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Hierarchical organization of temporal patterns

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In two reproduction experiments, limitations of a hierarchical organization of temporal patterns were investigated by varying the way lower levels relate to higher levels in the hierarchy. From the systematic errors subjects made in reproducing temporal patterns, it is concluded that an accurate internal representation will be arrived at only if the temporal structure of a pattern enables an organization in which hierarchical levels relate as integers with prime factors 2 or 3. Implications for the temporal pattern perception theory are discussed.

A general notion in characterizing the cognitive organization of temporal patterns is that the time structure is coded in some hierarchical form (Jones, 1976, 1981b; Longuet-Higgins & Lee, 1984; Martin, 1972; Michon, 1974). Hierarchical organization is typically pictured abstractly as a tree representing multiple levels of time units with lower levels nested within higher levels (see Jones, 1981a). Various theoretical representations to describe the time structure of a temporal pattern differing in the way lower levels relate to higher levels have been proposed (Longuet-Higgins, 1978). This study is concerned with the actual organization of higher and lower levels in a hierarchical representation of temporal patterns.

Models specifying which characteristics of temporal patterns determine their actual organization have been proposed by Povel (1981, 1984) and Povel and Essens (1985). Related models confined to temporal patterns that occur in music have been presented by Longuet-Higgins and Lee (1982, 1984).

Povel (1981) found empirical support for a hierarchical model of temporal pattern perception that consists of at least two levels: a higher order level, called *beat*, and a lower level of subdivisions of that beat level. This organization is arrived at by segmentation of the temporal pattern into equal intervals, the beat unit, and expressing the intervals smaller than the beat unit as a subdivision of the beat unit in which they occur. Thus, a temporal pattern with intervals of 250 250 250 750 (msec) can be represented, according to the model, as two beat units of 750 msec, the first unit subdivided into three equal parts. In later studies, Povel (1984) and Povel and Essens (1985) extended this idea, and in the latter article they introduced the concept of *internal clock*, comparable to the *beat* concept.

The clock model assumes that, in perceiving a temporal pattern, a listener tries to generate an internal clock which is subsequently used as a device to specify the temporal structure of the pattern. Furthermore, the model assumes that the distribution of the accents perceived in the sequence determines whether an internal clock actually is induced and which clock will provide the hierarchical organization of the pattern. For example, consider the tone pattern with intervals 600 200 400 200 200 200 600 (msec). A clock with unit 600 (msec) organizes the pattern in four equal parts (600) (200 400) (200 200 200) (600). On the other hand, when a clock unit of 800 (msec) is used, the pattern is segmented in (600 200) (400 200 200) (200 600). The clock model specifies the strength of induction of each theoretically possible clock. It was shown that temporal patterns conceived with a strongly induced clock are reproduced more accurately than patterns not so conceived (Essens & Povel, 1985; Povel & Essens, 1985). This paper is concerned with patterns that, in terms of the clock model, have a strong clock induction.

The purpose of the present study was to determine which subdivisions can be adequately represented in a hierarchical model. In two experiments, subjects reproduced temporal patterns in which subdivisions of the higher order level were systematically varied.

EXPERIMENT 1

Three ways of subdividing the clock unit can be distinguished: empty, filled with equal intervals, and filled with intervals that subdivide the clock unit unequally. For example, in the temporal pattern with intervals 600 200 800 400 200 200 800 (msec) with a theoretical clock unit equal to 800 msec, according to the clock model, the first clock unit is subdivided into two parts with a ratio of 3:1. The third unit is subdivided into three intervals with a ratio of 2:1:1. The other units are not subdivided. To determine the nature of the relationship between clock level and its subdivisions, other, more complex ratios must also be studied. For example, consider the temporal pattern 700 200 900 500 200 200 900 msec. The theoretical clock unit, equal to 900 msec, is subdivided into parts that form nonintegers (700 200 and 500 200 200). As it is formulated now, the clock model emphasizes the necessity of

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Table 1
Patterns Presented in Two Conditions of Experiment 1

