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The perceived similarity of auditory polyrhythms

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This experiment explored the structural representation of rhythm by having subjects rate the similarity of pairs of polyrhythms. Three different polyrhythms were employed (3×4, 3×5, and 4×5). Although subjects were instructed to ignore pitch, two types of pitch information (pitch proximity and tonal relatedness) were varied between the tones defining the polyrhythms in order to assess their influence on the similarity space of the rhythms. The results showed that, independently of pitch, some rhythm combinations were considered more similar than others. Pitch information had a uniform effect on polyrhythm similarity, systematically increasing or decreasing the similarity among all rhythms by roughly the same amount. This suggests that pitch information may have been processed independently of rhythmic information, and that only at another stage in processing is information from the two dimensions integrated.

Current theoretical models of rhythm perception employ hierarchical trees of varying degrees of complexity to explain perceptual grouping of temporal sequences (Jones, 1981; Lerdahl & Jackendoff, 1983; Longuet-Higgins & Lee, 1982; Martin, 1972; Povel, 1981; Povel & Essens, 1985; Yeston, 1976). Common among them is the notion that rhythm is internally structured on the basis of the relative duration of temporal elements. Duration ratios composed of integer multiples have been found to be the most accurately represented, especially 2:1, although Essens and Povel (1985) provide evidence that suggests that noninteger multiples may be encoded equally well. The present study was undertaken to explore further the cognitive structure of rhythm by examining the perceived similarity of rhythms. The following questions were asked: What does the similarity space between different rhythms look like? How do variations in another musical dimension (pitch) alter the similarity space?

Research examining the spatial representation of rhythm was conducted by Gabrielsson (1973a, 1973b) and most recently by Monahan and Carterette (1985). Monahan and Carterette investigated the psychological similarity of rhythms; in their study, trained musicians rated the similarity of six-note melodies in which a number of pitch and rhythm variables were altered. The results revealed that subjects attended to three factors when basing their judgments on the dimension of rhythm. These were meter of the melodies (duple or triple), accent placement on a rhythmic grouping (accent first as opposed to accent last), and duration pattern of the rhythms. (Anapestic patterns were grouped with trochaic patterns, and iambic patterns with dactylic.) These results suggest that subjects were quite sensitive to rhythmic variables and could evaluate the similarity of the melodies reliably by using rhythmic factors. They also indicate that subjects are able to analyze critically the components of a rhythmic pattern. In addition, the results provided encouragement for the present study, which required subjects to rate the similarity of considerably more complex rhythmic patterns.

Polyrhythms were chosen as the type of pattern to be used in this study. These are defined as the simultaneous presentation of two (or more) conflicting but isochronous pulse trains. For example, a 3×4 ("3 by 4") polyrhythm has one line that beats three times to four beats of the other line (Figure 1, first example). Polyrhythms are repeating rhythmic patterns with the pulse trains coinciding once per cycle. The decision to use polyrhythms was based on a consideration of the emergence of perceived rhythm in music. Rhythmic structure can be highly complex in polyphonic music, where many independent rhythmic lines are occurring simultaneously. These lines can be "consonant" with each other (Yeston, 1976), and thereby strengthen accent or grouping, or they can be "dissonant," creating syncopation and ambiguous rhythmic interpretations. In the context of many co-occurring rhythmic lines, it seems highly unlikely that the rhythmic percept can be located at only one level of a composition. Rather, perceived rhythm probably emerges from the combined interaction of many of the levels. Using polyrhythms is an attempt to employ stimuli that simulate this interaction. Also, polyrhythms lend themselves to system-

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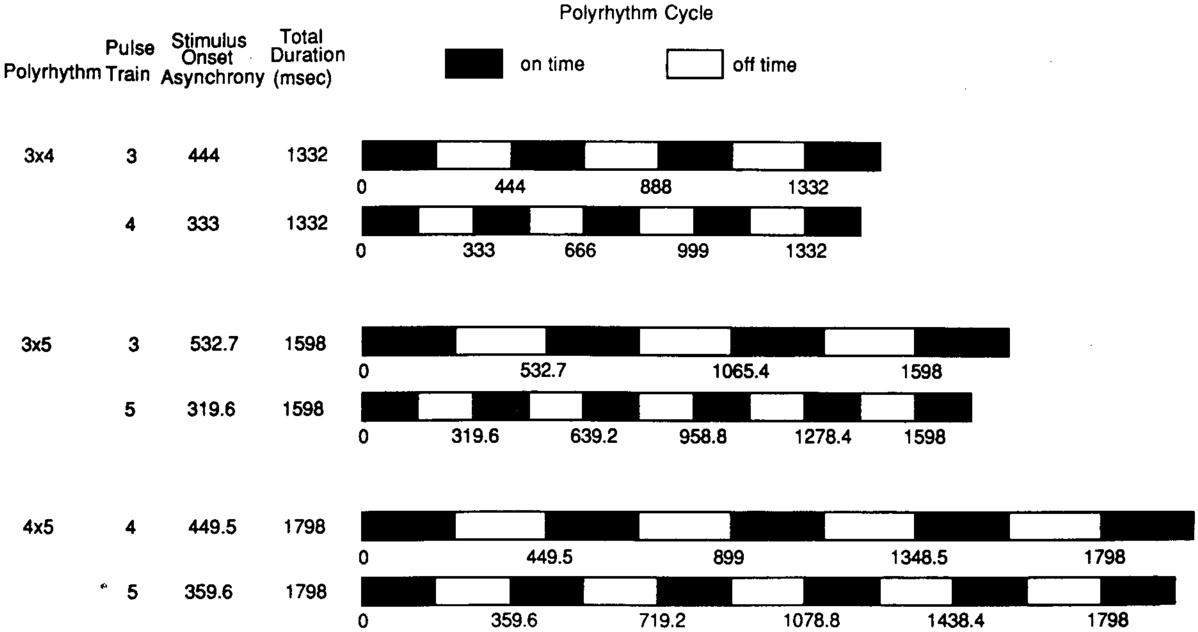

Figure 1. Timing of each polyrhythm for one cycle. The numbers below each pulse-train cycle denote the consecutive onset times (in milliseconds) of the pulse train in one cycle. The first "on time" of each pulse train in the next polyrhythm cycle is also shown.

atic variation through the combination of pulse trains with different values (e.g., 3 with 4, as well as 3 with 5).

Handel and Oshinsky (1981) and Handel (1984) argue for the same position and provide evidence that rhythmic interpretation is dependent on the current musical context. In a series of experiments (Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978; see Handel, 1984, for a review), rhythmic interpretation, as measured by the subject's tapping to components of the polyrhythm, could be altered by changing several variables that comprise the complex rhythm. For instance, presentation rate proved to be a major factor affecting interpretation. At slow rates, subjects tapped to the faster pulse trains; at fast rates, subjects tapped to the slower pulse trains. At the fastest rates, subjects gave a "unit response," tapping only once at the coincidence of the pulse trains comprising the polyrhythm.

Other variables that Handel and his colleagues have shown can affect the perceived rhythm are: (1) polyrhythm configuration (e.g., 3×4 or 2×5); (2) pitch values of the independent pulse trains—low-pitch pulse trains were tapped to more often than high-pitch pulse trains; (3) relative intensity of the individual pulse trains; (4) alteration of the note durations in a rhythmic line. The last factor amounts to varying the proportion of a time interval that is sound-filled, and related to the musical dimension legato-staccato.

The above variables do not always affect polyrhythm interpretation. Handel and Oshinsky (1981) and Handel and Lawson (1983) found that the controlling factor that determined what variables affected rhythmic interpretation was polyrhythm configuration. So, although the only factor that affected interpretation of a 3×5 rhythm was presentation rate, both this and pitch-interval differences between the rhythmic lines contributed to the final percept of the 3×4 pattern. These results suggest that polyrhythm interpretation emerged from its current context, being influenced by nonrhythmic as well as rhythmic factors.

