The Effect of Tempo and Musical Experience on Perceived Beat

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This research investigated the effect of musical tempo on the rhythmical interpretation of six temporal patterns of varying rhythmic complexity. For each pattern, listeners tapped at regular intervals in synchrony with what they perceived to be the most natural placement of beats. Consistent with previous research, the perceived time interval (period) of successive beats was at a lower metrical level at slow tempos than at fast tempos. Tempo effects were dependent on musical experience, with musically trained participants demonstrating a stronger tendency to perceive a different relative beat period with changes in tempo, than were musically untrained participants. Musically untrained participants tended to select the same relative beat period, independent of tempo. The predictions of three models permit the observed differences to be interpreted in terms of the relative use of positive and negative evidence in assigning beats to a rhythmic pattern. This explanation offers an alternative to preferred tempo hypotheses.

Two fundamental characteristics of the rhythmic organisation of music are the related concepts of beat and tempo. The beat refers to a series of accents heard at regular time intervals in the music, while tempo refers to the prevailing pace (i.e., how fast or slow the music is). Most music evokes a sense of the beat. It is what we dance to, tap along with, and so on. However, it is clear from listening to music that there are temporal limits to the range of time intervals (tempos) over which beats are felt. If a piece of music is performed too slowly, the beat can disappear, while if it is performed too quickly, successive beats become indistinguishable (Fraisse, 1982). The general question addressed in this research is how the tempo of the music affects the perceived beat. There are three related components of the perceived beat to consider: the time interval of the beat (absolute beat period), the relative relationship between the beat period and the rhythmic structure of the music (relative beat period), and the specific alignment of beats with the pattern (phase). In this article, we examine the first two of these: the *absolute beat period* and the *relative beat period*.

To clarify the use of the term relative beat period, consider musical notation for a simple Waltz rhythm (shown in Figure 1). Musically, this Waltz conforms to a 3/4 *meter*. This means that the duration of each event, note (tone), or rest (silence) is defined relative to a quarter note (an abstract base time unit), with successive quarter notes grouped by threes. Thus, for the waltz excerpt, there are two hierarchically nested *time levels* (the quarter-note level and the measure level), which share a 3:1 relationship. Moreover, all possible notes in the music can be related to the base time unit, as simple multiples or subdivisions. For a piece of music, the perceived beat period typically corresponds to one of the time levels of the metric hierarchy. This time level can be expressed either in musical terms (e.g., quarter note, half note, dotted-half) or as a ratio relative to the base time unit (e.g., 1:1, 1:2, 1:3). We will use the two different representations of the relative beat period interchangeably.

Studies of rhythmic organisation have revealed important temporal constraints on perception of the absolute and relative beat periods. In the absolute sense of the beat, Fraisse (1982) identifies 500 to 700 ms as the approximate range of preferred time intervals in rhythmic tapping. There is not a clear upper limit to rhythmic tapping, but perceptual studies suggest a similar optimal range of time intervals in duration/tempo discrimination, with shorter and longer time intervals over- and under-estimated, respectively (Drake & Botte, 1993; Fraisse, 1978; McAuley & Kidd, 1998; Vos, Assen, & Franek, 1997; Woodrow, 1951).

In the relative sense of the term, perceived beat has been examined several different ways. Some studies have assessed relative beat period by comparing tapping variability for reproduction tasks involving simple and complex rhythmic patterns placed in different metrical contexts (Essens, 1995; Essens & Povel, 1985; Povel & Essens, 1985). Others have used probe tones to examine the perceptual salience of different relative time levels within a particular metrical context (Palmer & Krumhansl, 1990). Overall, these studies provide general evidence that people structure the representation of rhythm according to its meter, at least for meters typically encountered in Western music. Recent studies by Handel qualify some of this previous research, placing a greater emphasis on general grouping principles in rhythmic interpretation (Handel, 1992, 1993, 1998).

In this research, we focus on those studies specifically investigating the effect of tempo on perceived beat. These have mainly involved asking people to tap out the most salient metrical level for simple and complex rhythms presented at different tempos (Duke, 1989; Handel, 1984; Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978; Parncutt, 1994). Some of the earliest research on rhythm (Bolton, 1894; Woodrow, 1909) demonstrated subjective preferences for 1:2, 1:3, and 1:4 ratios (grouping tones by twos, threes, and fours) for simple isochronous sequences, such as the Pulse pattern in Figure 1. In these cases, the first tone of a group of two, three, or four is typically perceived as accented, with the time interval between groups subjectively lengthened.

