Auditory pattern perception: The effect of tone location on the discrimination of tonal sequences

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This study examined the effect of tonal location on the discrimination of sequences differing in the order of the tones and on their perceived grouping. The frequency range between the sequential tones was held constant. When all tones came from the same location, the sequence was rated as integrated, but when the higher frequency tones came from a different location than the lower frequency tones, the sequence was rated as segregated. Listeners discriminated the sequences in a 3IFC task. Discrimination performance was impaired when the sequence was split between two locations and tonal order was changed in only one location, even though the order of tones in different locations was changed. This result suggests that listeners have difficulty relating tones across locations or in different perceptual groups. Performance in this experiment is generally better than that observed by Barsz (1988), and it is suggested that the level of stimulus uncertainty explains this difference.

This paper explores how the perceptual grouping of sequential tones affects our ability to discriminate the sequences. By perceptual grouping I mean the tendency to hear some tones as belonging together in a group. This group may include all the tones in the sequence, or some tones may be heard as grouped together and perceptually separated from other tones, which may in turn form their own group. Frequency relationships strongly affect the grouping of tones (Barsz, 1988; Bregman & Campbell, 1971; Deutsch, 1975; Dowling, 1973; Miller & Heise, 1950; van Noorden, 1975), although other factors are believed to affect grouping. Some examples are intensity (van Noorden, 1975), location (Judd, 1979; Steiger & Bregman, 1982), tempo (van Noorden, 1975), and sequence length (Bregman, 1978).

No factor independently determines which tones will form an auditory group. Instead, how a particular sequence is grouped depends on the interaction of all factors. For example, while most researchers have used tones of about 100 msec duration, the tempo needed for a sequence to segregate into multiple groups depends on the frequency relationships of the tones (van Noorden, 1975). Barsz (1988) obtained multiple groupings using 200-msec tones when the subgroups were separated by an octave. Deutsch (1975) found that listeners grouped 250-msec

tones on the basis of frequency relationships when tonal location was also manipulated. These studies demonstrate that perceptual grouping does not depend only on tonal duration, or only on tonal frequency, or only on tonal location, but on all factors working together.

Barsz (1988) explored how the discrimination of sequences depends on their perceptual grouping. In that study, subjects performed a 3IFC discrimination task. The stimuli were nonrepeating sequences with four target tones; each tone had a duration of 200 msec. The first and third target tones were close together in frequency, as were the second and fourth target tones. In the experimental condition, these two subgroups were far apart from each other in frequency, so that the sequence was rated as segregated in a control experiment. The comparison sequence differed from the standard in the order of the tones in just one of the frequency subgroups; however, the order of tones widely separated in frequency always changed. If subjects were able to use information about the order of tones in different frequency groups, they should have been able to perform the discrimination task. This condition was presented with three control conditions. In one control condition the order of target tones was changed in both frequency subgroups; the other two conditions had the same two order changes just described, but all target tones were close together in frequency. Thus, in the three control conditions, the order of tones in each frequency subgroup was changed.

Although subjects performed the discrimination task well in the control conditions, performance in the experimental condition was at chance. This result suggested that listeners were unable to relate tones in the different subgroups. Note that listeners could have correctly discriminated as many as 20 of the 30 sequences in the experimental condition without being able to relate tones in different frequency groups. By consistently attending to

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one of the groups, they would hear the order change on 15 trials, and they should by chance have obtained 5 more correct by chance. That performance did not reach this level suggests that listeners were not consistently listening to one group.

Because it has been found that discrimination improves as fewer different sequences are presented to the listener (reduced stimulus uncertainty; Leek & Watson, 1984), Barsz (1988) repeated the discrimination task using the experimental sequence and only one of the control sequences. To further reduce uncertainty, each kind of sequence was presented alone in a block. Under those conditions, discrimination of the experimental sequences rose to better-than-chance levels. This result suggests that stimulus uncertainty may interact with perceived grouping to affect sequence discrimination. The relationships between tones belonging to different groups seemed to be less accessible to listeners than relationships of tones belonging to the same subgroup, so that when uncertainty was high, discriminations depending on relationships of tones in different subgroups was at chance.

