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Perception of Temporal Patterns

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To gain insight into the internal representation of temporal patterns, we studied the perception and reproduction of tone sequences in which only the tone-onset intervals were varied. A theory of the processing of such sequences, partly implemented as a computer program, is presented. A basic assumption of the theory is that perceivers try to generate an internal clock while listening to a temporal pattern. This internal clock is of a flexible nature that adapts itself to certain characteristics of the pattern under consideration. The distribution of accented events perceived in the sequence is supposed to determine whether a clock can (and which clock will) be generated internally. Further it is assumed that if a clock is induced in the perceiver, it will be used as a measuring device to specify the temporal structure of the pattern. The nature of this specification is formalized in a tentative coding model. Three experiments are reported that test different aspects of the model. In Experiment 1, subjects reproduced various temporal patterns that only differed structurally in order to test the hypothesis that patterns more readily inducing an internal clock will give rise to more accurate percepts. In Experiment 2, clock induction is manipulated experimentally to test the clock notion more directly. Experiment 3 tests the coding portion of the model by correlating theoretical complexity of temporal patterns based on the coding model with complexity judgments. The experiments yield data that support the theoretical ideas.

THIS article is concerned with time perception and, more specifically, with the perception of temporal patterns: tone sequences in which only the intervals between tone onsets are varied. Such sequences are thus pure temporal patterns: they not only develop in time, the pattern is itself formed by the series of temporal intervals. We wish to determine which structural characteristics people can extract from temporal patterns and what mechanisms they use to do this. If we have a correct understanding of these matters we ought to be able to predict which temporal patterns give rise to accurate and stable percepts and which do not. Such predictions can be tested in

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experiments in which subjects reproduce temporal patterns differing in their temporal structure.

We will propose a model for the perception of temporal patterns that is an extension of the model presented by Povel (1981, 1984) and is related to the models of metrical interpretation of musical patterns of Lewin (1981), Longuet-Higgins and Lee (1982), and Steedman (1977). The model, partly formalized in a computer program, incorporates the notion of an internal clock that is induced in the perceiver of a temporal pattern. On the basis of certain characteristics of a temporal pattern, the model is used to determine the likelihood that the pattern will induce a particular internal clock. Further it is assumed that if an internal clock is induced in a listener, this clock will be used as a means for specifying the temporal structure in the pattern. A tentative proposal of the coding of the temporal structure is advanced. Before embarking on a description of the model, we will discuss the special nature of temporal patterns.

The Special Nature of Temporal Patterns

Temporal patterns comprise a special class of serial patterns. Research on serial patterns has included studies of patterned sequences formed of letter and number series (Jones & Zamostny, 1975; Leeuwenberg, 1969; Simon & Kotovsky, 1963; Vitz & Todd, 1969), patterns of lights (Restle, 1970, 1976; Restle & Brown, 1970), patterns of sound (Garner, 1974; Royer & Garner, 1966; Leeuwenberg, 1971), musical patterns (Deutsch & Feroe, 1981; Simon & Sumner, 1968), and finger-tapping patterns (Collard & Povel, 1982; Povel & Collard, 1982; Rosenbaum, Kenny, & Derr, 1983). These studies show that the internal representation of serial patterns can adequately be described by means of coding models incorporating a limited set of elementary transformations defined on a given alphabet: repetition, transposition, and mirroring (Collard & Povel, 1982; Deutsch & Feroe, 1981; Leeuwenberg, 1969; Restle, 1970; Simon, 1972).

Can such models help us in understanding the perception of temporal patterns? Mach (1886) pointed out that symmetry is not perceived in the case of temporal patterns, a finding later confirmed by Restle (1976). Similarly, it may be shown that the basic operations of repetition and transposition do not apply in the temporal domain: an interval repeated later in a sequence is not usually recognized as such. The transformation "transpose" or "next" does not seem to make any sense in the case of temporal patterns: one can say which letter it is that follows d, but not which interval it is that follows an interval of 200 msec.

The essential point is that intervals do not form alphabets; therefore those coding models applicable to the serial patterns mentioned earlier cannot apply to temporal patterns. This need not mean that structural aspects play no role in the perception of temporal patterns. On the contrary, it has been shown that the ease and accuracy of reproducing even very simple temporal patterns is strongly determined by structural characteristics (Povel, 1981). Temporal patterns seem to be processed in a special way, which is probably related to the fact that a series of time intervals cannot as such be stored in a sensory register.

The Model

The Notion of an Internal Clock. A basic notion underlying the development of the present model is that time, and therefore sequences of temporal intervals, can only be assessed by means of a clock. Since this cannot be an external clock we assume that the subject has access to an internal clock of some kind. Even the simplest clock consists of a periodic pulse and a counter. Several authors have stressed the importance of such a clock concept, usually formulated in terms of music theory: meter and beat (Handel & Lawson, 1983; Handel & Oshinsky, 1981; Longuet-Higgins & Lee, 1982; Povel, 1981, 1984; Steedman, 1977).

What is the nature of this internal clock? We will discuss some possible clock models, starting with the simplest one and see how well they are able to predict the results emerging from research on temporal patterns.

1. The absolute clock. Assume that subjects possess a clock having a fixed unit of very short duration, 1 msec for instance. Such a clock would enable the subject to measure each interval in a sequence—for example, 200, 400, and 800 msec—and to store these values in memory. This model fails, for instance, to predict the filled duration illusion (Thomas & Brown, 1974; Buffardi, 1971) and it is equally unable to explain why a temporal pattern presented at a different tempo will be recognized as structurally identical. More importantly, such a model would imply that all sequences having the same number of intervals will be equally well perceived and reproduced regardless of the durations of the intervals. This prediction is convincingly disconfirmed by the experimental results of Fraisse (1956), Povel (1981), and Sternberg, Knoll, and Zukofsky (1982).

2. A clock with a time unit derived from the sequence. The measuring problem would be simplified if the subject were able to select a time unit for his clock identical to the shortest interval in the sequence. In the example given, the time unit selected could be 200 msec, enabling the representation of the pattern as being formed of 1, 2, and 4 times the unit. Such a representation is independent of the actual tempo of the pattern. The model predicts that all sequences having the same number of intervals will be equally well conceptualized, provided that all intervals in the sequences comprise integer multiples of the smallest interval. Hence both the sequence 200 200 400 and 200 400 400 ought to be easy to conceptualize and consequently they should both be equally well reproduced. In fact, however, subjects repro-

duce the first sequence perfectly, but the second poorly. For additional examples, see Povel (1981). We may therefore conclude that listeners do not use either Clock 1 or Clock 2, both of which code the pattern as a chain of intervals lacking descriptive efficiency.

3. A hierarchical clock. The concept of a hierarchical clock comes from considering certain rhythmical characteristics in music. In simple music at least, there is an equally spaced pulsing which might very well determine the unit of an internal clock. Interestingly, these pulsed intervals are not composed of very small durations, but are rather of a medium duration which can either be subdivided or concatenated. Such a clock thus resembles the hierarchical organization into hours, minutes, and seconds of clocks used in everyday life. A major difference, however, is that the unit of time and its subdivisions are not fixed but flexible, continuously adapting to the sequence under consideration. Since the two former clock models are inadequate, we assume that the clock listeners internally generate is of the latter type. Moreover, this model can explain the majority of the findings on reproduction of simple temporal patterns reported by Povel (1981).

For the time being we suppose that the clock has two levels: one that defines the *unit* of the clock and the other that determines the *subdivision* of the unit. Thus this clock is far less hierarchical than the models proposed by Martin (1972) and Jones (1976). The question now arises as to which characteristics in the sequence determine the setting of this internal clock.

Determinants of the Internal Clock. First, it should be noted that various clocks differing in unit duration can, theoretically at least, be associated with one temporal pattern. Figure 1 shows a simple temporal pattern together with a series of potential clocks. We see that the clocks differ in their unit length (e.g., the first and third clocks) as well as in the way they are synchronized with the sequence (e.g., the first and second clocks have the same unit, but are synchronized differently with the sequence). Thus a clock has two parameters: its unit (interval between ticks) and its location (synchronization).

It is well known that the foot tapping of music listeners, itself interpretable as reflecting their internal clock, is mainly determined by the occurrence of accented events in the music. At first sight it seems likely that in the case of the temporal patterns under study here, the selection of the internal clock would also mainly be determined by the occurrence of accents. But what constitutes an accent in such sequences? Since the perception of accents is usually associated with tones that are louder, longer, or deviating in pitch (Thomassen, 1982), one might assume that no accents would be perceived in such sequences of identical tones. It turns out, however, that these sequences yield a quite strong impression of accented and unaccented tones. It is even difficult for subjects to believe that all tones are really identical.