The implications of these results for the present study are that the similarity space between polyrhythms might change as a function of other variables present in the rhythmic context. Introducing pitch changes between pairs of polyrhythms may alter the relationship between them so that one pair of rhythms may sound more similar whereas another pair may sound more different. To examine this possibility, we varied the pitch interval between pulse trains comprising the polyrhythms.

Research investigating the perceived similarity of pitches has found that frequency proximity (Stevens & Volkman, 1940), tone chroma (Shepard, 1964), and tonality (Bartlett & Dowling, 1980; Krumhansl, 1979; Krumhansl & Shepard, 1979) are salient dimensions of pitch space. Krumhansl (1979) showed that the similarity ratings of two notes within a tonal context (a diatonic scale played prior to presentation of the test tones) were based on the relative distance between the two notes as well as on their relationship to the tonal system. With the latter finding, there emerged a hierarchy of tonal relatedness: the major third and perfect fifth were judged to be the most similar in the context; these were followed by the other tones of the diatonic scale, which, in turn, were considered more similar to the context than nondiatonic notes. Using a different paradigm, Krumhansl and Shepard (1979) and Krumhansl and Kessler (1982) have obtained similar results. Krumhansl (1979) found an asymmetry in similarity ratings that was due to the ordering of the test tones. Pitches were rated as more similar when the first tone of the two-tone test sequence was less closely related to the tonal context than was the second tone. Presenting the notes in the reverse order yielded lower ratings.

THE CURRENT STUDY

Rhythm Factors

Three polyrhythms were employed in the experiment. The 3×4 and 4×5 patterns were chosen because pitch had influenced their rhythmic interpretation in earlier work (Handel & Lawson, 1983; Handel & Oshinsky, 1981). We chose 3×5 as the third polyrhythm in order to compare all possible pairings of 3-, 4-, and 5-pulse trains. In addition, pitch did not influence interpretation of the 3×5 pattern in the studies by Handel and his colleagues. A parallel result in the present study implies that the perceived distance between 3×4 and 4×5 patterns will be different from those between 3×5 and 3×4 or 4×5 patterns.

The order in which two polyrhythms are heard may differentially affect their perceived similarity. Order of polyrhythm presentation within a pair was therefore included as a variable.

Pitch-Interval Factors

We chose the pitch intervals between the two pulse trains of each polyrhythm in order to permit variations in the dimensions of pitch proximity and tonal relatedness. Four different intervals were chosen: major second (M2), perfect fourth (P4), perfect fifth (P5), and major seventh (M7). M2 and M7 are dissonant intervals, and each represents an extreme in frequency proximity within an octave: M2 is the smallest diatonic interval and M7 is the largest. P4 and P5 are both consonant intervals and represent moderate values of frequency proximity. If, when judging the similarity of the rhythms, subjects are influenced by pitch proximity, then ratings should decrease as the distance between comparison intervals increases. In this case, the M2/M7 interval pair would be expected to yield the lowest ratings whereas the P4/P5 pair should produce the highest. If, on the other hand, subjects attend to the tonal relatedness of the notes, an asymmetry in the rating profiles should emerge from the presentation order of the pitch intervals (Krumhansl, 1979). That is, judgments of rhythms possessing the interval pair M7/P5 should be considered as more similar in this order than in the reverse order—P5/M7 (Figure 2, Panels A and B). An asymmetry based on presentation order would not be expected if only pitch proximity was being employed. The order in which pitch intervals were presented was therefore included as a variable to test this possibility.

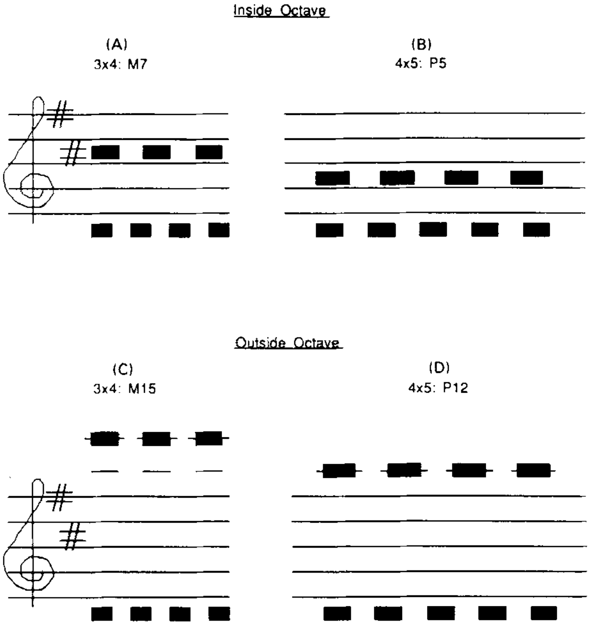

Figure 2. Examples of a trial consisting of a pair of different pitch intervals in both the inside-octave (Panels A and B) and outside-octave (Panels C and D) conditions, with polyrhythms 3×4 and 4×5, respectively. Intervals presented in the order shown should yield higher ratings than intervals presented in the reverse order if tonality is being attended to. The thick bars represent both pitch and duration values.

Octave Equivalence

In addition to the two manipulations of pitch interval, we also explored how similarity ratings might change by the addition of an octave to all the pitch intervals. This amounts to choosing the note in the next octave that possesses the same tone chroma as the current top note (i.e., D or G). So, for example, along with comparing M7 with P5, there was also an equivalent comparison of M15 with P12 (Figure 2, Panels C and D). The inclusion of this factor allowed us to examine if and how the influence of the two pitch dimensions changed beyond 1 octave. If tonality is truly abstracted from the context, the same asymmetry results obtained within an octave should hold outside of 1 octave. It is difficult to predict how ratings based on pitch proximity alter when the comparison intervals span more than an octave, although we hypothesized that interval discrimination might not be as good, given that people rarely hear dyads in music of more than an octave.

How this octave manipulation would affect perception of the polyrhythms was also difficult to assess. Attentional and processing demands might conceivably be greater when the notes are spread beyond an octave. If processing load is too great and subjects are unable to focus on the whole rhythmic pattern, the phenomenon of "rhythmic fission" or stream segregation may arise (Bregman, 1978; Bregman & Campbell, 1971; Dowling, 1967; van Noorden, 1975). This results in the auditory percept's being segmented into different "streams," with attention being directed to just one of the streams and others being disregarded. Streaming is governed in part by the presentation rate of the auditory patterns as well as by the frequency separation between the stimuli. Care was taken here, when choosing a presentation rate, to ensure that stream segregation was not obligatory, although streaming could have been consciously induced. To avoid subjects' attending to just one rhythmic line (streaming), they were instructed to focus on the entire polyrhythm and also to disregard pitch.

Design

The effects of the preceding variables were evaluated in four different experimental conditions, each of which was constructed to be conceptually more complex than the previous one. The first, and simplest, condition (same rhythm × same pitch interval) consisted of trials in which subjects heard identical polyrhythms paired with identical pitch intervals (Table 1, Condition 1). This condition was included, in part, as a control condition to assess whether subjects could perform the similarity rating task reliably. In addition, any observed differences between the two octave conditions might indicate the presence of processing limitations. An originally planned condition in which the notes of a polyrhythm were identical (i.e., there was no pitch interval) was omitted because the perception of two independent rhythmic lines was lost when the "on time" of both lines overlapped (see Figure 1).

In the second complexity condition (same rhythm × different pitch interval), identical polyrhythms were paired with different pitch intervals (Table 1, Condition 2). Here we examined the independent effect of pitch interval. Because the rhythms were the same in this condition, similarity judgments should be identical throughout all pitch-interval combinations, provided subjects were not influenced by pitch information while attending to the polyrhythms.

The third complexity condition (different rhythm × same pitch interval) paired different polyrhythms with each other, but the pitch intervals remained identical in each rhythm. This enabled us to assess the similarity space of different polyrhythms in the absence of any pitch changes between rhythms. Finally, the fourth, and most complex, condition (different rhythm × different pitch interval) included comparisons between different polyrhythms that possessed different pitch intervals. This condition allowed us to determine how the relative similarity of different polyrhythms was altered by changing the pitch intervals between them.