Noninteger	Integer
	Set 1
/200 200 500/200 500 200/900/900/	**/200 200 400/200 400 200**/800/800/
/500 200 200/200 500 200/900/900/	**/400 200 200/200 400 200**/800/800/
/700 200/**200 200 500/500 200 200**/900/	/600 200/**200 200 400/400 200 200**/800/
	Set 2
/500 200 200/**700 200/700 200**/900/	/400 200 200/**600 200/600 200**/800/
/500 200 200/**200 700/200 700**/900/	/400 200 200/**200 600/200 600**/800/
/500 200 200/**200 700/700 200**/200 700/	/400 200 200/**200 600/600 200**/200 600/
/500 200 200/**200 700/200 700**/200 700/	/400 200 200/**200 600/200 600**/200 600/

Note—Intervals in milliseconds. Slant lines mark clock units. The subdivisions under consideration are set in bold type. The subdivisions relate basically as 2.5:1 and 2:1 in Set 1, and 3.5:1 and 3:1 in Set 2.

using an internal clock to arrive at an accurate representation. If the presence of an internal clock as a metric device is a sufficient condition for an adequate description of a temporal pattern, patterns containing subdivisions with ratios 2.5:1 and 3.5:1 would be reproduced as well as patterns with subdivisions with 2:1 and 3:1 ratios.

Patterns containing subdivisions with integer ratios formed the integer condition; patterns containing subdivisions not in integer ratios formed the noninteger condition. The performance in the two conditions was compared using a reproduction paradigm.

Method

Stimuli. Two sets of temporal patterns were formed in which the relevant ratios of the subdivisions of the clock units were 2.5:1 (e.g., 500 200 200) or 2:1 (e.g., 400 200 200) in Set 1 and 3.5:1 (e.g., 700 200) or 3:1 (e.g., 600 200) in Set 2. In Table 1, the temporal patterns are shown as sequences of tone onset intervals (msec) with the clock units marked by slant lines and the subdivisions under consideration set in bold type. The duration of the shortest intervals was 200 msec in all patterns.

The tones in the stimuli were made of 50-msec 830-Hz square waves with 5-msec rise and fall times. The tones were presented to the subjects in combination with a low-pitch isochronic tone sequence, whose only purpose was to strongly induce the indicated clock. This isochronic sequence consisted of tones of 50-msec 125-Hz square waves with 5-msec rise and fall times. For example, in the temporal sequence consisting of the time intervals 200 200 500 200 500 200 900 900 (msec) with a theoretical clock unit equal to 900 (msec), the low-pitch tones coincide with the first, fourth, seventh, and eighth tone of the sequence.

Procedure. The experiment was performed in two parts, first the noninteger condition and then, after a short pause, the integer condition. Order of presentation of the stimuli within each part was randomized. The task was practiced before each part of the experiment. The stimulus was presented cyclically through loudspeakers. The subject's task was to reproduce the presented pattern as precisely as possible. The subject listened to each stimulus and practiced tapping with his/her index finger for as long as he/she wished. The subject stopped stimulus presentation by pushing a button, and then reproduced the pattern four times, cyclically, on a response plate. Each tap produced the same tone as that used in the stimulus. If variability of performance of a pattern was such that standard deviation exceeded 15% of the mean, the subject was asked to produce that pattern again, repeating the procedure of listening and practicing the stimulus involved. Stimulus generation and response registration were controlled by a PDP-11/03 computer.

Subjects. Twenty subjects, students in psychology, participated in the experiment. Ten were musically trained, having played an instrument for at least 5 years.