This phenomenon has been studied by Povel and Okkerman (1981). This

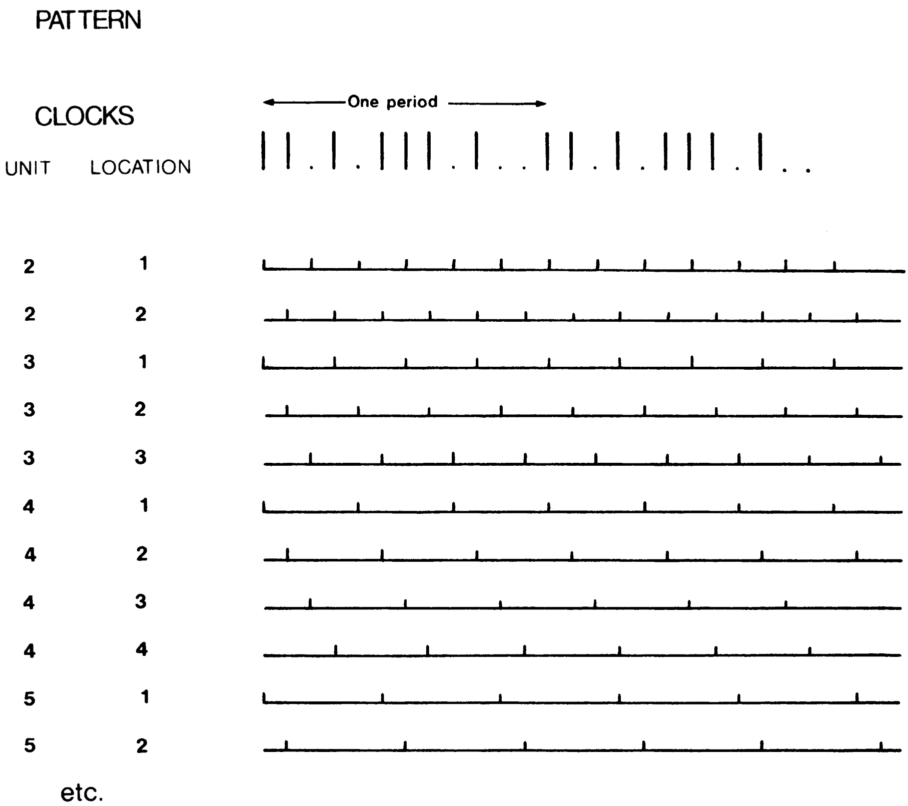


Fig. 1. A temporal pattern (two periods shown). Each vertical line represents a tone of 50 msec. Smallest interval between two tone onsets is 200 msec. The dots have no physical meaning whatsoever, their only function is to represent the relative duration of the intervals. Below the pattern, clocks differing in unit and location are shown.

study and some other pilot experiments suggest that in temporal sequences composed of identical tones the following become perceptually marked: (1) relatively isolated tones, (2) the second tone of a cluster of two tones, and (3) the initial and final tones of a cluster consisting of three or more tones. In Figure 2 we indicate how these rules would apply to a specimen sequence. Since perceptually these sequences do possess accented and nonaccented events, it seems reasonable to assume that the occurrence—and, more precisely, the distribution—of the accented events is the main determinant of the hypothesized internal clock.

Formalization of the Clock-Induction Process. A computer program[1] has been written that accepts a series of intervals as input and computes which clock is most strongly induced by the pattern. To accomplish this, the

1. The program, written in FORTRAN, is available on request.

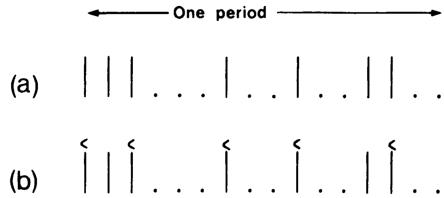
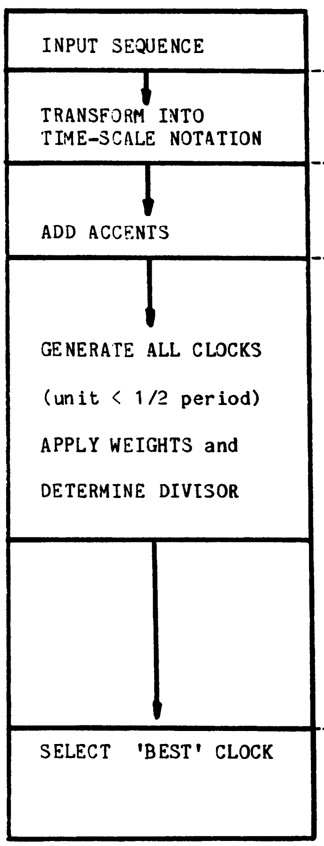


Fig. 2. A temporal pattern as presented (a), with the accent rule applied (b) indicating the perceived accents.

PROGRAM

SAMPLE OUTPUT



Input sequence: 1 2 2 1 1 2 3

Time-scale notation: 1 1 0 1 0 1 1 1 0 1 0 0

Accents added: 1 2 0 2 0 2 1 2 0 2 0 0

unit	loc	+ev	0ev	-ev	div	strength
1	1	5	2	5	1	22
2	1	0	2	4	1	18
2	2	5	0	1	1	4
3	1	2	2	0	1	2
3	2	2	0	2	1	3
3	3	1	0	3	1	12
4	1	0	1	2	1	9
4	2	3	0	0	1	0
4	3	0	1	2	1	9
4	4	2	0	1	1	4
5	1	1	1	1	0	5
5	2	1	1	1	0	5
5	3	1	1	1	0	5
5	4	2	0	1	0	4
5	5	1	0	2	0	8

unit	loc	+ev	0ev	-ev	div	best
4	2	3	0	0	1	0

Fig. 3. A flow chart of the model as implemented in the program together with its output at the various stages.

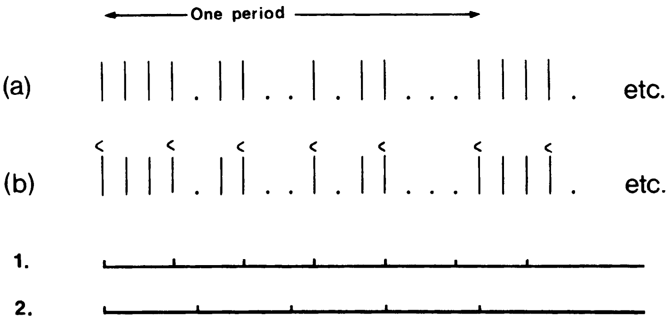


Fig. 4. A temporal pattern as presented (a), with its perceived accents (b). Two clocks are indicated: (1) a clock that is strongly suggested but inadequate and (2) a clock that is hardly suggested but that would be adequate.

program goes through the following steps (Figure 3). After inputting a sequence in interval notation, such as 1 2 2 1 1 2 3, it is transcribed on a time axis. Next the accents are added using the rules given above. Accented elements are indicated as 2, unaccented elements as 1. All possible clocks with a unit smaller than half the period duration are then generated. (We believe that clocks with longer units are not considered by a listener, see below.) For each clock the program determines how many ticks coincide with an accented event (+ev), an unaccented event (0ev), or with silence (−ev). Next, for each clock the induction strength is determined by means of a score (C) which computes the amount of counterevidence a clock meets in an actual sequence, according to the following formula:

$$C = (W * {}^{-}\text{ev}) + (1 * 0\text{ev}).$$

W is a parameter concerning the relationship between −ev and 0ev. In fact, it reflects the relative negative effect of −ev and 0ev on the induction of clocks. Since it is assumed that −ev is more effective in this respect, *W* should be larger than 1. In the example presented in Figure 3, *W* was set at 4. Next we will deal with some other aspects of the model.

First we should introduce a distinction between clocks having a unit that is a divisor of the sequence length and clocks with a nondivisor unit. The former would fit with a sequence properly, the latter not. This can be clarified by means of an example. A specific pattern may strongly induce an internal clock that is nevertheless unable to specify adequately the temporal structure in the sequence. This, for instance, is the case for the sequence 1 1 1 2 1 3 2 1 4 (numbers indicate intervals in an arbitrary time unit). This strongly suggests a clock with unit 3 which is inadequate, whereas a clock with unit 4, which would be adequate, is hardly induced or not at all (Figure 4).

In accordance with this distinction, the program determines for each

TABLE 1
Sets of Patterns

			Categories								
			1	2	3	4	5	6	7	8	9
		-ev	0	0	0	0	1	1	1	1	2
Combination	N	0ev	0	1	2	3	0	1	2	3	0
1. 1 2 2 2 2 3 4	30		3	3			13	5			6
2. 1 1 1 2 2 2 3 4	140		10	20	6		45	45	6		8
3. 1 1 1 1 1 2 2 3 4	168		10	32	19	5	41	52	9		
4. 1 1 1 1 1 1 1 2 3 4	72		3	18	13	2	11	23	2		
5. 1 1 2 2 3 3 4	90		3	6	3		31	28	3		16
6. 1 1 1 1 2 3 3 4	105		4	15	14	3	23	35	6		5

NOTE. For six combinations, the number of noncyclic permutations that can be formed and their distribution over the categories of the model are shown. -ev = number of clock ticks coinciding with silence; 0ev = number of clock ticks coinciding with unaccented events.

clock whether its unit is a divisor. In its final step the program selects from those clocks with a unit that is a divisor the one that is most strongly induced. This clock will further be called the "best" clock.

