding Robin *et al.*'s hypothesis. For example, the hypothesis predicts that by increasing the intensity of the fourth sound element of the unambiguous sequence it should be possible to completely reverse the perceptual organization so that a new, unambiguous pattern beginning with the fourth sound element would emerge. This outcome was not obtained in experiment 1, nor was it obtained in experiment 2 even though the intensity increment from baseline was 9 dB greater than that in experiment 1. However, the averaged results do not accurately reflect the responses of all of the listeners. In experiment 1, the expected reversal in pattern perception was evident in the response patterns of two of the ten listeners (from 93% to 10% and from 80% to 20% in the baseline and 83-dB intensity conditions, respectively). On the other hand, performance remained relatively stable across all of the intensity conditions for three of the ten listeners, while the remaining five individuals demonstrated performance patterns similar to the averaged data. About the same degree of between-subjects variability was evident in the data from experiment 2. Three of the ten listeners demonstrated the expected reversal in pattern perception (from 97% to 7%, from 100% to 37%, and from 97% to 3% in the baseline and 83-dB conditions, respectively), and performance remained relatively stable across all intensity conditions for two of the ten listeners. The remaining five individuals showed performance patterns represented in the averaged data.

Furthermore, in experiment 3, increments in the intensity of the first and third sound elements of the ambiguous sequence biased the perceptual organization in favor of the pattern beginning with the altered sound element, but in neither condition did the pattern change from a perceptually ambiguous organization to a perceptually unambiguous organization. In addition, increments in signal strength of the fourth sound element did not have a significant effect on the perceived pattern organization. In general, the changes in pattern organization with increases in signal intensity observed in this study were significant but incomplete.

There are several possibilities that might explain why some of the expected results were not obtained. First, it may be that the magnitude of the intensity increments used in this study was insufficient to obtain the predicted results. Although the results of experiment 2 argue against this possi-

bility, additional research is needed to completely address this issue. Second, it may be that a ceiling effect was experienced due to the narrow-band frequency of the auditory stimuli used in this study. Each sound element consisted of a short-duration pulse of a 250-Hz computer-generated tone. This stimulus would have activated only a limited subset of auditory-nerve fibers, primarily those responsive to a signal frequency of 250 Hz. The intensity increments may have had a limited impact on the overall levels of neural activation, and this may have led to the overall limited perceptual changes observed. Robin *et al.* (1990a) used short-duration pulses of a white-noise stimulus. This broad-frequency-band stimulus would produce overall greater changes in the levels of neural activation with changes in signal intensity (e.g., Abbas, 1979), and might produce a clearer set of results regarding the relationship between sound-element intensity and auditory pattern organization.

A third possibility may be that the perceptual organization of these auditory sequences is not determined solely by the pattern of the neuronal responses proposed to underlie the run and gap principles, but may also be influenced by other organizing factors. For example, Povel (1981), Povel and Okkerman (1981), and Essens and Povel (1985) have identified several important factors in the perception of rhythm using temporally structured tone sequences similar to those used in the baseline conditions of this study. These factors include tempo, accent distribution (beats), starting point of the sequence, and inter-tone-interval ratios. Although in the present study the effects of starting point were controlled by randomly selecting the starting point of the sequence on each trial, the influence of the remaining factors on the perceptual pattern organization in this study is unknown and warrants further investigation.

V. CONCLUSIONS

The data from this study provide preliminary support for Robin *et al.*'s (1990a) notion that the relative pattern of neuronal response amplitude (i.e., the pattern of neuronal adaptation due to repeated stimulation and recovery from adaptation following a pause in stimulation) may underlie the run and gap principles that determine the perceived organization of cyclic auditory sequences. Variations in the intensity of specific sound elements in the sequences, which should have produced specific changes in the relative pattern of neuronal response amplitude, produced predictable changes in the perceived pattern organization reported by human listeners. However, not all of the predictions were supported by the data. The source of this discrepancy is unclear, but may be related to the narrow range of signal increments tested, the narrow-band nature of the stimuli used, or the presence of other organizing factors such as the distribution of perceived accents. Although the data clearly suggest an association between the perceptual organization of temporally structured auditory sequences and the pattern of neuronal response amplitude, additional research is needed to substantiate the link with regards to human listeners. Further verification of the hypothesis requires studies using techniques such as auditory evoked responses. Preliminary data by Hug *et al.* (1989) using auditory brainstem responses indicate that the neurosen-

sory responses of humans listening to the same ambiguous and unambiguous sequences as used in this study are similar to those of the cats studied by Robin *et al.* (1990a). A more extensive continuation of this work is needed.

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