Results

Since an examination of the performance of individuals revealed no differences attributable to musical training, data from all subjects were pooled. Ratios were calculated from the relevant mean long and short intervals reproduced in each sequence. In Figure 1, these ratios are presented averaged over subjects for the patterns in the conditions of the two sets separately. Large deviations were found in the noninteger condition: reproduced ratios, which showed a strong tendency toward integer ratios in both Set 1 and Set 2, differed significantly from the presented interval ratios [$t(19) = 13.7, p < .01$, for Set 1, and $t(19) = 9.9, p < .01$, for Set 2]. The means

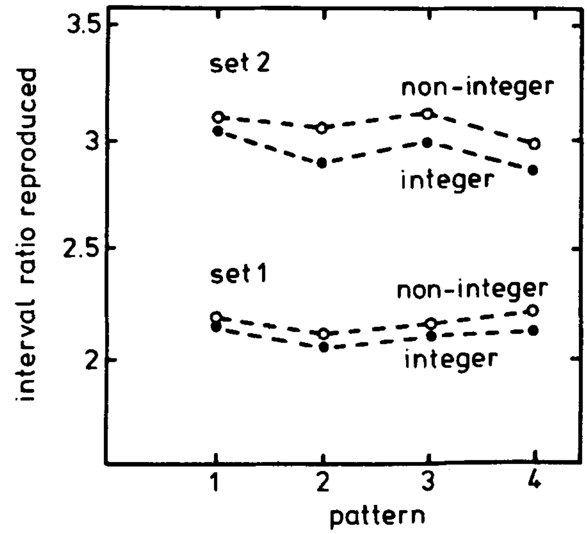

Figure 1. Mean reproduced interval ratios for the noninteger and integer conditions in the two sets. The dotted lines connect data points of each condition.

(and standard deviations) of the reproduced ratios for the integer and noninteger conditions were 2.10 (.12) and 2.14 (.12), respectively, for Set 1 and 2.94 (.18) and 3.07 (.20), respectively, for Set 2.

Although the ratios of the long and short intervals in the noninteger ratio condition changed in reproduction, the sum of these intervals, making up the clock unit, remained constant (t test, $p > .05$). In this condition (noninteger), means (and standard deviations) for the long and short intervals were 460 (18.4) and 216 (8.6) for Set 1 and 667 (37.9) and 217 (10.1) for Set 2, respectively. In the integer ratio condition, means (and *SD*s) were 417 (18.7) and 199 (6.1) for Set 1 and 594 (33.7) and 202 (7.0) for Set 2. Deviations of the short interval in the noninteger condition were significant as compared with the integer condition [$F(1,19) = 196.0$, $p < .0001$].

Discussion

Data clearly show that integer interval ratios are better reproduced than noninteger ratios. Moreover, in reproduction, noninteger ratios tend to be reproduced as integers, whereas the clock unit remains unchanged. It can be concluded that adequate representation will be arrived at only if subdivisions of a present clock form integer ratios. This suggests a representation in which the clock interval is partitioned into equal parts such that the smallest part equals the shortest interval. Intervals longer than the smallest part can be specified by combining parts.

Subdivision of the clock unit may be characterized by the way the intervals relate to the clock unit. In the sample pattern 600 200 800 400 200 200 800 with clock unit equal to 800 msec, the first unit (600 200) and third unit (400 200 200) both contain a 4-division. Experiment 2 examines the question whether a division of one clock unit is related to the division of another clock unit in the same pattern.

EXPERIMENT 2

In Experiment 1, the ratios of the intervals within a clock unit were studied. To determine the hierarchical nature of the temporal organization, Experiment 2 was concerned with the relationship between the lower and higher levels (the clock unit). For example, in the pattern of 200 200 200 600 400 200 600 msec with a theoretical clock unit equal to 600 msec, the subdivisions of the first clock unit (200 200 200) and the third unit (400 200) both relate to the clock unit as a 3-division; the intervals are, respectively, ⅓ ⅓ and ⅔ ⅓ of the clock unit. However, in the pattern 300 300 600 400 200 600 msec with a clock unit equal to 600 msec, relations between subdivision and clock level differ; the intervals within the first and third unit are, respectively, ½ ½ (a 2-division) and ⅔ ⅓ (a 3-division) of the clock unit. The question addressed was whether different types of division (e.g., 2-division and 3-division) were conceivable within the same pattern.

This experiment compared the reproduction of patterns in two conditions: one in which subdivisions differed between clock units within a pattern, for example, 2-division versus 5-division (different condition) and one in which subdivisions were similar (same condition).