Sets of Patterns

As mentioned earlier, we make use of sets of patterns derived from a single combination of intervals. From the combination 1 2 2 2 2 3 4, for instance, 30 permutations can be formed, if we exclude those that are cyclical permutations of one another.[2] Cyclic permutations like 4 1 2 2 2 2 3, 1 2 2 2 2 3 4, 2 2 2 2 3 4 1, and 2 2 3 4 1 2 2, when presented repetitively (which is the case in all our experiments), are perceptually identical: on the basis of the "gap" principle of Garner (1974), subjects will always hear the sequence as 1 2 2 2 2 3 4, that is, ending with the largest interval. From the combination 1 2 2 2 2 3 4, for instance, a set of 30 patterns can be built, none of them being a cyclic permutation of any other, and each pattern containing the same intervals but in a different order. Hence the patterns within a set are only structurally different. We have determined how many patterns can be derived from several combinations sharing a period duration of 16 units, one interval of size 4, and at least one interval of sizes 1, 2, and 3. The result is displayed in Table 1.

Now instead of one pattern we can feed a complete set of patterns into the program and let it distribute the sequences into categories in accordance

2. The program that infers all non-cyclical permutations, written in C, is available on request.

with the computed induction strength of each sequence. For all sets of Table 1, setting $W=4$, the program computes nine different levels of induction strength and consequently needs nine different categories for the distribution of the sequences. Table 1 shows for the six combinations how many of the permutated patterns are allotted to the different categories. We see that the distribution of the patterns over the categories differs greatly and that for all combinations one or more categories remain empty. The patterns in the different categories can be characterized with respect to the degree they induce the best clock as follows:

Category 1. Best clock is induced by accented elements only.

Categories 2, 3, and 4. Best clock is induced by accented and unaccented elements: 1, 2, and 3 unaccented elements for the three categories respectively.

Categories 5, 6, and 7. The ticks of the best clock of these sequences coincide once with a silence (− ev) and depending on the category with zero, one, or two unaccented elements (0ev). For all of the patterns in Table 1, category 8 is empty.

Category 9. In these sequences the best clock has two ticks that coincide with a silence (− ev). In Figure 5, specimen sequences (derived from the interval combination 1 1 1 1 2 3 3 4, which has sequences in all categories except number 8) are shown together with the best clock for each sequence.

We will now discuss two aspects of the model. First, the use of counterevidence as a criterion for clock selection. As shown in the formula, we assume that the ultimate clock-induction strength is determined by counterevidence coming from − ev and 0ev. We believe, however, that the suggestion for potential clocks comes from positive evidence, that is, from accented events (+ ev). Second, we should point out that the model as implemented is not a process model. It does not work from left to right through the sequence developing hypothetical clocks in the process. On the contrary, the approach adopted here is an exhaustive one that tests all potential clocks and selects that one most strongly induced. In this respect, the model differs from that of Longuet-Higgins and Lee (1982), for example, which aims at mirroring the actual process of beat selection. From a computational viewpoint, the difference between the two types of models is small: they form algorithmic variants that may arrive at the same solution. Of importance for the present study is that although our model is not a process model it still pretends to make distinctions that are psychologically relevant.

Coding the Temporal Structure If, while listening to a temporal pattern, a subject develops an internal clock, it is assumed that this is used as a (time) scale to specify the temporal structure of the pattern. Basically the coding lies in the description of how the successive clock units are subdivided. Generally speaking, coding aims at efficiency of description. For the present

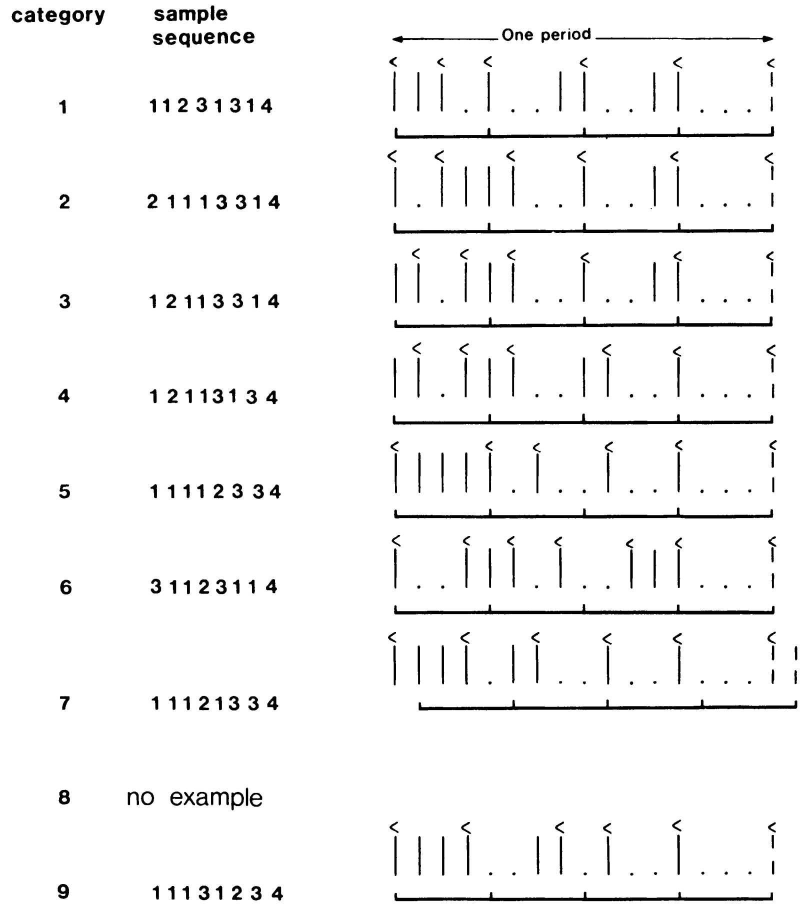


Fig. 5. Specimen patterns from the different categories distinguished by the model together with their best clocks. The patterns are permutations of the combination 1 1 1 1 2 3 3 4. Perceived accents are indicated with the symbol < above the tones.

we suppose that the efficiency of a code is inversely related to the number of symbols needed. In the case of temporal patterns efficient coding can be achieved if the intervals within one clock unit can be described in a reduced form. This is evidently the case when these intervals are equal.

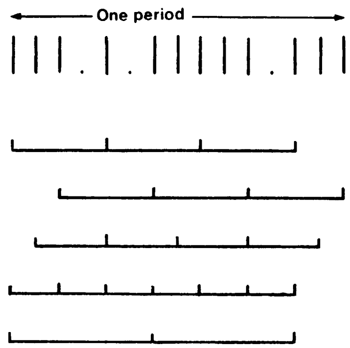
We therefore propose the following tentative coding rules:

1. If a clock unit is subdivided into equal intervals, this is described in the code by means of the symbol S and a subscript indicating the number of intervals in that unit.

2. If a clock unit is empty, this is indicated with the symbol E. Although this transcription obviously does not make the code more efficient, it makes it more abstract.

3. If a clock unit is subdivided in intervals of unequal length, no reduction

PATTERN 1 1 2 2 1 1 1 1 2



Clock	Unit	Loc.	Code
1	4	1	1-1-2, 2-1-1, 1-1-2
2	4	3	S_2, S_4, 2-1-1
3	3	2	1-2, 2-1, S_3, 2-1
4	2	1	S_2, E, E, S_2, S_2, E
5	6	1	1-1-2-2, 1-1-1-1-2

Fig. 6. The coding of the pattern 1 1 2 1 1 1 1 2 in terms of different clocks.

is possible and the successive intervals are described by indicating which proportion of the clock unit they take. Hence, if a clock unit is subdivided into two intervals of 200 and 600 msec, respectively, this will be described as 1–3. In principle, the coding of a given sequence depends on the characteristics of the internal clock, its unit, and location. Examples of how the coding of one pattern varies with different clocks are shown in Figure 6. From the examples presented it will be clear that the clock unit must be of an intermediate length if it is to yield an efficient description. If the clock unit is either very short or very long no reduction can be accomplished at all, since the code will contain the same amount of symbols as the uncoded sequence of intervals. In the coding model proposed here, the minimal number of symbols will never be less than the number of clock units needed to cover one period of the sequence. It is conceivable, however, that in a more elaborate version of the model, further encoding would be incorporated by taking into account regularities in the code itself. For instance, the sequence 1 1 1 2 1 2 1 2 1, assuming a clock with unit 3 at location 1, could as a first step be coded S1, 2–1, 2–1, 2–1. In a second step the 3 groups at the end could be coded more efficiently, taking advantage of their identity. Since the sequences we have been studying so far are relatively short, such higher order coding is as yet unnecessary.

We have designed and performed three experiments that test different aspects of the model. Experiments 1 and 2 are related to the clock-induction part of the model, while Experiment 3 is related to coding.