Table 1
Rhythm and Pitch-Interval Combinations in Each of the Four Experimental Conditions

	Combination		
Condition	Rhythm	Pitch Interval	Set of Pitch and Rhythm Combinations
1	Same	Same	3×4/3×4,3×5/3×5,4×5/4×5 M2/M2,P4/P4,P5/P5,M7/M7
2	Same	Different†	3×4/3×4,3×5/3×5,4×5/4×5 M2/P4,M2/P5,M2/M7,P4/P5 P4/M7,P5/M7
3	Different*	Same	3×4/4×5,3×4/3×5,3×5/4×5 M2/M2,P4/P4,P5/P5,M7/M7
4	Different*	Different†	3×4/4×5,3×4/3×5,3×5/4×5 M2/P4,M2/P5,M2/M7,P4/P5 P4/M7,P5/M7

*Rhythm order: Presentation order of the polyrhythms was varied (i.e., 3×4/4×5 was presented as well as 4×5/3×4). †Pitch-interval order: Presentation order of the pitch intervals was varied (i.e., M2/P4 was presented as well as P4/M2).

By comparing performance across experimental conditions, a measure of rhythm discriminability in each pitch context can be obtained. Comparison of Conditions 1 and 3 gives an estimate of the discriminability of rhythms while pitch interval is held constant in a particular comparison. Conditions 2 and 4 give an estimate of discriminability of rhythms when pitch interval varies between rhythms.

Method

Subjects. Twenty Yale undergraduates (9 female, 11 male) participated in this experiment as part of a course requirement. They possessed diverse musical backgrounds, and the range of musical experience, with 0 to 10 years of training, was wide. No subject reported any hearing problems.

Materials and Apparatus. A Commodore 64 microcomputer was employed to control stimulus construction, presentation, and response collection. The stimuli were formed by the computer's internal signal processor; the tones approximated square waves, and covered a range of 3 octaves, from C3 (130.81 Hz) to B5 (987.77 Hz); all frequency values were those of the equal-tempered 12-tone chromatic scale (note values in hertz were taken from Backus, 1977). The attack and decay/release times of the notes were uniformly set at 8 and 24 msec, respectively. The remainder of the note duration was a constant sustain. "On time" of the tones was set at 50% of the stimulus onset asynchrony.

The notes were passed through an amplifier (Realistic, QA-620) to one free-standing speaker (Realistic, Solo-103) positioned 2 ft in front of the subject. The polyrhythms were played at a comfortable listening level and testing took place in a small, quiet room. The subjects responded by using the numbered keys 1 through 7 on the computer keyboard.

Polyrhythms may be equated temporally in either of two ways: (1) by maintaining a fixed cycle time for all the polyrhythms, which results in a higher note density per unit time for rhythms with a larger number of pulses; and (2) by establishing a constant note density across polyrhythms, which results in the polyrhythms' having unequal cycle times. We chose the latter type of temporal equivalence. The implication of our choice is that the effect of perceived polyrhythm similarity is totally confounded with the effect of cycle length or tempo but independent of note density. The effect of the first choice would be to confound perceived polyrhythm similarity with note density and make it independent of cycle length. However, if the polyrhythms are matched for cycle length, then two of the pulse trains will beat at exactly the same rate (e.g., the 5-pulse train when 3×5 and 4×5 are compared). Under such conditions, subjects could more easily ignore the identical 5-pulse train and simply rate the similarity of the different pulse trains (3 and 4) instead of listening to the rhythms as wholes. Alternatively, the subjects could focus on the identical 5-pulse train, although this seems less likely. We believe our choice better ensured that listeners were comparing whole patterns and not particular pulse trains or subpatterns.

Polyrhythms were equated for note density at about 1 note per every 225 msec. This value falls within the time boundaries in which rhythm is perceived (Fraisse, 1982). For the outside-octave condition, this rate, through extrapolation, appears to fit within the timing region in which streaming is an optional percept (van Noorden, 1975, p.15). For the 3×4 polyrhythm, there was a cycle time of 1,332 msec (this value should have been about 1,398 msec, but computer limitations prevented our achieving the desired accuracy.) Stimulus onset asynchronies (SOA) for the 3×4 pattern were set at 444 and 333 msec, respectively (see Figure 1). The 3×5 polyrhythm had a cycle time of 1,598 msec and SOAs of 532.7 and 319.6 msec. The 4×5 pattern had a cycle time of 1,798 msec and SOAs of 449.5 and 359.6 msec.

On each trial, pitch assignment to the pulse trains that comprised the polyrhythms obeyed the following rule: the lower note of the pitch interval was assigned to the faster pulse train in both polyrhythms, and the higher tones (which defined the pitch interval of the polyrhythms) were assigned to the slower pulse trains.

The procedure for choosing pitch intervals was as follows: All tones stayed within the 3-octave range bounded by C3 and B6. The lower note was chosen randomly from the 12 tones of the C4–B4 octave. Next, each top note, which created the appropriate pitch interval, was chosen by moving up from the lower note the specified number of steps on the diatonic scale. This was followed by deciding with equal likelihood whether the interval was to be within an octave or greater than an octave. If the inside condition was chosen, the interval was left as is. If the outside condition was chosen, one of two things happened: (1) the top note was raised an octave only if it stayed within the upper boundary (B6); and (2) the lower note was lowered an octave and the top note remained in the same place if the upper boundary was exceeded when the top note was raised an octave.

Experimental design. The overall experiment consisted of one between-groups factor (pitch-interval order) and four within-group factors (rhythm, rhythm order, pitch interval, octave). In Condition 1 (24 trials), there were three same-rhythm pairs × four same-pitch-interval pairs × two octave conditions (see Table 1). Condition 2 (72 trials) differed from Condition 1 by using six different-pitch intervals and by presenting each pitch-interval pair in two orders. Condition 3 (48 trials) was identical to Condition 1 except that three different-rhythm pairs were presented as well as two presentation orders of each rhythm pair. Condition 4 (144 trials) differed from Condition 2 by using the different-rhythm pair manipulations of Condition 3.

Each subject received a total of 180 trials. This number was arrived at as follows. All subjects received all trials of Conditions 1 and 3, because pitch-interval order, the between-groups factor, was not varied in these conditions. This yielded 72 trials (24+48). The between-groups factor did arise in Conditions 2 and 4; the number of trials for each group was therefore half of the total in these two conditions. For Condition 2, this amounted to 36 trials, and for Condition 4, 72 trials. Combined, this produced two stimulus sets, each containing 180 trials (24+48+36+72). Each set was generated by computer and presented in a randomly permuted order. Group assignment was also random.

Procedure. The subjects first filled out a questionnaire about their music background (training and listening tastes). They were told that two complex rhythms would be presented on each trial and that their task was to rate the similarity of the rhythms from 1 to 7 by pressing a corresponding key on the computer keyboard. The listeners were instructed to think of the numbers as a scale of increasing similarity, in which 1 meant *not similar at all*, 6 meant *very similar*, 7 equaled *identical*, and "the values in between represent varying degrees of relatedness." If the concepts of rhythm and pitch were unclear, then these terms were defined. The subjects were instructed to disregard all manipulations of pitch.

Next, 10 practice trials were given. There were two examples of each of the four experimental conditions and two randomly chosen examples. The practice trials started with Condition 1 and moved progressively to the more complex conditions. The subjects were informed of the different rhythm and pitch manipulations at each level. This was done with the intent of improving the subjects' understanding of what to focus on when listening to the polyrhythms (i.e., attend to rhythm differences and ignore pitch differences). Once the practice trials were completed, uncertainties about the experiment were clarified. The subjects were tested individually in one 2-h session.