On the basis of those results, Barsz (1988) proposed a *hybrid hypothesis* to describe how sequences are processed by the auditory system. According to this hypothesis, the entire sequence is processed as a temporal compound, similar to those described by Warren (Warren, 1974; Warren & Ackroff, 1976; Warren & Byrnes, 1975). That is, the sequential components are not individually perceived but contribute to a global property that may be used to discriminate the sequence. These compounds may form subgroups, similar to the streams described by Bregman (Bregman & Campbell, 1971), on the basis of the overall composition of the sequence. The hybrid hypothesis states that the relationship of components in different subgroups may be used to discriminate sequences because those components contribute to the temporal compound. However, discriminations based on the relationships of components belonging to the same subgroup will be made more readily.

The hybrid hypothesis integrates the notions of temporal compounds and streams, which have been offered as alternate explanations of Warren, Obusek, Farmer, and Warren's (1969) finding that listeners were unable to identify the order of unrelated sounds in a rapid sequence. The temporal-compound hypothesis states that order identification failed because component order is not directly perceived in rapid sequences (Warren & Ackroff, 1976). The streaming hypothesis states that order identification failed because unrelated tones split into subgroups and the order of components in different subgroups is not preserved (Bregman & Campbell, 1971). Both explain the listener's failure to identify temporal order but make different predictions about discrimination. The temporal-compound hypothesis predicts better-than-chance discrimination of sequences differing in the order of their components, while the streaming hypothesis predicts that discrimination based on the order of components in different subgroups will be at chance. Barsz (1988) found that, when the most reliable cue was the order of tones in differ-

ent subgroups, discrimination was good under low stimulus uncertainty but poor under high stimulus uncertainty. Because both the temporal-order hypothesis and the streaming hypothesis were confirmed, she sought to integrate them.

The success of this integration depends on whether the two hypotheses refer to the same kinds of sequences. Warren and Ackroff (1976) state that temporal compounds form at component durations of a few milliseconds to a few hundred milliseconds. Warren (1974) gives the limits as 10 msec or less to well over 100 msec and states that temporal compounds can form at component durations long enough for temporal-order identification. Sequences have been reported to segregate into subgroups at rates of 50 msec to over 200 msec (Barsz, 1988; Bregman & Campbell, 1971; Deutsch, 1975; van Noorden, 1975). These rates are within the range of temporal compounds, suggesting that the temporal-compound hypothesis and the streaming hypothesis may in fact be applied to the same sequences.

Thomas and Fitzgibbons (1971) report that, when the frequency range of sequential tones is within a musical fourth, tonal order is accurately perceived at tone durations as low as 125 msec. However, as the frequency range of the sequence increases, the tone duration must be raised to as much as 500 msec for comparable performance. Although temporal compounds explain how temporal-order information could be available, it seems that a concept such as streaming is also needed to explain degraded performance across wide frequency ranges. The hybrid hypothesis is an attempt to develop a single explanation of sequence discrimination.

However, Barsz (1988) noted that such results could be explained if the auditory system is less able to process order information across wide frequency intervals than across narrow frequency intervals. If this is the case, then the impaired discrimination may not be related to perceptual grouping at all, but rather to the wide frequency intervals. For this reason, it is of interest to know whether the effects of grouping and uncertainty on discrimination are limited to sequences that segregate because of the frequencies of the components, or if those effects will generalize to sequences in which frequency intervals are held constant but that segregate on the basis of other factors.

In the present study, perceptual grouping was manipulated by varying the location of sequential tones. The frequency intervals between the sequential tones were held constant across conditions. In all other respects, the experimental conditions (e.g., the subject pool, subject instructions, and amount of practice) were the same as those used by Barsz (1988).

EXPERIMENT 1

It could not be predicted in advance how listeners would group the tones in the present sequences because these sequences differed with respect to frequency relationships, tonal location, tempo, and sequence length from those used in other studies. For example, Barsz (1988) obtained

segregation of similar sequences, but manipulated perceived grouping by frequency range rather than by tonal location. It is known that perceived grouping does not always conform to tonal location (Deutsch, 1975; Judd, 1979; Steiger & Bregman, 1982). Therefore, the first experiment tested the perceived grouping of the sequences to be used in the discrimination task.

Method

Subjects. Each undergraduate volunteer was given a standard audiometric test. The mean difference in thresholds for the two ears was determined at 1000, 2000, and 4000 Hz, and those with a difference greater than 5 dB were excluded from the study. Ten listeners were included and were compensated with course credit.