Experiment 1

This experiment tests the prediction that temporal patterns that strongly induce an internal clock form better internal representations and are consequently better reproduced than weaker clock-inducing patterns. For this purpose, sets of sequences were constructed in which only the order of the respective intervals was varied, thus ensuring that only structural variations were introduced. In this design experimental effects cannot be attributed to differences in type and number of intervals occurring between sequences.

Two dependent variables were studied: the time subjects needed to learn the sequences and the quality of their reproductions. The data were also analyzed separately for subjects with high and low scores.

Method

The stimuli consisted of 35 sequences, all of them permutations of the combination 1 1 1 1 1 2 2 3 4. Numbers 1 through 4 respectively indicate onset intervals of 200, 400, 600, and 800 msec. The tones were formed of 830-Hz square waves with a duration of 50 msec which included 5-msec rise and fall times. From each of seven categories (see Table 1, combination 3), five sequences were chosen. Table 2 shows the 35 stimuli ordered according to the seven categories. Ten other sequences, permutations of the same combination, were used for training purposes.

Procedure Twenty-four subjects, undergraduate and graduate students of the Psychology Department at Nijmegen University, participated in the experiment individually. Each subject first trained with the 10 practice trials to get acquainted with the procedure, which ran as follows. The subject was placed in front of a push-button panel containing some function buttons and one response key. A sequence was presented through earphones in a repetitive fashion. The subject was allowed to listen as long as (s)he wished and was encouraged to tap along with the sequence during stimulus presentation. When the subject felt that the stimulus was sufficiently known to reproduce it, (s)he pressed a button that stopped stimulus presentation, after which the subject reproduced four periods of the sequence in a repetitive fashion. Each tapping of the response key produced the same tone from which the stimuli were constructed, thus making the audible correlates of stimulus and response stage highly compatible. Besides, the cessation of the tones during the response stage indicated to the subject that reproduction could be stopped. At this stage the subject could either call the next stimulus or repeat the current one if (s)he so wished by pushing the appropriate function key. In this self-paced way the subject worked through all 35 stimuli, taking on the average about 50 min. The stimuli were presented in random order, different for each subject. Stimulus generation and response collection were controlled by a PDP 11/03 computer. After the experiment the subjects were interviewed about their musical training and were asked to give an introspective account of how they had performed the task.

Results

Acquisition Data Figure 7 shows the mean number of times subjects listened to the sequences in each of the seven categories before starting to respond. It can be seen that except for Category 3 there is a monotonic relation between category and number of presentations: the higher the category the longer the subjects listened to the sequence. An analysis of variance shows that the factor Categories is significant ($p = .004$). The main difference is between Categories 1 and 2.

TABLE 2
Stimuli of Experiment 1

No.	Sequence	Category
1	1 1 1 1 3 1 2 2 4	1
2	1 1 2 2 1 1 3 1 4	
3	2 1 1 2 1 1 3 1 4	
4	2 2 1 1 1 1 3 1 4	
5	3 1 2 2 1 1 1 1 4	
6	1 1 2 1 1 2 1 3 4	2
7	2 1 1 1 2 1 3 1 4	
8	1 3 1 1 1 1 2 2 4	
9	1 3 2 1 1 2 1 1 4	
10	2 1 1 2 1 1 1 3 4	
11	1 1 2 1 3 1 2 1 4	3
12	1 2 1 1 1 2 3 1 4	
13	1 2 1 2 1 1 1 3 4	
14	1 3 1 2 1 2 1 1 4	
15	3 1 1 2 1 1 2 1 4	
16	1 2 1 1 1 2 1 3 4	4
17	1 2 1 1 2 1 1 3 4	
18	1 2 1 1 3 1 2 1 4	
19	1 3 1 2 1 1 1 2 4	
20	1 3 1 2 1 1 2 1 4	
21	1 1 1 1 2 1 2 3 4	5
22	1 1 1 2 3 1 1 2 4	
23	1 1 3 1 2 1 1 2 4	
24	2 1 1 3 2 1 1 1 4	
25	2 3 1 1 1 2 1 1 4	
26	1 1 1 2 2 3 1 1 4	6
27	1 2 1 1 2 3 1 1 4	
28	1 2 3 1 1 2 1 1 4	
29	2 1 1 1 2 3 1 1 4	
30	3 1 1 1 1 2 1 2 4	
31	1 1 1 2 1 1 3 2 4	7
32	1 1 1 3 1 2 1 2 4	
33	1 2 1 1 1 3 1 2 4	
34	1 2 3 1 1 1 1 2 4	
35	2 3 1 1 2 1 1 1 4	

Reproduction Data Figure 8 gives reproduction data, showing for each category the mean deviation score averaged over subjects. The deviation score is obtained by summing the absolute differences between the corresponding intervals in the reproduced sequence and the stimulus. We did not apply a tempo correction to this score. Such a correction is only warranted

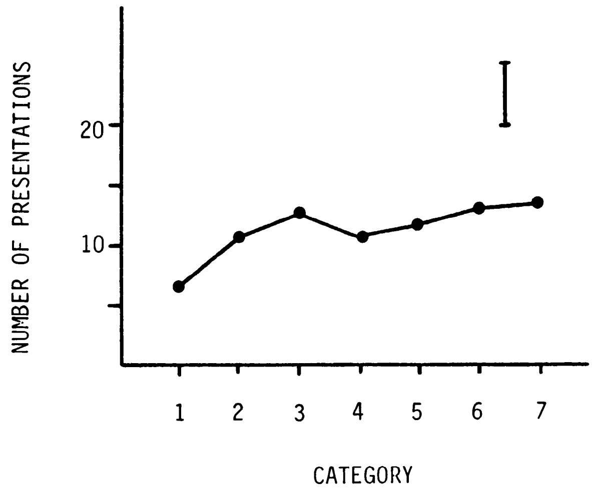


Fig. 7. Mean acquisition time (number of presentations of the stimulus) observed for each of the seven categories. Inset: standard error.

if all reproduced intervals are either systematically shortened or lengthened. A most inadequate measure is obtained if tempo correction is applied in those cases where only one or two of the intervals are considerably lengthened while the others are reproduced correctly. Moreover, we found that on the average the subjects kept tempo very well. The used score therefore seems a fair approximation of the subjects' imitative ability.

The figure presents data for all 24 subjects as well as for the 6 most-skilled and 6 least-skilled subjects; the latter selection was based purely on the data. The difference between the two groups of subjects is considerable: the mean deviation score of the skilled subjects is 140.4 msec (SD = 2.54), of the unskilled subjects 224.1 msec (SD = 3.64). The data for all subjects reveal the same overall picture: the higher the category, the higher the deviation score. There is a tendency for the sequences of Category 5 to be reproduced somewhat better, however.

Analysis of variance on the data of all subjects shows that the factors Categories ($p < .001$) and Stimuli ($p = .01$) are significant. Separate analyses of the data of the six most-skilled and six least-skilled subjects show that for both groups only the factor Categories is significant ($p = .02$ and $p = .05$, respectively). Figure 9 shows the reproduction scores for all 35 stimuli averaged over subjects along with the mean scores obtained in the seven categories.

The subjects experienced great differences between the stimuli. Those stimuli experienced as simple seemed to organize themselves automatically and were remembered without any cognitive activity. For difficult sequences subjects reported that they used various mnemonics such as assigning numbers to successive tones.

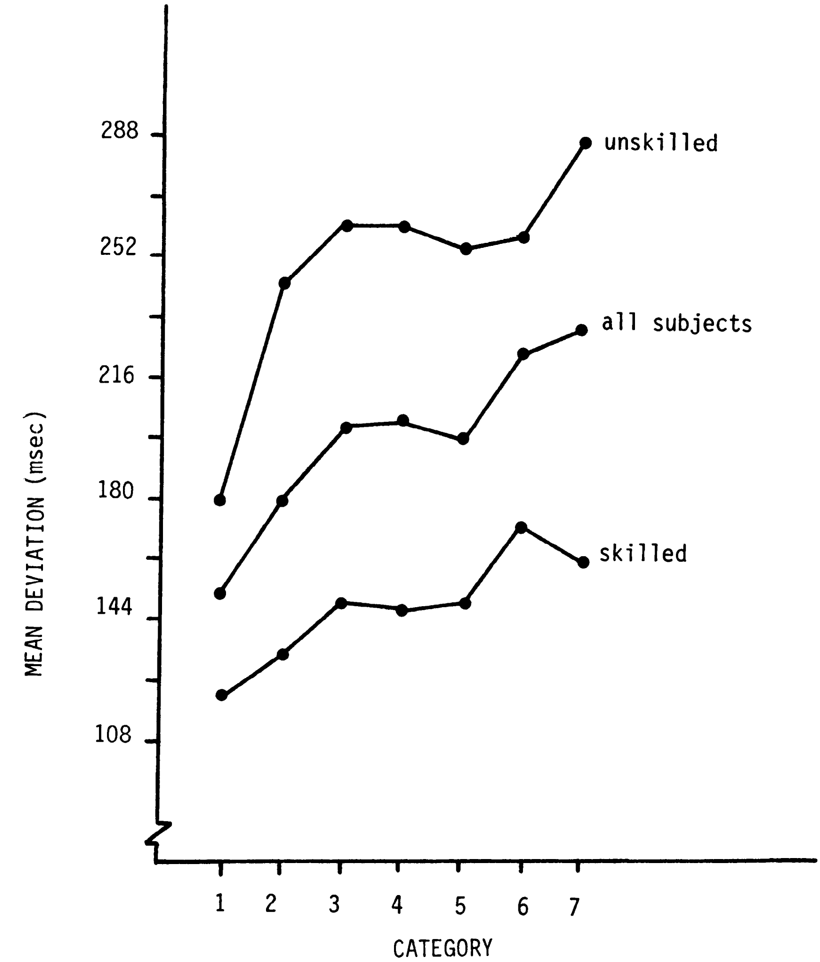


Fig. 8. Mean deviation scores of the sequences in the seven categories, separately displayed for the 6 most skilled, the 6 least skilled, and for all 24 subjects in the experiment.