The subjects initiated each trial by pressing the keyboard spacebar; there was a 1.5-sec pause followed by presentation of the first polyrhythm, another pause of 2.0 sec, and the second polyrhythm. Both polyrhythms were presented for five cycles. The subjects were prompted to respond with a similarity rating after the last cycle of the second polyrhythm; responding was self-paced. After every 50 trials, the listeners were offered a 5-min break.

Results and Discussion

An alpha level of .01 was adopted to ensure the validity of the results and as a precaution against spurious effects. Results reliable at the .05 level will be mentioned only briefly. The data from each of the four experimental conditions were first analyzed separately, and then cross-conditional comparisons were made between Conditions 1 and 3 and between Conditions 2 and 4. The results are presented below.

Due to an error in programming, it was decided to pool subjects' data to form supersubjects[1] (combining 2 subjects' data to form 1 subject). Of the 10 newly constructed supersubjects, 4 had had fewer than 2 years of musical training (mean = .88, *SD* = .89) and 6 had had more than 5 years (mean = 6.75, *SD* = 1.03). Because of the large difference between the groups, musical experience was included as a factor in the analysis. Research investigating the dimensions of pitch (Krumhansl & Shepard, 1979) has found that musicians perform differently from nonmusicians. Musicians abstract tonality from the musical context, whereas nonmusicians do not. We hypothesized that if tonality was abstracted in the present experiment, the effect might be stronger for musicians than for nonmusicians.

Same rhythm × same pitch interval. Condition 1 consisted of trials in which the polyrhythms were the *same* and the pitch intervals were the *same*. Four variables were manipulated in this condition: same rhythm, same pitch interval, octave, and musical experience. A four-way analysis of variance produced no statistically significant main effects or interactions. This is what would be expected given that subjects were rating the similarity of two identical presentations. The absence of a main effect for rhythm (Table 2, top row of means) indicates that subjects did not differentially consider some rhythms more similar to themselves than to others. In addition, the lack

Table 2
Mean Similarity Rating of Same Rhythms in Same-Pitch-Interval and Different-Pitch-Interval Conditions (Conditions 1 and 2)

Pitch Interval	Rhythm Combination		
	3×4/3×4	3×5/3×5	4×5/4×5
Same	6.36	6.28	6.21
Different	5.43	5.21	5.38

of any main effect for octave, or its interaction with pitch interval or rhythm, indicates that subjects' processing of stimuli spanning more than an octave may not have been different from their processing stimuli within an octave. This suggests that the subjects were, indeed, able to focus on the whole stimulus pattern when the notes of the rhythms were separated by distances greater than an octave. Furthermore, the lack of any statistically significant results suggests that the subjects could perform the similarity rating task reliably. Had differences emerged in the similarity ratings of identical presentations, it might have suggested random guessing or perhaps changes in polyrhythm interpretation.

Same rhythm × different pitch interval. In this experimental condition (2), the polyrhythms that were compared were the *same* but the pitch intervals between them were *different*. Presentation order of the pitch-interval pairs was varied in this condition because different pitch intervals were employed. Five variables were manipulated: same rhythm, different pitch interval, pitch-interval order, octave, and musical experience. An analysis of variance again revealed no main effect for rhythm or pitch-interval order. There was a main effect for pitch interval [$F(5,40) = 10.72, p < .001$], a main effect for octave [$F(1,8) = 26.94, p < .01$], and an interaction of pitch interval with octave [$F(5,40) = 4.00, p < .01$].

Focusing on the interaction allows us to examine the effect of pitch interval and octave. The mean similarity ratings (collapsed across all other conditions) for the pitch-interval pairs are given in Figure 3 (two sets of nonhashed bars). They are ordered sequentially along the abscissa by the difference between the pitch intervals (in diatonic steps) that comprise the polyrhythms on each trial. For example, P4 and P5 polyrhythms are 1 diatonic step from each other and are placed at the beginning of the scale. Likewise, M2 and M7 polyrhythms are 5 diatonic steps from each other, and so are placed at the other end of the continuum. Krumhansl (1979) found physical distance between notes to be one criterion of similarity. The same effect appears here using intervals, although it is restricted to pitch intervals within an octave. Mean similarity ratings decrease as pitch-interval difference increases in the inside-octave condition, whereas the means vary little across the six pitch-interval conditions in the outside-octave condition.

These results indicate that subjects' ratings varied little between the octave conditions when pitch-interval differences were small. Only when these differences were large (5 diatonic steps) did the octave condition differentially affect similarity ratings. This suggests that subjects were simply more sensitive to the physical distance between pitch intervals within an octave than to those outside of an octave. Although the cause of this difference in sensitivity is difficult to determine from the obtained results, it is more likely the result of information processing constraints than of sensitivity limitations of the auditory system. (Tone discrimination is good within the range of frequencies used; Moore, 1973.) When listening to music, people are accustomed to processing dyads within a pitch range of less than an octave. Dyads exceeding this range, such as M9, may not be easily encoded simply because one's processing resources are not accustomed to handling such information.

There was also an interaction of musical experience with pitch interval [$F(5,40) = 4.80, p < .01$]. We found it helpful to examine the current interaction in the context of the octave condition in order to relate it to the results reported in Figure 3. The means of the nonsignificant

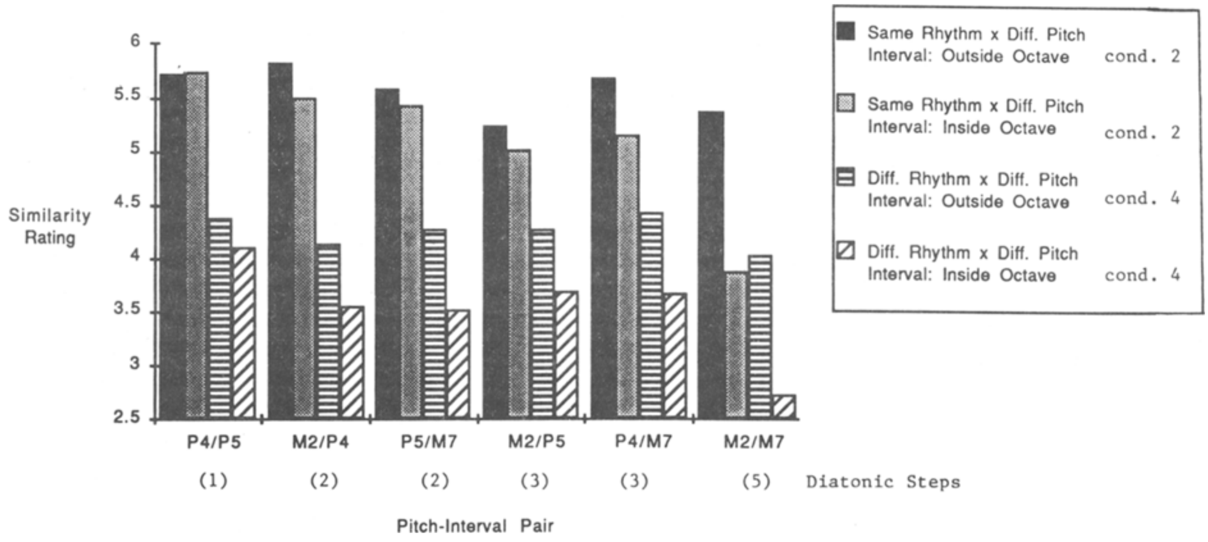

Figure 3. Mean similarity rating as a function of pitch-interval pair and octave in same rhythm × different-pitch-interval condition (two sets of nonhatched bars) and different rhythm × different-pitch-interval condition (two sets of hatched bars). The interval pairs are ordered along the abscissa by the difference in diatonic steps between each pair.