Method

Stimuli. Five sets of two patterns each were formed in which subdivisions of the clock units were either *different* (first pattern) or *same* (second pattern) (see Table 2). The clock unit in each pattern was equal to the longest interval in the pattern. Sets 1 and 2 and Sets 3 and 4 differed only in tempo. Because the longest clock unit used was 1,000 msec and the shortest was 200 msec, Set 5 had no equivalent in a different tempo. Patterns in the *different* condition contained a 2-division in the first clock unit and a different division in the third clock unit, whereas in the *same* condition, the divisions were of the same type in the first and third clock units. The tones that marked the intervals in the stimuli consisted of 50-msec 830-Hz square waves that included 5-msec rise and fall times.

Procedure. The order of presentation of the five sets was randomized; order within sets was fixed—first *different*, then *same* division. To avoid interference from other sets, each set was preceded by a practice pattern in which the first clock unit was undivided and the third clock unit was subdivided similar to the subdivision in the set. For example, the practice pattern in Set 1 was 800 800 533 267 800 msec.

The subject's task was to reproduce the cyclically presented patterns as precisely as possible. Stimulus presentation and response procedures were similar to those in Experiment 1.

Subjects. Twelve subjects, students in psychology, participated in the experiment. Six had played a musical instrument for at least 5 years.

Results

As in Experiment 1, the data of musically trained and untrained subjects were pooled because no systematic differences related to musical training were found. Since systematic effects were revealed only in the ratios of the reproduced intervals within the third clock unit, Table 3 presents these ratios averaged over subjects and their standard deviations. Note that ratios 2:1, 3:1, and 4:1 refer to division types 3, 4, and 5, respectively, and that in the *different* division condition a 2-division preceded these division types. Figure 2 shows, for all conditions on a scale of ratios, the relation between the ratio in the stimulus (vertical line) and the ratio in the reproduced sequence (arrow end point). The data showed strong effects of *different* versus *same* conditions in some sets. Effects of

Table 2
Patterns in Two Conditions Presented in Experiment 2 and Division of First and Third Clock Unit of Each Pattern

Set	Patterns	Division	
1. *Different*	/400 400/800/533 267/800/	2	3
Same	/267 267 267/800/533 267/800/	3	3
2. *Different*	/500 500/1000/667 333/1000/	2	3
Same	/333 333 333/1000/667 333/1000/	3	3
3. *Different*	/400 400/800/600 200/800/	2	4
Same	/200 200 200 200/800/600 200/800/	4	4
4. *Different*	/500 500/1000/750 250/1000/	2	4
Same	/250 250 250 250/1000/750 250/1000/	4	4
5. *Different*	/500 500/1000/800 200/1000/	2	5
Same	/200 200 200 200 200/1000/800 200/1000/	5	5

Note—Intervals in milliseconds. Slant lines mark clock units.

condition (*different* vs. *same*) were significant in Set 1 and Set 2 [$F(2,18) = 29.1, p < .0001$, and $F(2,18) = 29.1, p < .0001$, respectively]. The trend of the effect in the conditions of Set 1 and Set 2 is toward a 3:1 ratio. No significant differences between conditions were found in Sets 3, 4, and 5. In Set 5, reproduction deviated strongly in both conditions, suggesting that the tendency toward the 3:1 ratio in the *different* condition might be due to factors other than difference in division. In agreement with the results in Experiment 1, the observed deviations of the interval ratios in the different conditions did not modify the clock unit. Tempo (Set 1 vs. Set 2 and Set 3 vs. Set 4 in both conditions) had no significant effect on reproduction.

Subjects had great problems with the patterns in Set 5. Verbal comments about the *same* condition indicated that the six tones in the beginning of the pattern were particularly difficult to organize.

Discussion

The results may be summarized in terms of division: (1) A 3-division preceded by a 2-division in the same pattern is not reproduced accurately, whereas a 3-division preceded by a 3-division is. (2) A 4-division preceded by a 2-division is reproduced accurately, as is a 4-division preceded by a 4-division. (3) 5-divisions are reproduced badly irrespective of the preceding division. However, deviant reproductions did not affect accuracy of the clock unit, from which it may be concluded that the clock unit is used as a reference in the representation of temporal patterns.