Discussion

The prediction that subjects would have more difficulty in forming an accurate representation of a sequence, the weaker that sequence induces a clock, is supported by the data: we find a significant tendency showing that the higher the category a sequence belongs to, the worse the reproduction. The function seems to reach an asymptotic value beyond a certain point. This may be explained by assuming that clock induction of sequences of higher categories is so weak that no internal clock is actually evoked.

If no clock is used in the processing of these sequences, the question arises how these sequences are coded. It is true that these sequences make a

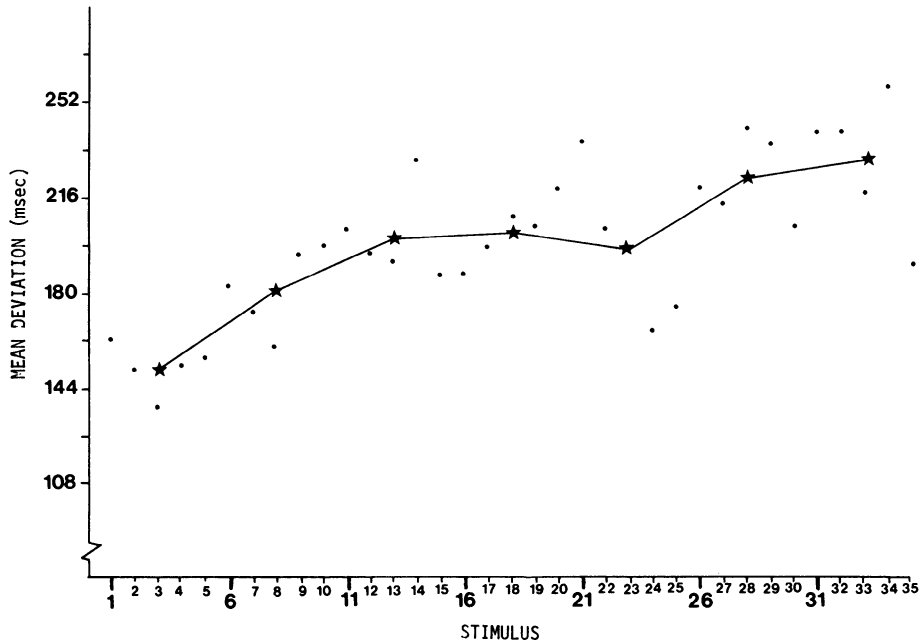


Fig. 9. Mean deviation scores for all 35 stimuli in the experiment. Stars represent the mean deviation scores of the sequences in the seven categories.

perceptual impression completely different from those of Category 1. They do not seem to give rise to a clear percept: one remains uncertain about what the sequence really is. This was confirmed by almost all subjects during and after the experiment. It was frequently mentioned that some of the sequences could be reproduced almost automatically, while others were difficult to grasp and had to be memorized by means of mnemonic tricks like counting. The sequences of the higher categories indeed suggest organization in terms of tone clusters rather than in terms of a temporal structure; that is, in the same way as we *see* the patterns of lines in Figure 6. In her research on how children memorize rhythmical patterns, Bamberger (1978) showed that her subjects actually did use different ways of coding temporal patterns. In particular, she distinguished "durational" and "figural" coding, which may very well correspond to coding in terms of an internal clock versus coding in terms of tone clusters. Additional evidence in support of the relevance of this distinction has been reported by Smith (1983) and Essens and Povel (in press).

In this way Stimulus 21 (1 1 1 1 2 1 2 3 4), for instance, would be perceived as consisting of a group of five tones followed by a group of two tones, followed by two isolated tones. Of course, such a coding lacks any precise timing information. Since subjects do not seem to rely on an internal clock to specify the temporal structure in these sequences, we suppose that subjects code them in terms of a limited number of perceptual categories of duration such as the "long" and "short" durations proposed by Fraisse (1956).

Most important in the present case is that we have been able to show that the strength of induction of the hypothesized clock does play a crucial role. While evaluating the results of this experiment it occurred to us that the clock notion could be tested differently by manipulating clock induction more directly. Such an attempt has been undertaken in Experiment 2.

Experiment 2

This experiment was designed to test the hypothesized function of an internal clock more directly. Twenty sequences from the previous experiment were therefore combined with a low-pitched isochronous sequence which itself strongly induces an internal clock appropriate to the first sequence. We reasoned that if an internal clock really is a necessary condition for the conceptualization of a temporal pattern, then providing a listener with a condition that strongly induces such a clock should result in significantly better reproductions.

Method

Sequences 1–20 from the previous experiment were selected as patterns to be used. The stimuli in this experiment were formed by combining each pattern with a low-pitched isochronous sequence. The patterned sequence of each stimulus was formed of 50-msec, 830-Hz square wave sounds, while the isochronic sequence was formed from 50-msec, 125-Hz square waves. The latter was about 10 dB lower in intensity. Two examples of such stimuli are presented in Figure 10. In a pilot experiment with this type of stimuli, we found that subjects could easily reproduce the high-pitched sequence as long as all tones of the low-pitched sequence coincided with a tone of the high-pitched sequence (as is the case in Figure 10a).

If, however, one of the tones of the low-pitched sequence did not coincide with a tone in the other sequence (Figure 10b), subjects became confused and could no longer carry out the task correctly: tones from the low-pitched sequence tended to be introduced in their reproduction. For this reason we only used the sequences from Categories 1–4, which have best clocks in which all ticks coincide with elements in the sequence (see Figure 5). In fact, according to the model, the best clock of all these sequences has a time unit of four located at the first tone of the sequence. Therefore in all 20 stimuli the high-pitched pattern was combined with a low-pitched sequence having a fixed time unit of four starting at the first tone of the sequence. The sequences of Category 1 were included as a control. Since it is supposed that these sequences already strongly suggest an appropriate clock, the extra suggestion of the low-pitched sequence should not play a role.

The procedure was in all respects identical to that of Experiment 1: subjects could listen to the sequence as long as desired, then pushed a button that stopped stimulus presentation and reproduced the high-pitched sequence four times. In order to ensure comparability of the data the same 24 subjects of the previous experiment participated in this experiment. All

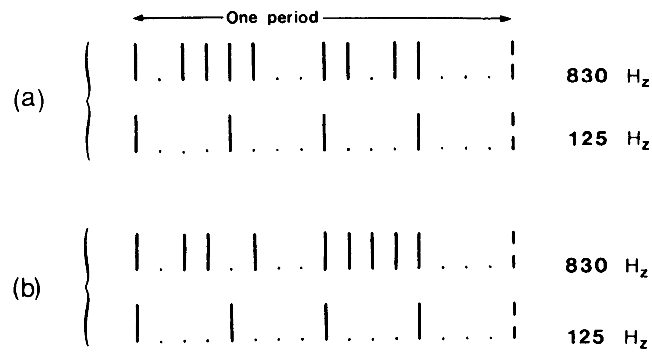


Fig. 10. Two examples of double sequences.

subjects found it self-evident that they had to reproduce the patterned high-pitched sequence and not the repeating interval of the low-pitched sequence.

Results

In order to facilitate comparison of the results of this and the former experiment we have displayed the relevant results of both in Figures 11 and 12. Figure 11 shows the number of times subjects listened to the sequences in each of the four categories. In an analysis of variance on the data of this experiment the factor Categories was significant ($p<.001$), meaning, as the diagram shows, that subjects needed more presentations for the sequences of higher categories.

As in the previous experiment we show the reproduction data of all 24 subjects together and, separately, the data of the 6 most-skilled and 6 least-skilled subjects. These data are shown in Figure 12. An analysis of variance on the data of all subjects shows that Categories ($p<.001$) and Stimuli ($p=.001$) are significant. An analysis of the 6 skilled subjects yielded significance only for the factor Stimuli ($p=.05$), while an analysis of the 6 unskilled subjects yielded significance only for the factor Categories ($p<.001$).

Further, we performed an analysis of variance on the combined reproduction data of this and the former experiment (only Stimuli 1–20) in which the additional clock induction figured as a condition. This factor appeared to be significant for all subjects ($p<.001$), for the skilled subjects ($p=.05$) as well as for the unskilled subjects ($p<.001$).