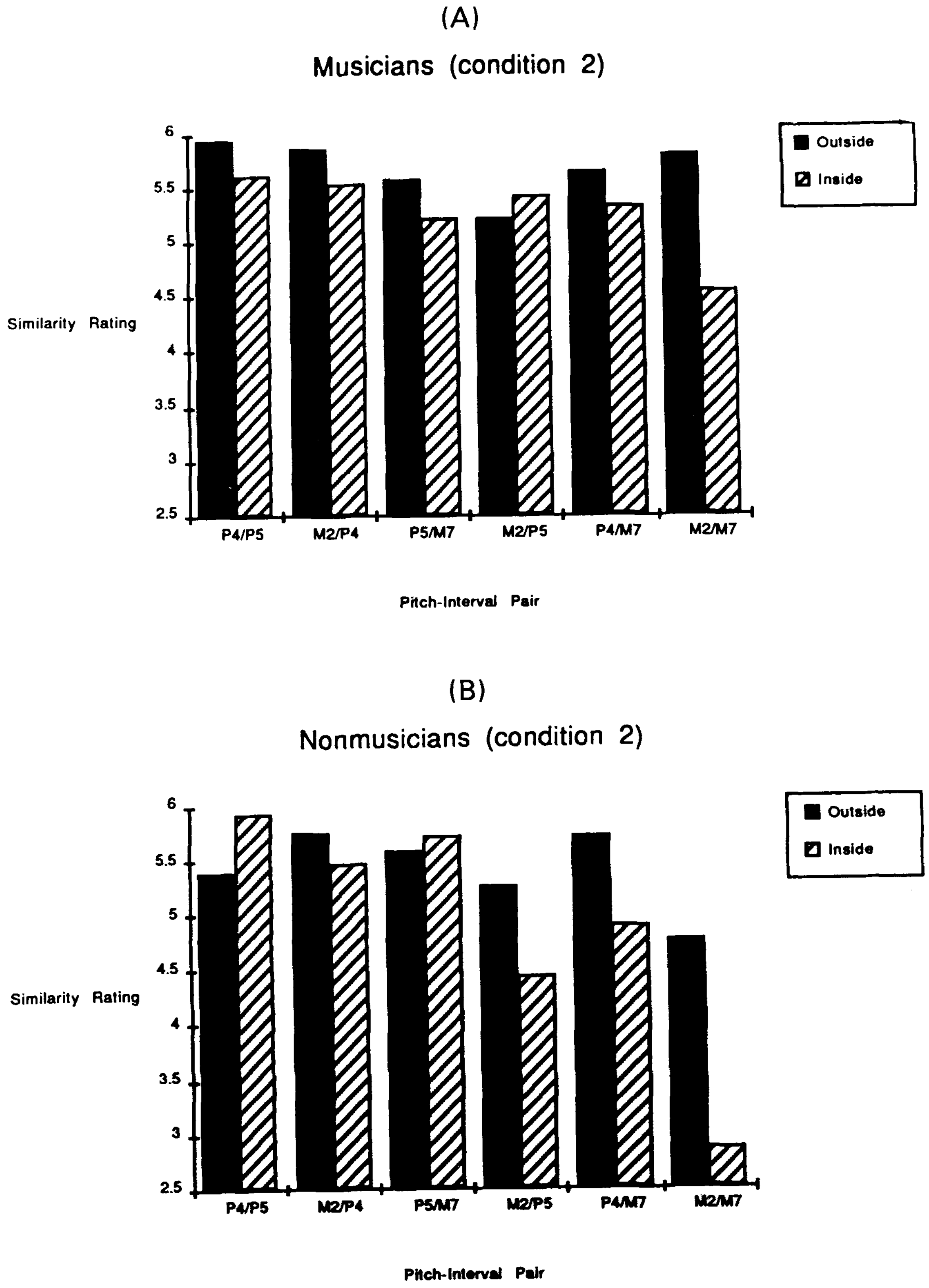

Figure 4. Mean similarity rating as a function of pitch-interval pair and octave for musicians (A) and nonmusicians (B). The interval pairs are ordered along the abscissa by the difference in diatonic steps between each pair.

($p > .05$) three-way (musical experience × pitch interval × octave) interaction are graphed in Figures 4A (musicians) and 4B (nonmusicians).

The similarity-rating profiles of the outside-octave condition for both musicians and nonmusicians remained relatively flat as pitch-interval pair difference increased. Although this was also the case for the inside-octave condition for musicians, the mean ratings for nonmusicians decreased as the difference between pitch-interval pairs increased. If one considers that the task of the subjects was to rate the similarity of the polyrhythms and disregard pitch, these results tend to suggest that within an octave, musicians were better able to filter out changes in pitch interval than were nonmusicians. Or conversely, that when making the similarity judgments, musicians were better able to attend selectively to rhythm than were nonmusicians.

Condition 2 (same rhythm × different pitch interval) was constructed in order to examine a possible independent influence of pitch information on similarity ratings. It was found that the dimension of pitch proximity influenced the perceived similarity of identical polyrhythms: This was true of both musicians and nonmusicians, although the former were able to ignore pitch proximity better than the latter. The lack of any main effect for pitch-interval order or its interaction with other variables indicates that the pitch dimension of tonal relatedness was probably not used in this condition. The lack of a significant effect for rhythm (which was always the same on each trial) suggests that subjects were attending to the polyrhythms and not just to pitch proximity. This confirms the observation made previously, that subjects were doing what was asked of them.

In Table 2, the means of the three identical rhythm combinations are presented for both the same pitch-interval and the different pitch-interval conditions. The almost uniform drop in rhythm similarity ratings resulting from a mere change in the pitch interval between identical polyrhythms is interesting. Since the decrease in polyrhythm similarity is a result of the pitch intervals involved, the current data reveal that, despite instructions to the contrary, listeners were influenced by pitch-proximity information, which may have been integrated with rhythm information; this conclusion applies only to identical rhythmic patterns for the moment.

Different rhythm × same pitch interval. In Condition 3, we analyzed ratings of similarity for *different* pairs of polyrhythms comprising the *same* pitch interval. Because different pairs of rhythms were compared, the order of their presentation was varied. There were five variables in this condition: different rhythm, rhythm order, pitch interval, octave, and musical experience. An analysis of variance yielded the following results: a main effect for rhythm [$F(2,16) = 23.92, p < .001$] and a main effect for same-pitch interval [$F(3,24) = 4.98, p < .001$]. No statistically significant interactions or main effects of rhythm order or octave were found.

The main effect for rhythm is shown in Figure 5 (nonhashed bars). As can be seen, subjects judged 3×4 and 4×5 to be more similar to each other than either was to 3×5. In addition, 3×5 was considered to be about as similar to 4×5 as it was to 3×4; this was true for both octave

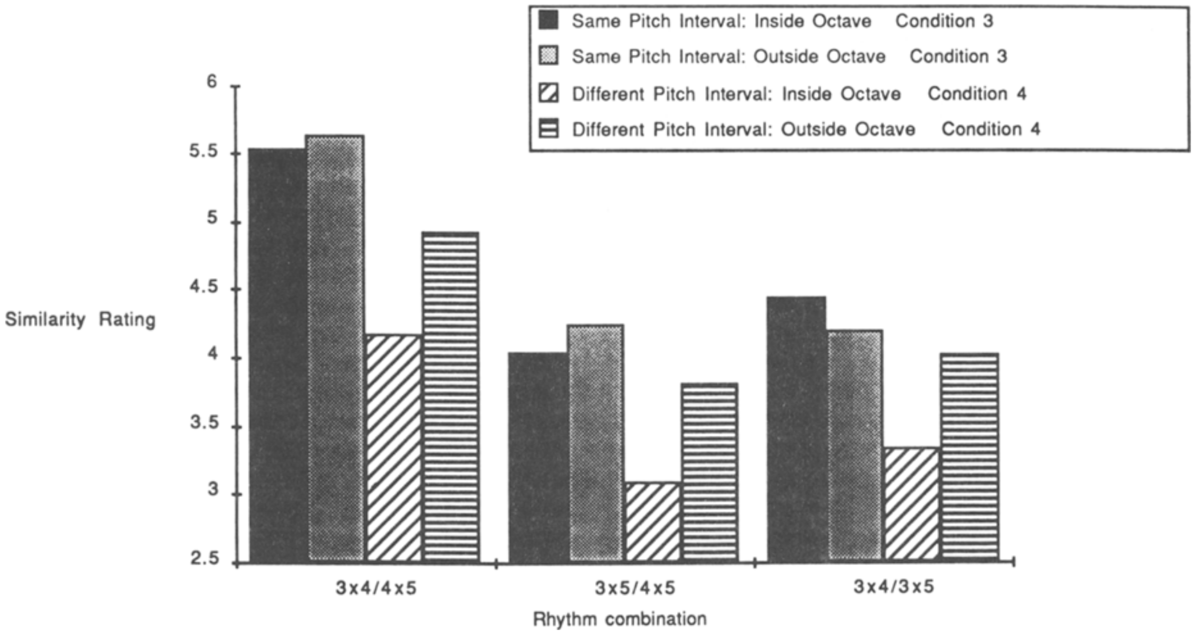

Figure 5. Mean similarity ratings of each different-rhythm pair. Nonhatched bars represent means from Condition 3 (same pitch interval), hatched bars from Condition 4 (different pitch interval).