Equipment. Sine tones were generated by a Wavetek (Model 185) voltage-controlled oscillator. Frequencies were varied between 1159 and 3000 Hz using an Adalab D/A converter controlled by an Apple II microcomputer. A 6522 chip driven by the computer's quartz crystal time base was used to time all events. Frequencies and time intervals were measured with a Hewlett-Packard electronic frequency counter. Frequencies were accurate to within about 2 Hz. Intensity levels were monitored at the loudspeakers with a Hewlett-Packard 3400A true-rms voltmeter, which was calibrated using a General Radio (Model 1982) decibel meter placed at the location of the listener's head.

Tones presented on both speakers had a level of 70 dB SPL. Loudness matches by three experienced listeners established that a 7-dB intensity difference served to compensate for binaural loudness summation (Stevens & Davis, 1983). Consequently, tones presented on only one speaker had a level of 77 dB SPL. The frequencies used in this experiment have been shown to be equally loud (Stevens & Davis, 1983) when presented at 70–80 dB. These measures, along with the audiometric screening of the listeners, ensure that loudness variations are related to the manipulation of tonal location rather than the number of speakers presenting the tones, frequency differences among the tones, or interaural sensitivity differences. No listener in any of the experiments reported that some sequences or tones sounded louder than others.

The sequences were presented over speakers in an IAC sound-treated chamber. The speakers were placed 42 in. apart, and each speaker stood on a table at about the level of the listener's ears. The listener sat directly in between them so that one speaker faced the listener's right ear and the other faced the listener's left ear. Listeners were free to move their heads.

Sequences. Sequences were derived from different orders of sets of four tones, referred to as 1, 2, 3, and 4 from the highest frequency tone to the lowest. The 200-msec onset-onset duration included a 5-msec rise/decay time, 163-msec steady duration, and 27-msec intertone interval.

Each standard sequence began and ended with the same tone as its comparison, reducing the probability that sequences could be discriminated on the basis of the first or final tone of the sequence (Warren, 1974). In order to maximize the effectiveness of this tone (called a neutral tone, or N), its perceived grouping was made as ambiguous as possible by setting its frequency between that of the other tones and by presenting it on both speakers.

Thirty sets of frequencies were constructed by varying the frequency of Tone 1 between 2275 and 3000 Hz in steps of 25 Hz. The frequencies of Tones 1 and 2 were separated by a constant factor of .9. The frequencies of Tones 3 and 4 were .567 that of Tones 1 and 2, respectively, so that Tones 3 and 4 were somewhat lower in frequency than Tones 1 and 2. The frequency of the neutral tone (N) was the mean frequency of Tones 2 and 3. For example, when Tone 1 was 3000 Hz, Tone 2 was 2699 Hz, Tone 3 was 1700 Hz, Tone 4 was 1530 Hz, and N was 2199 Hz. These frequency intervals ensured that the tones were readily discriminable and that the

sequences did not form frequency-based perceptual groups when the tones were presented on both speakers.

Each set of frequencies was used in each condition. The tones were arranged in the orders N1324N or N2413N for Conditions 1 and 2; N1423N or N2413N for Condition 4; and N1423N or its comparison order for Condition 3. Half the Condition 3 comparison sequences had the order N2413N and half N1324N. These were the standard and comparison pairs to be discriminated in Experiment 2.

In Conditions 1 and 4, each tone was presented on both speakers. In Conditions 2 and 3, Tones 1 and 2 were presented on one speaker and the alternating Tones 3 and 4 were presented on the other speaker. In order to prevent conflicts between grouping by frequency range and grouping by tone location in Conditions 2 and 3 (Deutsch, 1975; Judd, 1979), the higher frequency tones were presented on one speaker and the lower frequency tones on the other speaker. The neutral tone was always presented on both speakers.

Procedure. Half of the listeners first heard a sequence of tones presented on both speakers. This was an example of a minimally segregated sequence, in which all the tones came from the same location. They next heard the same sequence with the higher frequency tones presented on one speaker alternating with the lower frequency tones on the other speaker. This was an example of a maximally segregated sequence, in which the higher frequency tones came from a different location than the lower frequency tones. The other half of the listeners heard these examples in the opposite order. These practice sequences ensured that the listeners understood the task. Practice sequences were constructed in the same manner as the experimental sequences but using different frequencies and tonal orders.