Discussion

We may conclude that the additional induction of an internal clock does have a positive effect on reproduction. We find a significant improvement in

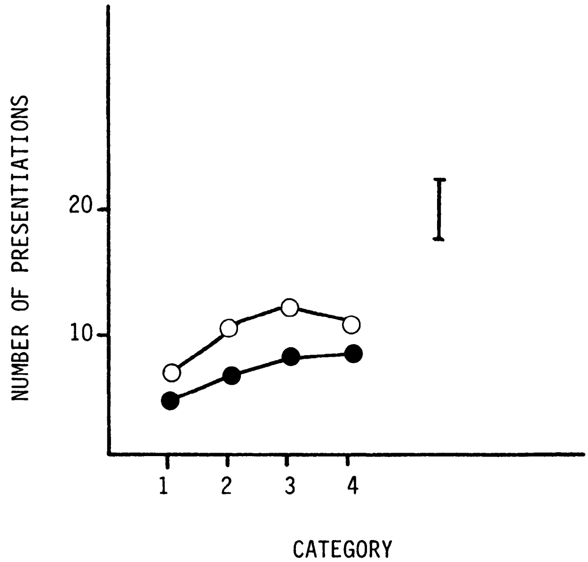


Fig. 11. Comparison of the mean acquisition scores of the sequences in the four categories observed in Experiments 1 and 2. ○, Expt. 1; ●, Expt. 2.

the imitations by all subjects, both skilled and unskilled. This finding gives additional support to the hypothesis that the presence of an internal clock is a necessary condition for an accurate internal representation. It is noteworthy that the reproduction of the sequences of Category 1 also improves with the extra clock induction. Apparently the presence of the low-pitched sequence enhances the strength of clock induction. Another important finding is that the skilled subjects reproduce all sequences equally well in the plus-clock condition, while the other subjects tend to reproduce the sequences from the higher categories less well (see Figure 12). There are two factors that may explain these findings: the distribution of accents and the complexity of the temporal structure in the different sequences. We will deal with these two points in succession.

1. Local accents and beats. We have argued that sequences of the type studied here contain accented events. We will call these accents "local accents" since they arise locally and are not the result of global processing. Further, we have argued that part of the process in the perception of temporal patterns consists of the generation of an internal clock, to some degree determined by these local accents. Once an internal clock has been established it will in turn cause those events coinciding with clock ticks to be perceived as accentuated. In order to distinguish these accents from the local accents we will borrow the word "beat" from music theory. It is possible that (unskilled) subjects tend to confuse local accents with beats, which may

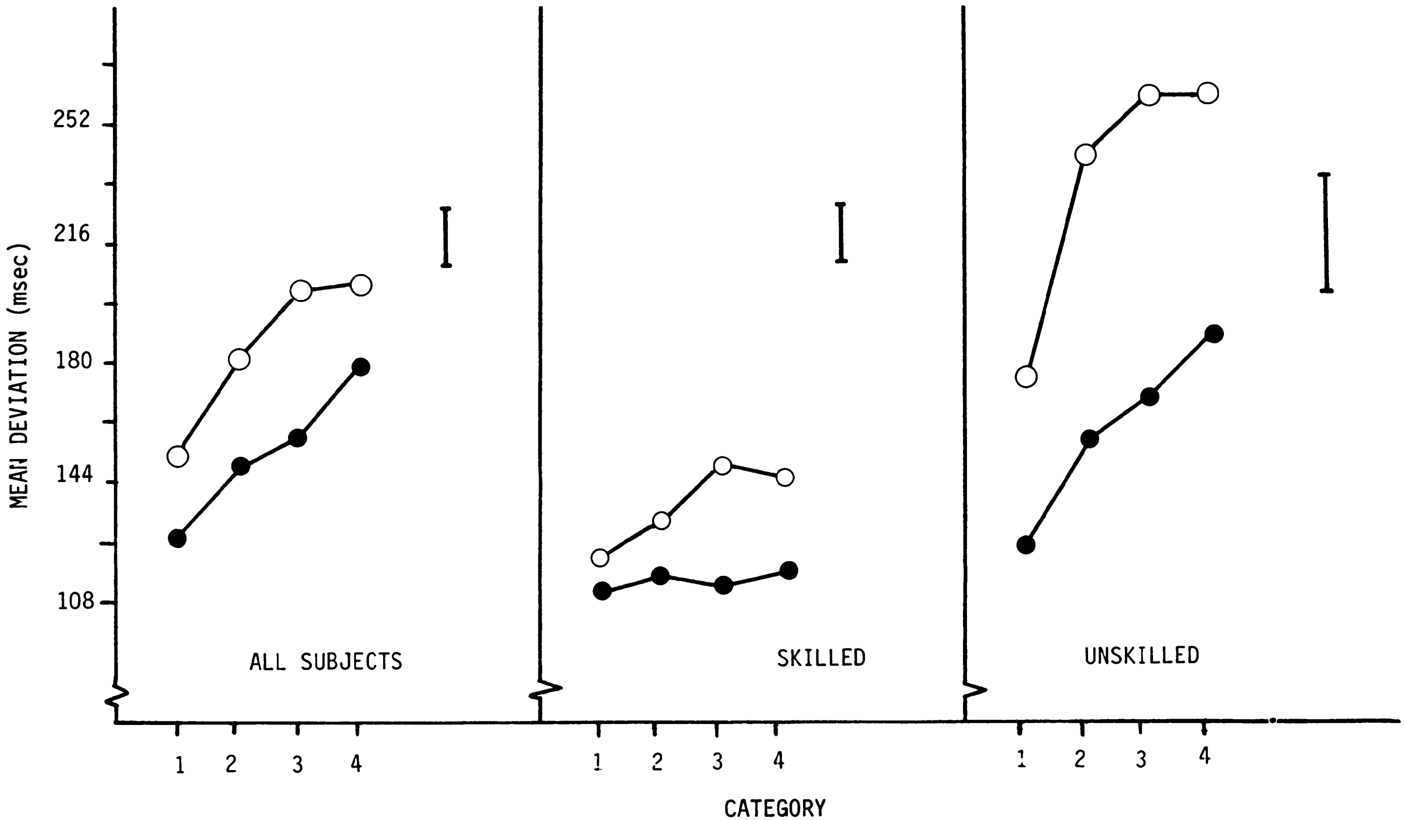


Fig. 12. Comparison of the mean deviation scores of the sequences in the four categories observed in Experiments 1 and 2, displayed separately for all subjects, the 6 skilled, and the 6 unskilled subjects. ○, Expt. 1; ●, Expt. 2.

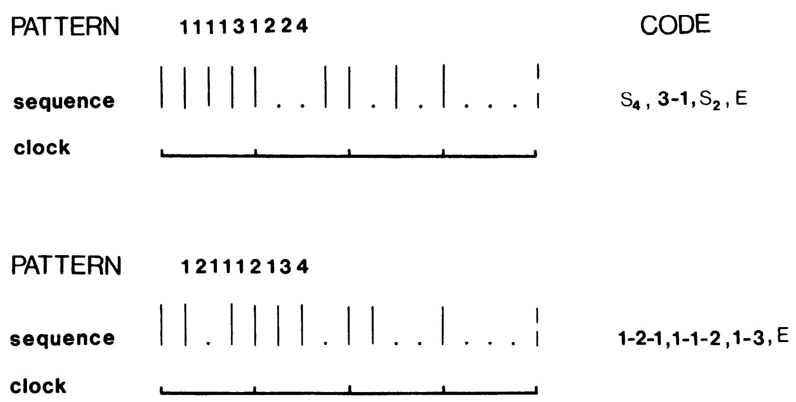


Fig. 13. Two examples of patterns used in Experiment 2 (Stimuli 1 and 16) along with their coding in terms of the induced clocks.

result in a degraded reproduction. Such confusion is more likely to occur, the more beats that fail to coincide with local accents or, in other words, the higher the category to which the sequence belongs. This confusion of accents might explain the finding that sequences from higher categories are less well reproduced.

2. Complexity of structural code. A second explanation is related to the actual coding of the sequence. In the introduction we proposed a tentative coding model that specified how the temporal structure in a pattern is coded by means of the internal clock. There we have shown that the intervals in a temporal pattern can be described in a more efficient way depending on how the intervals in a sequence are divided over the clock intervals. In principle, reduction of description is possible if a clock unit is either empty or subdivided in equal intervals. Now it will generally be the case that more reductions are feasible when the sequence belongs to a lower category. Figure 13 presents as an example two sequences (Sequences 1 and 16 from the present experiment) and their coding in terms of the imposed clocks. Although this coding is still tentative, it is clear that the memory's representation of the second sequence is much more complicated than that of the first. Thus, the observed differences in the reproduction of sequences from different categories may be caused by the way they are internally represented.