conditions. Note also that similarity judgments for polyrhythm intervals are very close both inside and outside the octave.

The main effect for same pitch interval indicates that the size of the interval used on a trial (e.g., M2 or P5) differentially affected perceived similarity of the rhythms. The means (collapsed over all other conditions) are given here along with their pitch-interval condition (M2/M2 = 4.34, P4/P4 = 4.48, P5/P5 = 4.71, M7/M7 = 5.19). As can be seen, pitch-interval size was correlated with similarity rating. As the size of the pitch interval increased, similarity ratings also increased. A Newman-Keuls test revealed that the M7 mean differed significantly from all the other means ($p < .05$), which did not differ significantly from each other.

This result is rather curious because the pitch-interval means are nearly identical in both octave conditions. Explanations for this outcome are difficult to formulate at present, but there is apparently a consistent response to tone chroma that was independent of octave in Condition 3.

In Condition 3, there was also a main effect for musical ability [$F(1,8) = 5.55, p < .05$] and a rhythm × pitch interaction [$F(6,48) = 2.32, p < .05$]. The interaction is probably not an important result, as it was produced by the fact that the M5 pitch interval received much higher similarity ratings for the 3×5/4×5 rhythm combination than for the 3×4/3×5 combination. In the other pitch-interval conditions, the mean similarity ratings of both of these rhythm combinations were very close. Because only one of the four pitch-interval conditions yielded differential results across the different rhythm combinations, and because the interaction was statistically significant at only the .05 level, it is difficult to assess the significance of these findings. We therefore withhold judgment until further replications are produced.

In the main effect for musical ability, musicians consistently rated the rhythms less similar than did nonmusicians (means = 4.43 and 5.06, respectively), although the rhythm and pitch-interval profiles were the same for both groups. Musicians were simply less influenced by pitch-interval information, and they more clearly discriminated among the rhythms: Recall that the data of Condition 2 suggested that nonmusicians were affected more by pitch information.

In summary, a similarity space among the three polyrhythms was uncovered in the different rhythm × same pitch-interval condition: 3×4 and 4×5 were considered more similar than either was to 3×5. The presence of a main effect for same pitch interval indicated that the size of the interval affected the similarity of the different rhythms. This effect was fairly uniform across the different polyrhythm conditions. The significant effects of rhythm and pitch interval again suggest that subjects' judgments were being influenced by both rhythm and pitch factors. Listeners attended to both of these aspects, and then integrated them to form a final similarity judgment. Furthermore, the fact that the effect of pitch interval was relatively independent of the effect of rhythm indicates that the integration of pitch with rhythm information is systematic.

Different rhythm × different pitch interval. The fourth experimental condition explored how the similarity space obtained for the polyrhythms in Condition 3 was altered by pitch-interval changes between the comparison rhythms. This condition provides the most direct test of the original rationale for this research: *Different* polyrhythm combinations were compared with *different* pitch intervals. Presentation order of rhythms and pitch intervals was varied, yielding six independent variables: different rhythm, rhythm order, different pitch interval, pitch-interval order, octave, and musical experience. An analysis of variance revealed that there were no statistically significant results of rhythm order or musical experience.

The main effect for rhythm that was found in the previous experimental condition also emerged here (Figure 5, combined hatched bars) [$F(2,16) = 28.66, p < .001$]. Even in the context of differing pitch intervals, the similarity profile among rhythms remained the same. However, overall similarity ratings of each polyrhythm combination decreased. Furthermore, a main effect for octave [$F(1,8) = 29.23, p < .001$] revealed that ratings within the octave were about three quarters of a point lower than ratings outside of the octave. This drop in similarity ratings, as can be seen, was uniform across all rhythm combinations. Discrimination of rhythms seems to be much better within an octave than between octaves.

A main effect of different pitch interval was obtained [$F(5,40) = 12.26, p < .001$], but it was qualified by a pitch interval × octave interaction [$F(5,40) = 3.53, p < .01$]. The mean similarity ratings for the interaction are displayed in Figure 3 (two sets of hatched bars). The form of the interaction for Condition 4 is quite similar to that for Condition 2 (nonhatched bars). However, in Condition 4, the effect of an octave difference between the pitches comprising the intervals was far more robust. The influence of pitch-interval differences for the inside-octave condition was also greater here. This interaction confirms the results of the second experimental condition, in which pitch proximity was shown to influence similarity judgments. But, in addition, the importance of the octave condition was far greater, suggesting that the influence of pitch information was much stronger. However, this influence was again restricted to the inside-octave condition. Beyond 1 octave, the bonds between the notes that comprise an interval either break down perceptually or become weaker so that subjects apparently do not hear differences among rhythms well when their pitch intervals are large (see Figure 5).

Pitch interval also interacted significantly with pitch-interval order [$F(5,40) = 4.52, p < .01$] (see Figure 6): Ratings were always higher when P4 or P5 followed M2 or M7. The asymmetry is most evident with the middle four interval pairs on the graph. Krumhansl (1979) found a similar asymmetrical relationship in which less stable tones (M2, M7) were rated as being more similar to sta-

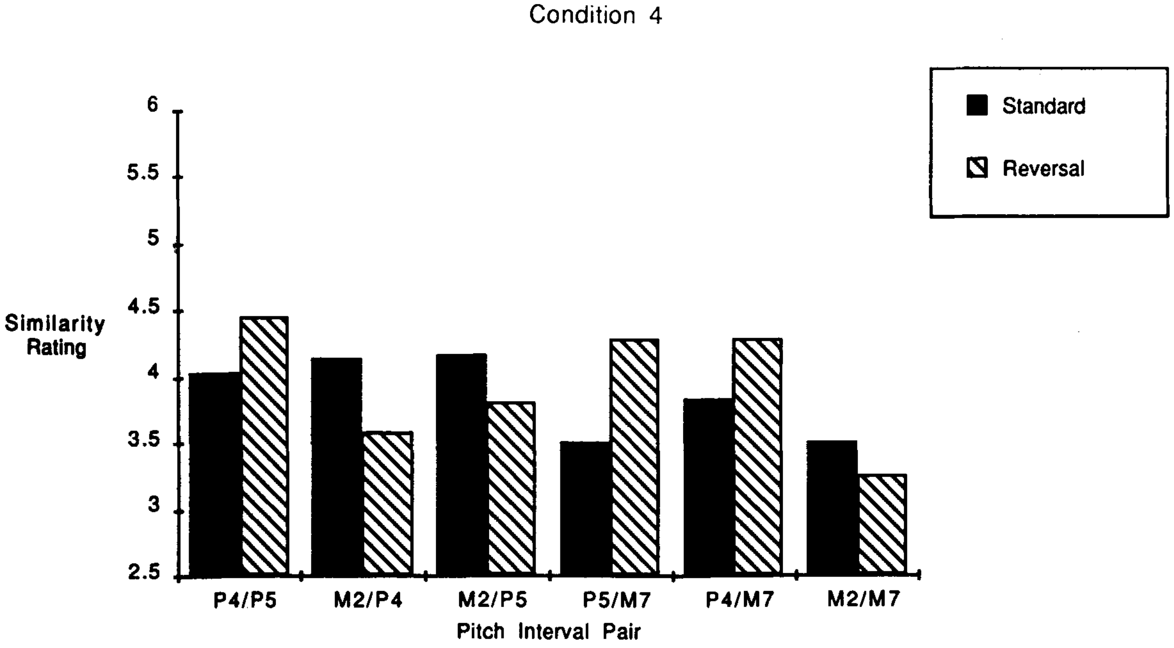

Figure 6. Mean similarity ratings based on pitch-interval pair and pitch-interval order from the different rhythm × different-pitch-interval condition. The interval pairs are labeled along the abscissa in the standard order (dark bars). The hatched bars correspond to the reverse ordering of the interval pairs (e.g., P5/P4, P4/M2).