After the practice sequences, listeners heard one randomly chosen member of each of the 120 pairs of experimental sequences (4 conditions $\times$ 30 sequences in each condition). They were asked to rate the segregation of each sequence relative to that of the practice sequences they had just heard and to respond by pressing one of six buttons on a response box. Buttons 1 to 3 were labeled "minimally segregated." Buttons 4 to 6 were labeled "maximally segregated." The extreme buttons (1 and 6) were labeled "very sure," the next two (2 and 5) were labeled "sure," and the two center buttons (3 and 4) were labeled "unsure."

The listeners heard the sequences in a single randomized block of 120 trials. A General Radio (Model 1382) noise generator was used to produce wide-band noise at a spectrum level of 15 dB to indicate when the block was ready to begin and when the block was over. Listeners were allowed to take as long as they wished to rate each sequence. An intertrial interval of 1 sec followed each response. Listeners took about 15 min to complete the task.

Results and Discussion

As shown in Table 1, Conditions 1 and 4 received mean ratings of 2.3 and 2.2, respectively. Conditions 2 and 3 received mean ratings of 5.4 and 5.5, respectively. These ratings differ significantly [$F(3,27) = 81.147$, $p < .001$]. A Tukey test of all pairwise comparisons showed that the ratings given to the sequences in Conditions 1 and 4 differed from those given to the sequences in Conditions 2 and 3 ($p < .01$). Condition 1 did not differ from Condition 4 and Condition 2 did not differ from Condition 3 ($p > .05$).

This result shows that these nonrepeating sequences segregated into subgroups when the higher frequency tones came from a different location than the lower frequency tones (Conditions 2 and 3), even at the slow tempo used here. When all the tones were presented on both speakers (Conditions 1 and 4), the sequences were rated

Table 1
Effect of Location

Condition	Rating	Experiment 2 Correct	Different From Chance	Experiment 3 Correct
CD1—one subgroup; order permuted as in CD2	2.3	20.5	$t = 5.8$ $p < .001$	
CD2—two subgroups; order permuted in each	5.4	21.6	$t = 6.4$ $p < .001$	
CD3—two subgroups; order not permuted in each	5.5	16.4	$t = 5.9$ $p < .001$	14.7
CD4—one subgroup; order permuted as in CD3	2.2	19.3	$t = 5.4$ $p < .001$	16.1

Note—A rating of 1 indicates that the sequence is perceived as integrated; a rating of 6 indicates that the sequence is segregated.

as integrated. This finding extends that reported in Barsz (1988), in which perceived grouping was manipulated using frequency range in nonrepeating sequences of similar tempo.

It is known that the interaural loudness difference produced when a tone is presented at the side of the listener is less pronounced at lower frequencies (Stevens & Davis, 1983). Although sequences were rated as slightly more integrated as the frequencies of the sequential tones decreased, this effect was not significant [$r(28) = .309$, $p > .05$], and the sequence using the set of tones with the lowest frequencies was rated as more segregated in Conditions 2 ($M = 4.5$) and 3 ($M = 5.1$) than in Conditions 1 ($M = 2.2$) and 4 ($M = 1.6$). Thus, interaural loudness differences were effective even for the sequence with the lowest frequency tones.

The function of the neutral tone was to prevent the listener from discriminating sequences based on the first or last tone, so that its grouping is of special concern. However, the rating data do not show which particular tones group together. The neutral tone may have grouped with the high frequency tones on one speaker, with the low frequency tones on the other speaker, or by itself in a medial location. Several listeners commented that some sequences sounded like one group while others split into two separate groups, each coming from a different location. These comments suggest that the neutral tone did not form a third group. This issue will be further discussed with the results of the discrimination task.

The Condition 1 and 4 sequences contained subgroups of tones separated in frequency, and it is possible that the listeners rated them as integrated because the nature of the practice implied that they should ignore frequency-based groups. However, the frequency intervals used here were selected so that, at the slow tempo used, frequency-based perceptual groups would not form in Conditions 1 and 4. These sequences were judged to sound integrated during informal listening prior to data collection, and the listeners' comments reported above support that notion.