The two explanations offered here are probably related: the more complex the coding, the more local accents will not coincide with beat accents. It is beyond the scope of this paper to elaborate further on this issue. The main purpose of this experiment has been to show that the induction of an appropriate clock does improve the internal representation of a temporal pattern. Such an effect has been found. That the effect of this clock, as

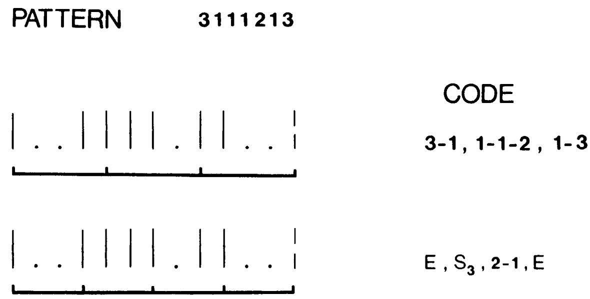


Fig. 14. The coding of pattern 3 1 1 1 2 1 3 in terms of clocks with units of 4 and 3, respectively.

measured by reproduction, is smaller for unskilled than for skilled subjects is easily understandable.

Experiment 3

This experiment is also concerned with the perception of what we will subsequently call "double sequences": sequences combined with a low-pitched isochronic sequence that is supposed to induce an internal clock. Suppose we ask a subject to listen to a double sequence consisting of the high-pitched sequence 3 1 1 1 2 1 3 together with a low-pitched isochronic sequence with a fixed interval of size 4. After several periods, the presentation is stopped and the subject is asked to compare the stimulus with the following one, which consists of the same sequence 3 1 1 1 2 1 3 but now combined with a low-pitched sequence with a fixed interval of size 3. (Note that, since the length of the sequence is 12, the two isochronic sequences with intervals 3 and 4, both being divisors of 12, fit well with the sequence.) (See Figure 14.) The second stimulus is also stopped after a few periods. The subject is then asked whether (s)he has recognized that the two stimuli contained the same rhythm or temporal pattern. Nine out of 10 times the answer will be negative.

This very interesting phenomenon is completely in keeping with our model, which assumes that the coding of the temporal structure in a temporal pattern is made in terms of the internal clock induced in the subject. Now, in the two double sequences presented, the clocks induced by the isochronic low-pitched sequence are supposedly different, having units of 3 and 4, respectively. Hence, the patterns will be coded differently and consequently be perceived as two different patterns. In Figure 14, the coding of the temporal structure of the sequences in the two clock contexts is presented. Given the difference in these codings, we can see why the similarity between the two double sequences is not discovered.

The possibility of combining one and the same sequence with different clock-inducing sequences presents an ideal opportunity to test the proposed coding model. We can select a number of suitable sequences and produce two double sequences by combining them with different low-pitched isochronic sequences. We thus obtain pairs of double sequences containing the same patterned sequence but differing in the induced internal clock. For each stimulus in such a pair we can determine how it will be coded and on the basis of this coding will be able to predict which of the double sequences in the pair is theoretically more complex. These predictions can then be tested by obtaining judgments from subjects about the relative perceptual complexity of the stimuli in a pair. This has been done in the following experiment.

Method

Stimuli Each stimulus pair consisted of two double sequences to be compared. In one double sequence a high-pitched sequence was combined with one low-pitched isochronic sequence, while in the other pair the same high-pitched sequence was paired with another low-pitched isochronic sequence. The tones used in the experiment consisted of square wave tones of 50-msec duration which included 5-msec rise and fall times. The high-pitched tones had a frequency of 1044 Hz, the low-pitched tones a frequency of 261 Hz, thus forming a pitch interval of two octaves. The total length of the interval sequences used was 2400 msec or 12 time units, thus allowing a specification in either a 3-clock or 4-clock. We avoided sequences in which one or more of the tones of the low-pitched sequence did not occur simultaneously with a tone of the interval sequence, since that might have introduced an undesirable inequality between stimulus pairs. This constraint, however, severely limited the number of possible stimuli. The 12 stimuli we constructed are displayed in Figure 15.

Table 3 indicates for each sequence how many complex or irreducible clock intervals there are when described in terms of a 3-clock or a 4-clock respectively, on the assumption that every clock interval is complex that is not empty or filled with identical intervals. On the basis of these specifications, we made predictions as to which of the two clocks would yield the simplest coding. These appear in Column 3. Moreover, Column 4 indicates whether the accents on the second tones of the two-tone clusters (which are the most salient accents) favor a 3-clock or a 4-clock.

From the table we see that there are four sequences that are theoretically coded more efficiently in a 4-clock, and four more efficiently coded in a 3-clock; the other three are neutral in this respect. Accents sometimes favor the most efficient clock, sometimes the less efficient one.

Procedure Twenty-five subjects, undergraduate and graduate students of psychology at Nijmegen University, participated individually in the experiment. A subject was seated at a table, provided with headphones and a panel containing two "call" buttons and two response buttons. Each "call" or "stimulus" button had a corresponding response button directly above it. At the beginning of each trial, a small lamp on one of the call buttons was lighted. If that button was pressed the subject received the corresponding stimulus pair binaurally through the headphones. The stimulus was presented continuously in a repeated fashion and could be silenced either by pressing the same call button or by pressing the other call button. In the latter case the current stimulus ended and was, after a 700-msec pause, replaced by the other one of the pair. In this way the subject could shift from one pair to the other as often as

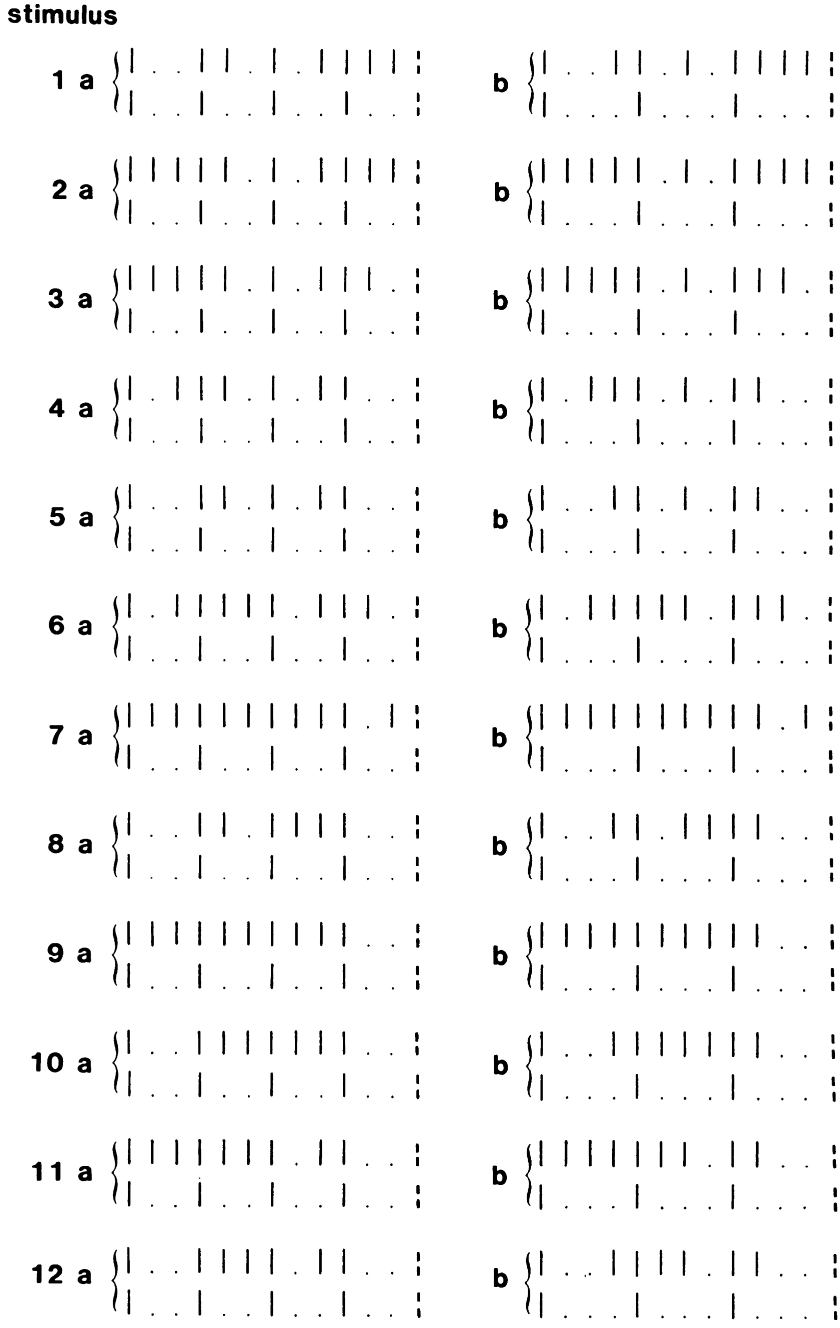


Fig. 15. The twelve stimulus pairs used in Experiment 3. (a) The pattern combined with a low-pitched sequence inducing a 3-clock. (b) The pattern combined with a low-pitched sequence inducing a 4-clock.