ble tones (M3, P5) than vice versa in a tonal context. The emergence of a like effect here strongly suggests that subjects were using the pitch dimension of tonality in making rhythmic similarity judgments. The fact that the lower note was the same in both pitch intervals probably facilitated the abstraction of a tonal context. There was virtually no order asymmetry for the M2/M7 interval pair, which is what would be expected given that both intervals are unstable. The P4/P5 asymmetry is in the wrong direction, but since both intervals can be interpreted as being stable in the current context (see below), the effect may be unimportant.

We note that the present asymmetry results differ from those of Krumhansl (1979) in that the perfect fourth (P4) in her study yielded no asymmetries when paired with other diatonic intervals (e.g., M2 and M7). This difference can probably be attributed to the ambiguity of the tonal context in the present study. Krumhansl defined a clear context by playing the major scale or major triad of a key, whereas subjects in this study were given only three notes from which to abstract a key. This enabled them to employ a much wider range of possible tonalities. In the absence of the other notes that contribute to the definition of a tonal context, the perfect fourth (P4) could have been interpreted as an inverted perfect fifth (P5). This would appear to explain the large asymmetry obtained in the present study between P4 and the other unstable intervals, M2 and M7. Also, tonality is generally acquired through musical training and experience. The interval-order asymmetry should be stronger for musicians than for nonmusicians, producing a three-way interaction composed of pitch interval, pitch-interval order, and musical experience. Although this interaction was not significant ($p > .10$), the effect was in the right direction, inasmuch as it was larger for musicians.

In summary, Condition 4 (different rhythm × different pitch interval) yielded a similarity profile for the polyrhythms that was almost identical to the one in Condition 3 (different rhythm × same pitch interval), except that the means were lower here. The reason for this seems to be a stronger influence of pitch proximity information as a result of the use of different pitch-interval pairs within rather than outside of the octave. Similarity ratings outside the octave were much higher, presumably because subjects may have been unable to use interval proximity information across such a distance. Subjects also relied upon the dimension of tonal relatedness in their ratings of the polyrhythms, as the asymmetry in pitch-interval order indicates.

The results obtained in Condition 4 support the proposal made earlier that pitch information has an almost independent effect on the perceived similarity of the three polyrhythms: The similarity of the three polyrhythm combinations changed relative to whether a manipulation in pitch increased or decreased the similarity between the pitch intervals. Along with indicating that subjects integrated both rhythm and pitch into their similarity judgments, the similar rhythm profiles of both different-rhythm conditions (3 and 4) suggest that subjects attended primarily to rhythmic factors when rating the stimuli.[2]

Two final questions are: (1) Can listeners discriminate among polyrhythms when the two rhythms share the same

Table 3
Mean Similarity Rating of Same-Pitch-Interval Polyrhythms as a Function of Same and Different Polyrhythm Pairs (Conditions 1 and 3) and Musical Experience

Polyrhythms	Musicians	Nonmusicians	Mean
Same	6.30	6.25	6.28
Different	4.43	5.06	4.68
Mean	5.36	5.65	

pitch interval or when they have different pitch intervals? (2) Is this discrimination the same for musicians and nonmusicians? To answer these questions, two 2 (musical experience) × 2 (experimental condition) analyses of variance, one for the same-pitch-interval conditions (1 and 3) and one for the different-pitch-interval conditions (2 and 4), were performed on overall subject means from each condition. This was done by computing for each subject a mean similarity rating for each condition.

The results from the comparison of the same-pitch-interval conditions are shown in Table 3. There was a main effect of experimental condition [$F(1,8) = 157.54$, $p < .0001$], indicating that different polyrhythms, relative to same polyrhythms, were more discriminable in the context of identical pitch intervals. Although the main effect for musical experience was not significant, the interaction of musical experience × experimental condition reached significance [$F(1,8) = 7.77, p < .025$]. This final result further supports the claim made earlier that musicians were better able than nonmusicians to disregard the influence of identical pitch intervals when attending to different rhythms.

The analysis of the two different-pitch-interval conditions yielded a main effect only of experimental condition [$F(1,8) = 271.6, p < .0001$], indicating that different polyrhythms, relative to same polyrhythms, could indeed be discriminated in the context of different pitch intervals. Discrimination was nearly the same for both musicians and nonmusicians in this analysis.

GENERAL DISCUSSION

The purpose of this investigation was to explore further the cognitive representation of rhythm in music. The current approach involved having subjects rate the perceived similarity of three polyrhythms with the idea of mapping the similarity space between them. Two dimensions of pitch (frequency proximity and tonal relatedness) were manipulated in the experiment to examine how they would affect the similarity space. Overall, the results revealed that the 3×4 and 4×5 polyrhythms were considered more similar to each other than either was to 3×5. This result was consistent across the two different-rhythm experimental conditions. Pitch proximity and tonal relatedness had uniform effects on all polyrhythm combinations, which suggests that pitch information may have had a completely independent influence on the similarity space between polyrhythms. However, further investigation into this last assertion is needed, given that all possible combinations of pitch assignments to the pairs of polyrhythms being compared were not made; that is, the tone with the lower pitch was always assigned to the faster pulse train and the tone with the higher pitch was always assigned to the slower pulse train.

So, what does the similarity space between the three rhythms look like? Since 3×4 and 4×5 were considered most similar, they should be placed closest together. Both of these were considered to be about equally similar to 3×5, so the distances from 3×4 and 4×5 to 3×5 should be about equal. The shape of the space that is suggested by this is that of an isosceles triangle (Figure 7, thick-line triangle). The angles possessing the shorter leg correspond to the 3×4 and 4×5 rhythms; the angle formed by the two longer legs represents the 3×5 rhythm.

One explanation for the 3×5 polyrhythm's being considered the most different from the other two rhythms is that it has the most highly disparate SOA for the slower (higher pitched) pulse train. The SOAs and tone durations ("on times") for each pulse in the three polyrhythms are given in Table 4. The effect of "on time" could be ruled out by performing a replication in which "on time" was a constant duration (e.g., 50 msec). Differences in "on times" and SOAs for the slower pulse train in this polyrhythm differ by about 20% from those in the other two pulse trains. Threshold detection of different SOAs (for either sound-filled or sound-empty intervals) at these tempi is typically 10% or less (Hirsh, 1987).[3]

A related reason for why the 3×5 polyrhythm was considered less similar to the other rhythms may be due to the fact that the pitch of the 5-pulse train occurs twice consecutively without an intervening beat from the 3-pulse

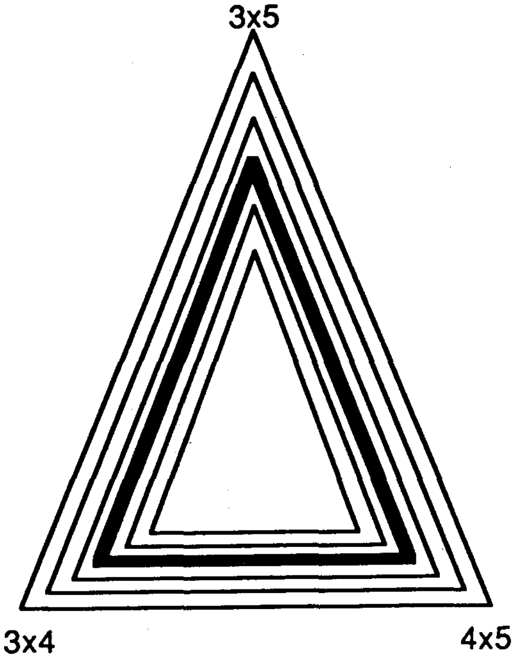

Figure 7. Similarity space of the three polyrhythms.