The purpose of this experiment was to determine how the sequences used in the discrimination task were perceptually grouped. The results suggest that the sequences

do not segregate when all tones are presented on both speakers but do segregate when the tones alternate between speakers. Nevertheless, we may not conclude that location cues are sufficient to induce the segregation of sequences, because the location cues were supported by the frequency relationships among the tones. The conclusion that location cues alone can cause sequence segregation would require the study of sequences whose tones all have the same frequency but vary in location.

EXPERIMENT 2

This experiment compared discrimination of sequences in which tonal order was changed in each subgroup with discrimination of sequences in which tonal order was not changed in all subgroups.

Method

Subjects. Ten new listeners, selected as in Experiment 1, participated in return for course credit.

Equipment and Stimuli. The equipment and sequences were those used in Experiment 1. In Conditions 2 and 3, the target tones alternated between speaker location. In Condition 2, the order of tones presented on each speaker was changed; that is, Tones 1 and 2 were exchanged and Tones 3 and 4 were exchanged. This condition controlled for the effect of interaural presentation on discrimination performance. In Condition 3 (the experimental condition), the order of Tones 1 and 2 or Tones 3 and 4 were exchanged. Thus, the order of tones presented on only the left speaker (for 15 trials) or right speaker (for 15 trials) was changed; the relationship of tones presented on different speakers (i.e., Tones 1 and 4, and Tones 2 and 3) always changed.

Conditions 1 and 4 had the same tones in the same tonal orders as Conditions 2 and 3, respectively, but all tones were presented on both speakers. These conditions controlled for the effects of the tonal order changes when all the tones were presented in one location. The Condition 4 sequences were not counterbalanced (as were the Condition 3 sequences) because all tones were presented on both speakers.

Procedure. The 120 sequence pairs were presented in random order. A trial consisted of two presentations of the standard (chosen randomly from each sequence pair) and one presentation of the comparison. The comparison could be presented first, second, or third with equal probability. There was a 500-msec intersequence interval.

After hearing the three sequences, the listener indicated whether the comparison was first, second, or third by pressing one of three

buttons, labeled "one," "two," and "three." Listeners were required to guess if uncertain. The next trial began 1 sec after the response.

Listeners were given four practice trials, one with a novel sequence in each condition, to ensure that they understood the task. Then the experimental trials were presented in four blocks of 30 trials each. All blocks contained sequences from each condition, lasted approximately 5 min, and were followed by a rest break. Noise was used to indicate when a block was ready to begin and when it was complete; listeners began each block by pressing a start button.

Results and Discussion

As shown in Table 1, the mean scores were 20.5 correct in Condition 1, 21.6 in Condition 2, 16.4 in Condition 3, and 19.3 in Condition 4. These means are significantly different [$F(3,27) = 8.824, p < .001$]. A Tukey test of all pairwise comparisons showed that performance in Condition 3 differed from performance in Conditions 1 and 2 ($p < .01$). No other differences were significant.

In Conditions 1 and 4 (rated as integrated in Experiment 1) and in Condition 2 (rated as segregated in Experiment 1), the tonal order of each location group was changed. Discrimination performance did not differ among these conditions. In Condition 3 (rated as segregated in Experiment 1), tonal order was maintained in one location group, although the order of tones presented in different locations was always changed. The fact that discrimination performance was impaired in this condition is consistent with the notion that listeners have difficulty relating tones in different locations.

These results extend those of Barsz (1988) to sequences in which the frequency intervals between the tones are held constant but which segregate on the basis of location cues. This result weakens the hypothesis that impaired discrimination performance in the experimental condition is due to listeners' difficulty in relating tones across wide frequency intervals, since a similar impairment in discrimination was obtained here with frequency intervals held constant. Rather, the impaired discrimination appears to be due to listeners' difficulty in relating tones in different perceptual subgroups.