TABLE 3
Features of the Sequences Used in Experiment 3

Stimulus Number	Sequence	Nonreducible Intervals 3-clock	Nonreducible Intervals 4-clock	Simpler Clock	Accent Favors
1	31221111	2	1	4	4
2	1111221111	2	0	4	
3	111122112	3	1	4	
4	2112213	3	2	4	3
5	312213	2	2	-	4,3
6	211112112	3	3	-	
7	11111111121	1	1	-	
8	3121113	1	3	3	4
9	111111113	0	1	3	
10	3111113	0	2	3	
11	11111213	1	2	3	3
12	3111213	1	3	3	3

desired. Subjects were requested to indicate which of the pairs (s)he judged more simple by pressing the corresponding response button. The subjects did not receive any instruction as to what was meant by simple. However, they practiced with eight stimulus pairs in which one pair was obviously perceptually simpler than the other. The subjects did not receive any feedback. The set of stimulus pairs was presented three times, each time in a different random order. Which stimulus of a pair was presented first (indicated by the lamp on one of the call buttons) was determined by chance. The whole experiment, including the practice trials and the 36 experimental trials, took on the average 30 minutes.

Results

One subject was unable to give the judgments requested. This subject could not integrate perceptually the two sequences, but instead heard them as two completely independent streams. The other subjects had no trouble in fulfilling the task; most subjects considered it easy. The fact that for several sequences (nos. 1, 2, 11, and 12) almost 100% of the responses indicated the same pair as the simpler, shows that the judgments are based on solid subjective evidence.

Figure 16 presents the results in terms of the percentage of responses in which the 4-clock combination was preferred. In this figure we have also indicated the predictions from Table 3. In those cases in which the factor Accents works in the opposite direction as the factor Efficiency (Stimuli 4 and 8) no exact prediction could, of course, be made.

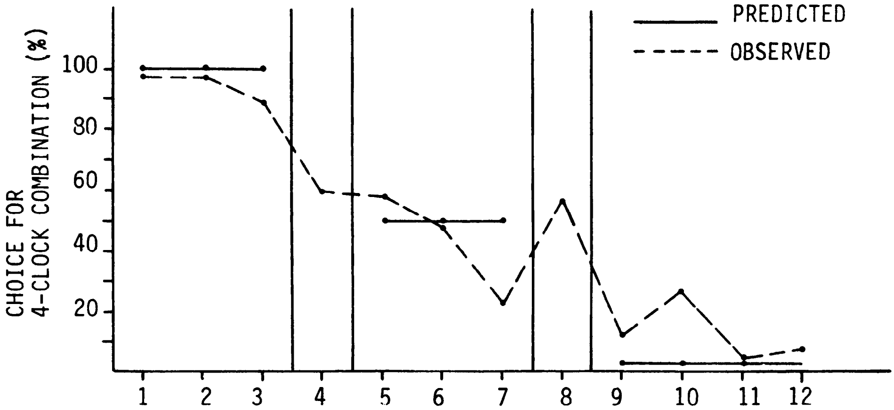


Fig. 16. Percentage of cases where subjects judged the 4-clock combination simpler than the 3-clock combination for the 12 stimuli of Experiment 3.

Discussion

The observed data closely agree with the theoretical predictions. Stimuli 1, 2, and 3, being theoretically more efficient when coded in a 4-clock, yield respectively 100, 100, and 90% responses in favor of the 4-clock combination. Stimulus 4, which is also coded more efficiently in a 4-clock but in which an accent occurs on Tone 7 that better fits a 3-clock, gives rise to a decrease to 60% in responses favoring the 4-clock combination. Stimuli 5, 6, and 7 can theoretically be coded just as efficiently in a 3-clock as in a 4-clock. The responses on Stimuli 5 and 6 reflect this prediction very well since judgments are equally split between 3-clock and 4-clock combinations. For Stimulus 7, however, the 3-clock combination is preferred. An ad hoc explanation for this finding may be that the description of the last 3-clock interval (two intervals relating as 2:1) is simpler than the description of the subdivision of the last 4-clock interval (three intervals relating as 1:2:1). In the responses to Stimulus 8 we again see the conflicting effects of the two factors. Finally, for Stimuli 9 through 12, a very high percentage of the responses judges the 3-clock combination to be the simpler of the two. Only for Stimulus 10 is a slightly deviating percentage found.

The results of this experiment seem to indicate that the temporal structure is indeed coded in terms of the units of the clock. If the clock is well chosen, it permits a more economical description of the intervals in the sequence, as in the case that intervals equally subdivide a clock interval.

General Discussion

The main goal of this work has been to gain a better understanding of how temporal patterns are perceived. We reasoned that a genuine proof of such understanding would be the ability to predict the relative complexity of temporal patterns. The experiments reported here concerned, therefore, either the reproduction of temporal patterns or complexity judgments of temporal patterns.

We have proposed a model that assumes that people attempt to generate an "internal clock" which enables the specification of the temporal structure in the pattern. We have argued that the selection of this clock is mainly based on the distribution of accents perceived in the pattern. In their turn these accents appear to be determined by the clustering of tones. We have also suggested how the temporal structure is coded in terms of the internal clock. Codes may differ in complexity. According to the model, not every pattern will actually invoke an internal clock. In those cases where no clock is induced the pattern is assumed to be coded differently. This alternative coding, called "figural coding" by Bamberger (1978), capitalizes on the perceptual grouping of events. In this latter grouping strategy, detailed information about the relative durations of intervals would seem to be left uncoded.

With the help of the above notions, we have been able to understand at least part of the observed phenomena. In sum, we can say that a given temporal pattern will be poorly reproduced or be judged complex when either no internal clock is induced or, where it is induced, when the coding of the pattern is relatively complex.

The ideas presented here about the processing of temporal patterns have important implications for the conduct of research in the field. Most essential is that it does not make sense to speak of *the* perception of a temporal pattern without further qualification. We have given evidence showing that the internal representation of a pattern completely depends on whether, and which, clock is internally induced. Instructive in this respect is that subjects do not recognize the same pattern when presented in different clock contexts (Experiment 3). Clock induction is in the first place determined by the distribution of accents in the sequence, but may also be influenced by another concurrent pattern (Experiments 2 and 3) or by perseveration of a clock induced through previously presented patterns.

The foregoing implies that one must be very well aware under what conditions an actual investigation has been performed. As a consequence, it may be quite inappropriate to compare the results of different studies. Consider, for instance, how the internal representation may depend on the method by which temporal patterns are generated and presented. A pattern can be generated synthetically the way we did or it may be clapped or performed on a musical instrument. In the latter case the performer will inevitably supplement accents or change the temporal structure so as to bring about the induction of some internal clock. The same would be true, of course, if the pattern were presented in the form of musical notation, which will invoke musical intuitions on the part of the subject. There is nothing wrong with these methods, but we want to make clear that although these investigations all pertain to temporal patterns, they may very well tap different aspects of the process.

We have attempted to approach the problem not from a musical viewpoint (which presupposes notions such as meter and beat, probably closely related to the clock notion) but from a more general viewpoint which seeks to understand how subjects code time and patterns of time. For this reason, we have avoided the use of concepts of music theory which are, in principle at least, applicable only to patterns occurring in music.

It seems proper to add a few remarks on the relationship of this work to other work in the field. We have mentioned before that several authors have stressed the relevance of some clock notion, usually called metrical interpretation, for the perception of temporal patterns. For instance, Handel and Oshinsky (1981) and Handel and Lawson (1983) have done a great amount of work on determining how subjects tap a beat with polyrhythms of varying complexity. Models for the metrical interpretation of musical rhythms have been developed by Longuet-Higgins and Lee (1982) and Steedman (1977). We should like to point out that there are some important differences between the latter approaches and ours. First, their models aim at mirroring the actual process of meter interpretation, which therefore works from left to right through the sequence. These models start from the intervals as they occur in the sequence, giving more weight to relatively longer intervals, but they do not take into account the possibility of accents playing a role in determining beat or meter. Second, these models will always supply some solution, that is, some metrical interpretation. Our model, on the contrary, only determines the chance that an internal clock will be induced, thus leaving open the possibility that no clock is internally generated, and that an alternative coding is employed. The outcome of the reported experiments may be taken as demonstrating the latter point.

In sum, we think that accents play a decisive role in inducing the internal clock. In fact, during an earlier stage of our work, we tried to understand the perception of temporal patterns purely in terms of their temporal characteristics (Povel, 1984), but attempts to test predictions from this model failed. We think that the finding of accented and unaccented events perceived within sequences consisting of identical tones is vital for an understanding of how these patterns are processed. Moreover, this finding has consequences for the perception of sequences in which tones are additionally made more salient by making them louder or longer. Probably, even more complicated interactions will occur here.

In future work we plan to further elaborate the clock-selection mechanism, to collect more data relevant to the proposed coding model (the technique used in Experiment 3 seems most suited to this purpose), to further analyze the characteristics of the two types of coding (figural and durational), and to determine the contributions of decoding and of motor aspects in the production of temporal patterns (see Essens and Povel, in press).[3]

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