Table 4
SOAs and Tone Durations (On Time) for Each Pulse Train in the Three Polyrhythms

	Slow Train		Fast Train	
Polyrhythm	SOA	"On Time"	SOA	"On Time"
3×4	444	222	333	166.5
3×5	532.67	266.33	319.6	159.8
4×5	449.5	224.75	359.6	179.8

train (Figure 1). In the other two polyrhythms, the pitches of the pulse trains always alternate.[4]

The lack of any significant effects of rhythm order suggests that the relationship between any two of the rhythms was symmetrical. That is, the space between the rhythms was the same irrespective of the order in which they were presented. This translates into needing only one leg to connect two rhythms. The effect of pitch on this shape is one of uniformly increasing or decreasing the size of the whole triangle (thin-line triangles). Changes in pitch that result in higher similarity ratings (intervals greater than an octave or consonant intervals following dissonant ones) decrease the length of the legs connecting the rhythms; changes that produce lower similarity judgments (intervals inside an octave or dissonant intervals following consonant ones) increase the size of the triangle, reflecting better discrimination among rhythms.

Our analysis of similarity ratings across experimental conditions suggests that it might be necessary to draw different triangles for musicians and nonmusicians such that, for musicians, the legs of the triangle would be longer (rhythms more discriminable) when patterns shared the same pitch interval and shorter when they did not; for nonmusicians, the legs of the triangle would be shorter when the patterns did not share the same rhythm.

The similarity space, as it is currently represented, adequately describes the data. However, the shape of the space might well change from two dimensions to three if another polyrhythm were included. Furthermore, the underlying physical dimensions of this space have yet to be defined. Once these dimensions are identified, it could be that the entire similarity space among the three rhythms will be restructured. In this regard, our aim here was not to uncover the definitive similarity space, but rather to explore how pitch could affect this space.

The large influence of pitch information on similarity ratings was not expected, especially when it is considered that subjects were instructed to focus on rhythm and ignore pitch. Because pitch is emphasized more heavily than rhythm in Western music, as opposed to other music cultures, subjects might have had difficulty in ignoring pitch information. This is indicated by (1) the emergence of pitch proximity and tonal relatedness as factors influencing rhythm similarity, and (2) comments from the subjects on how difficult it was to ignore pitch. These results suggest that subjects may not have attended to pitch information voluntarily, but rather that pitch processing was mandatory or automatic.

The ability of subjects in the current experiment to integrate rhythm and pitch into a final percept is at odds with the results of Monahan and Carterette (1985), who found that subjects attended to either rhythm variables or pitch variables, but not to both, when making similarity judgments of brief melodies. The discrepancy between the two studies, however, can be reconciled if we consider the difference between the types of stimuli used by Monahan and Carterette and those employed in the present study. It is quite possible that processing melodies is a task that is perceptually different from processing polyrhythms. Melodies have certain rule-governed properties (Jones, Boltz, & Kidd, 1982; Jones, Maser, & Kidd, 1978) that may call into play different, or require more, processing resources; melodies possess independent, time-varying structures for rhythm as well as for pitch. Although polyrhythms are structurally complex in the rhythm domain, they have virtually no melodic structure in the pitch domain. Because of this, it may be that the processing load of pitch information was slight enough to enable both rhythm and pitch variables to be integrated into the final percept.

Listeners familiar with polyrhythms may have structural representations of rhythm that are quite different from those of the novice listeners in the present study (only 1 of the 20 original subjects expressed any familiarity with polyrhythms). Such differences are observed between musicians and nonmusicians in their representations of pitch (Krumhansl & Shepard, 1979). Therefore, caution should be taken in generalizing the present results.

A final issue that warrants consideration in light of the reliability of the current findings is whether all subjects interpreted the polyrhythms uniformly. Handel and his colleagues (Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978) found that, although intrasubject interpretation was consistent across trials, there was a fair amount of intersubject variability. For instance, some subjects always tapped with one pulse train whereas others tapped only on the co-occurrence of all pulse trains. Different interpretations may have arisen here, but there are some indications that suggest this was not the case. First, subjects in Handel's studies were instructed to tap with the polyrhythms, a task that allows subjects to impose only one of many structural interpretations on the rhythmic patterns. In the current study, subjects were told to focus on the entire rhythmic pattern, an instruction that we hoped would unify interpretations. Second, if some subjects did adopt a different perceptual interpretation of the rhythms, we would expect that their ratings would vary systematically from other interpretations, producing different spatial representations of rhythm. This was not borne out in our data; the rhythm profiles for all subjects are similar to the overall pattern shown in Figure 5.

The results of this study have established that a stable similarity can be imposed on these three polyrhythms and that pitch information affects this space. The present data suggest that the influence of pitch is both independent of rhythm and uniform across all rhythm combinations. But, given that only four pitch intervals were used here, this conclusion must await further replication under conditions that employ a wider range of intervals. The large influence of pitch information on rhythm similarity suggests that, under the present conditions, rhythm and pitch were not completely separable in the evaluation process. How these two dimensions are internally integrated is a question worth pursuing.

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NOTES

1. Due to a programming error in generating the two stimulus sets, A and B, pitch-interval order, the between-subjects factor, was confounded with subjects in Conditions 2 and 4. This created a situation in which, for each subject, half of the trials were presented in one order and the other half in the reverse order, instead of all trials' being presented in one of the two orders for each group of subjects. Because subjects who were presented with Stimulus Set B received the complement set of confounded trials that were presented to subjects who received Set A, the problem was remedied by combining 2 subjects' data, one from each group, to form one "supersubject" (Crowder, 1982; Samuel, 1981). Supersubjects were matched for musical experience in order to minimize response variance within subjects. This was accomplished by having two judges rank-order the subjects from each group on the basis of musical experience and correlating their lists. Agreement between the two judges was quite good ($r = .94$ for subjects in Group A, $r = .86$ for subjects in Group B). The two orderings were then combined to form an overall list. Listeners were then matched and their similarity ratings combined. (Pitch-interval order therefore became a within-group variable.) The ratings from trials that both matched subjects received (Conditions 1 and 3) were averaged before assignment to the supersubject. This procedure reduced the N from 20 to 10 in all conditions.

2. In Condition 4, the analysis also produced a series of interactions that were marginally significant (.05 level). Their effects are difficult to interpret, and it is doubtful whether some are at all meaningful. We therefore withhold judgment on their significance and reliability until future replications are produced. The interactions were rhythm × pitch [$F(10,80) = 2.10$], rhythm × pitch interval × octave [$F(10,80) = 2.20$], rhythm × rhythm order × pitch-interval order × octave [$F(2,16) = 4.69$], rhythm × rhythm order × pitch interval × pitch-interval order [$F(10,80) = 2.36$].

3. Subjects could have based their ratings on polyrhythm cycle length. If this had been the case, the similarity space between the rhythms would have been quite different: the distance between 3×4 and 4×5 would have been largest, since these rhythms have the most disparate cycle times, and the distance between 3×5 and 4×5 would have been the smallest, since both of these polyrhythms have the most similar cycle times.

4. We thank an anonymous reviewer for this suggestion.