Barsz (1988) suggested that the sequences may perceptually segregate only when listeners are rating their perceived grouping, remaining perceptually integrated when listeners perform discrimination tasks. The impaired discrimination of sequences in which some groups have the same tonal order would then be explained by listeners' difficulty in relating tones that are widely separated on some physical dimensions (e.g., frequency or location) rather than their difficulty in relating tones in different groups. Note that since separation on physical dimensions is related to perceived grouping, both explanations predict the same results. A critical test would require measuring perceived grouping simultaneously with sequence discrimination (but see King, 1990, for a study addressing a similar confound in visual research). Until such a test is performed, it seems more acceptable to attribute changes in discrimination performance to one factor (per-

ceptual grouping) rather than to multiple factors (frequency range, location, etc.).

Performance in the experimental condition (16.4) did not reach the optimal level of 66% correct discussed in the introduction, again suggesting that listeners do not consistently listen to one group. However, in contrast to the earlier results (Barsz, 1988), performance in the present Condition 3 was better than chance [dependent two-tailed t test, $t(9) = 5.9, p < .001$]. Indeed, discrimination performance is better in each condition than that reported by Barsz (1988; Condition 1, 15.6; Condition 2, 17.1; Condition 3, 11.6; and Condition 4, 14.6). Some factor may have facilitated discrimination performance in the present experiment, elevating it above chance in Condition 3. The two experiments are distinguished by the size of the frequency intervals, the factor used to induce segregation, the grouping of the neutral tone, and stimulus uncertainty. Let us consider each of these.

The present Conditions 2 and 3 had narrower frequency intervals than the earlier Conditions 2 and 3. Performance may have been facilitated because listeners had an easier time relating tones across a narrower frequency range. If so, performance ought to be worse in the present Conditions 1 and 4, because the frequency range was wider than that used in Barsz's (1988) Conditions 1 and 4. However, performance in Conditions 1 and 4 was better in the present experiment, so that frequency interval does not appear to be related to discrimination performance.

Perhaps groups formed by location are weaker than groups formed by frequency range, so that performance in Conditions 2 and 3 was facilitated by weaker segregation. If this is true, performance in the present Conditions 1 and 4 ought to be similar in Barsz (1988) and the present experiment, because these sequences were rated as "one group" in both studies. As mentioned above, performance improved in Conditions 1 and 4 in this experiment, in contrast to this prediction.

Alternatively, although Conditions 1 and 4 were rated as integrated, their integration might be somewhat weakened by the wider frequency intervals used in these sequences. If so, performance in Condition 4 ought to be impaired, because tonal order was changed in only one of the frequency groups. Although the order change was not counterbalanced as it was in Condition 3, listeners do not appear to attend consistently to one group. Thus, successful discrimination of segregated Condition 4 sequences would seem to require relating tones across the wider frequency intervals. Since performance in Condition 4 improved in this experiment and was not significantly different from that in Condition 1, an explanation based on the weakened integration of the Condition 1 and 4 sequences is not supported.

Another factor to consider is the effectiveness of the neutral tone. In both Barsz (1988) and the present study, the grouping of the neutral tone was made as ambiguous as possible in Conditions 2 and 3 by setting its frequency in between that of the higher frequency and lower frequency groups. In addition, in the present experiment,

the neutral tone was presented on both speakers. As discussed earlier, this may have caused it to form a third group and thus reduced its effectiveness, facilitating discrimination performance. However, listeners' comments (similar to those noted in Barsz, 1988) suggest that in fact it did seem to belong to one of the other groups. Further, this explanation would not account for the improved performance in Conditions 1 and 4.

Barsz (1988) obtained improved discrimination of the Condition 3 sequences by reducing the number of tonal patterns presented in a block, and concluded that reducing stimulus uncertainty facilitated discrimination. In the present experiment, the same frequencies were used in each condition. Thus, the number of different frequency patterns was fewer than in Barsz (1988), in which perceived grouping was manipulated by changing the frequencies of the tones. It is possible that this reduced stimulus uncertainty is responsible for the uniform improvement in discrimination performance, which in turn resulted in above-chance discrimination of the Condition 3 sequences. Experiment 3 tested the effect of a further reduction of uncertainty on discrimination performance.

EXPERIMENT 3

This experiment further investigated the effect of reduced uncertainty. The Condition 3 sequences of Experiment 2, which were rated as segregated and which contained an order change on only one speaker, were presented in one block. The Condition 4 sequences, which have the same tonal order change as Condition 3 but which were rated as integrated, were presented in a separate block.

Method

Subjects. Ten new listeners, selected as for Experiment 1, participated in return for course credit.