Data suggest that 2- and 4-divisions are related divisions. This adds to the idea that in a hierarchical representation higher levels are partitioned equally into lower levels. When a 2- and a 4-division occur in one pattern, a hierarchy with two levels below the clock unit could adequately describe the pattern. When a 2- and a 3-division occur in one pattern, the level below the clock unit related to the 2-division cannot be equally divided to obtain a level that adequately describes the 3-division.

There is a puzzling aspect to the data of Set 3. In both conditions, the reproduced ratios were greater than 3; in Experiment 1, however, 3:1 ratios were reproduced as smaller than 3. These differences remain to be explained.

Table 3
Ratios of the Intervals Within the Third Clock Unit of the Stimuli of Experiment 2 and Their Mean Reproduction in Two Conditions

Set	Stimuli	Reproduction Mean	Reproduction *SD*
1. *Different*	2:1	2.55	.27
Same	2:1	2.09	.20
2. *Different*	2:1	2.39	.15
Same	2:1	2.08	.12
3. *Different*	3:1	3.11	.20
Same	3:1	3.07	.20
4. *Different*	3:1	3.02	.15
Same	3:1	2.97	.15
5. *Different*	4:1	3.55	.35
Same	4:1	3.51	.30

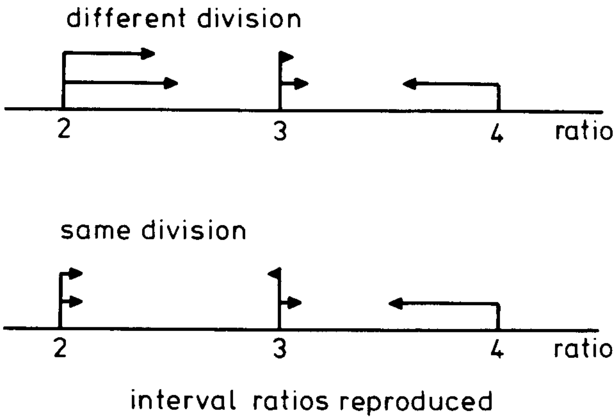

Figure 2. Mean reproduced interval ratios for the *different* and *same* conditions of Experiment 2, represented on a continuum of ratios as deviations from the presented interval ratio. The arrows refer to the stimuli. Vertical lines on the continuum mark the ratio in the stimulus; the end points of the arrows indicate the actual reproduced ratio.

GENERAL DISCUSSION

The main conclusion drawn from the experiments in this study is that temporal patterns, conceivable with a clock unit, are represented hierarchically, with higher order levels relating to lower levels as integers with prime factors 2 and 3. Accurate reproduction was found when the clock unit was subdivided into parts that formed ratios that were simple integers. If parts did not form integer ratios, reproduction was inaccurate, showing systematic errors toward integer ratios. An additional limitation of the subdivision of the clock unit was found in the fact that subdivisions in a temporal pattern have to be of one kind. The finding that 2- and 4-divisions did not interfere with each other suggests that these divisions are related. A third limitation concerned the maximal subdivision of the clock unit. It was found that 5-divisions were not reproduced accurately, which suggests that the relationship between levels is limited to divisions of 2, 3, and 4. The first two limitations apply to the domain of patterns that can be represented adequately; the third finding, inaccurate 5-divisions, indicates that the set of clock units from which the most likely selected clock unit is calculated can be limited to clock intervals with a subdivision of less than 5.

The present study supports a model of the internal representation of temporal patterns in which the perceived clock refers to a higher order time unit. This time unit is subdivided into two or three equal parts, which in turn are again subdivided into two or three parts, thus describing the intervals in the pattern.

A final remark concerns the conclusion that the conceptual structures necessary to describe the presented complex structures were not readily available or elicited. The research reported here restricts itself to conceptual structures used by subjects from a western culture. In other cultures, different conceptual structures might be used. Data across cultures could provide insights into the universal nature of our results.

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