Equipment and Stimuli. The equipment was that used in Experiment 1, and the sequences were those used in Conditions 3 and 4 of Experiment 2.

Procedure. Each block consisted of a randomized order of the 30 sequence pairs of one of the conditions. Half of the listeners heard the Condition 3 sequences first; the other listeners heard the Condition 4 sequences first. The listeners were given two practice trials, one with each kind of sequence. Otherwise, the procedure was the same as that followed in Experiment 2.

Results and Discussion

The results are shown in Table 1. The mean scores were 14.7 and 16.1 correct in Conditions 3 and 4, respectively. These means are not significantly different [$F(1,9) = 0.74$, n.s.]. Performance in Condition 3 remained significantly better than chance [$t(9) = 3.8$, $p < .01$] and was not significantly better in this experiment than in Experiment 2 [$F(1,18) = 1.07$, $p > .05$]. Neither did performance in Condition 4 differ between the two experiments [$F(1,18) = 1.66$, $p > .05$]. Thus, it would appear that

the level of uncertainty in Experiment 2 was low enough to optimize performance.

CONCLUSION

Experiment 1 showed that a nonrepeating sequence of 200-msec tones was rated as segregated when the higher frequency tones came from a different location than the lower frequency tones. When the same tones were presented at a single location, the sequence was rated as integrated. Barsz (1988) showed that nonrepeating sequences of 200-msec tones may be rated as integrated when all the tones are close together in frequency and segregated when some tones are far in frequency from other tones. Together, these results support Bregman and Campbell's (1971) proposal that auditory sequences are grouped according to heuristics that operate on the overall composition of the sequence. In the environment, different sound sources have different frequency characteristics and different spatial locations, so that such a grouping mechanism would be an adaptive method of sorting a complex sound wave into the components that are due to each contributing sound source. However, while it is tempting to assume that the perceived groups consist of the tones that are similar in frequency or that come from the same location, the rating data do not in fact indicate which tones were perceived to be in which group.

The results of Experiment 2 show that discrimination of sequences differing in tonal order is impaired when alternating tones come from different locations, and the most reliable discrimination cue is the relationship of tones in different locations. Assuming that the tones are grouped according to their location, this result would support the contention (Barsz, 1988; Bregman & Campbell, 1971) that listeners have difficulty relating tones in different subgroups and would extend the result of Barsz (1988) to sequences in which grouping is manipulated by location rather than frequency relationships.

Barsz (1988) found that, for sequences in which the most reliable cue was the relationship of tones far apart in frequency (and presumably in different perceptual groups), discrimination performance was at chance, but improved when stimulus uncertainty was reduced. Discrimination in the analogous condition of the present experiments was better than chance, again in conjunction with low stimulus uncertainty. Thus, the relationship of tones in different groups may be available, but not used when uncertainty is high. In this regard, Bregman and Campbell's (1971) first experiment is of interest. Their listeners were allowed to hear a repeating sequence until they were ready to identify the order of the tones. Presumably this condition represents minimal uncertainty; nevertheless, performance was impaired for tones in different frequency subgroups. Perhaps the order of tones in different subgroups is preserved in a manner that permits discrimination but not identification. Alternatively,

perhaps reduced uncertainty allows the listener to attend to more than one subgroup at a time (Barsz, 1988), a strategy which would not have helped Bregman and Campbell's (1971) listeners.

The present results are consistent with the hybrid hypothesis that sequences are grouped according to their overall composition and that while the relationships of components in different groups are preserved by the auditory system, they are not always accessible. This hypothesis is flawed in that disproving it involves showing that the relationships of components in different groups is *never* available. However, if the present results and those of Barsz (1988) can be shown to be due to listeners' ability to attend to multiple subgroups instead of their ability to use the relationships of components in different subgroups, the hypothesis would become untenable. Even if it is demonstrated that listeners are in fact using the relationships of components in different subgroups for discriminations, many questions remain. For example, can such relationships be identified, or are they merely available for discrimination? Does the hybrid hypothesis hold for types of sequences other than those used in the present study and by Barsz (1988) (e.g., sequences with unrelated tones, shorter tone durations, sequences in repeating loops, etc.)? Do conditions other than stimulus uncertainty facilitate the use of such relationships? Research exploring these issues is currently under way.

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