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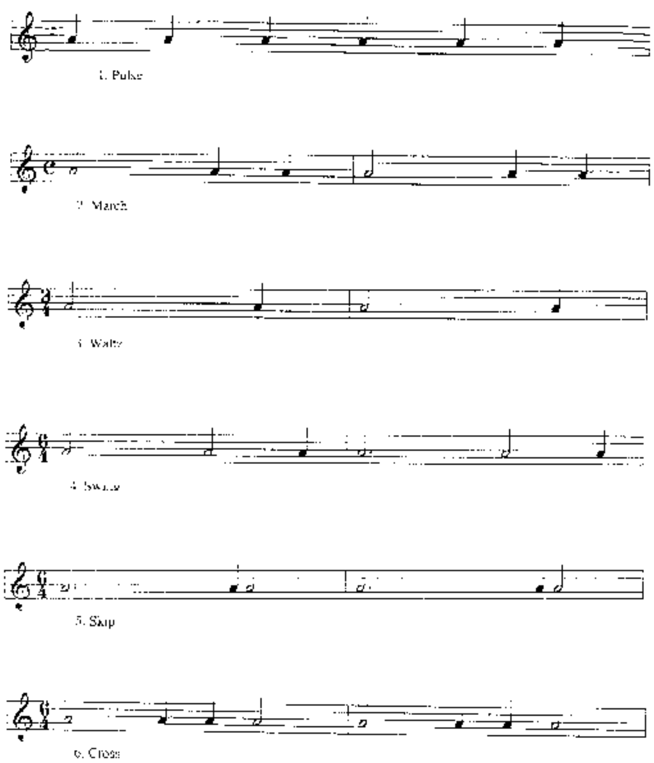

Figure 1
Musical notation for the six rhythmic patterns examined in this study.

More recently, Duke (1989) examined the effect of tempo on perceived beat for *isolated* isochronous sequences, asking musically trained listeners to tap out what they perceived to be regular accents at 15 different tempos ranging from fast to slow. In the absence of any pattern-defined metrical structure, Duke reported a tempo-dependent shift in listeners' responses: people marked out relatively higher time levels (in an implied metric hierarchy) at fast tempos than at slower tempos. This corresponds to preferring large time units at fast tempos and small time units at slow tempos. Specifically, listeners grouped tones in the sequence by twos, threes, and fours at fast tempos, tapped in synchrony with each tone at intermediate tempos, and subdivided the interval between tones at the slowest tempos.

Parncutt (1994: Exp. 1) found similar effects of tempo on perceived beat using both simple and complex rhythms. Like Duke (1989), Parncutt found that, with isochronous sequences, listeners group by twos, threes and fours at fast tempos, but not at slow tempos. For more complex rhythms, there was a clear tendency to tap out higher time levels in the implied metric hierarchy at fast tempos than at slower tempos. In many cases, at the faster tempos, many of the listeners tapped once with each repetition of the pattern (the highest level of the hierarchy).

In related research, Handel and colleagues (Handel, 1984; Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978) had listeners tap in synchrony with what they perceived to be the most natural placement of accents for a variety of constructed polyrhythms. Polyrhythms pit one isochronous sequence against another, and so naturally create several possible rhythmic interpretations of the emerging pattern. For a 3 x 4 polyrhythm, Oshinsky and Handel (1978) observed three different responses. Listeners subdivided the pattern into three equal time intervals, tapping in synchrony with the three-element isochronous sequence. They subdivided the pattern into four equal time intervals, tapping in synchrony with the four-element isochronous sequence. Or, they tapped once every 12 elements when the two sequences coincided. The most interesting aspect of these data was that the preferred response depended on tempo. Overall, listeners were more likely to subdivide into three equal time intervals at fast tempos than at slow tempos. Handel and colleagues reported similar effects of tempo for other polyrhythms. They interpreted these findings as a preference for large time units at fast tempos, and a preference for small time units at slow tempos.

In sum, for isochronous patterns (Duke, 1989), for simple and complex metrical patterns typical of Western music (Parncutt, 1994), and for polyrhythmic patterns (Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978), listeners' perceived beat tends to be at lower metrical levels (e.g., quarter-note or 1:1 ratios) at slow tempos than at fast tempos. One interpretation of these findings is that there is an interaction between preferred tempo and pattern structure: a preferred tempo hypothesis. The rationale is that, as the tempo of a pattern changes, the *relative* time level (e.g., quarter note, half-note, whole-note) that is nearest an *absolute* preferred time interval varies systematically, and thereby affects its salience. The closer a metrical level is to the preferred time interval, the more likely that level will be perceived as the beat. Parncutt (1994) supports this explanation by proposing a formal model incorporating the notion of preferred tempo. In this model, the strength of each metrical level is scaled according its temporal distance from the preferred time interval. For a preferred time interval of 710 ms, the proposed model provides a good quantitative explanation of listeners responses to the six patterns in Figure 1 tested at six different tempos, ranging from fast to slow. Below, we will offer an alternative to the preferred-tempo hypothesis based on the relative use of positive and negative evidence.

An additional consideration is the possible mediating effect of musical training. Notably, although Parncutt (1994: Exp. 1) showed effects of tempo on perceived beat that were consistent with a preferred time interval, for listeners with a wide range of musical experience, he chose to collapse across this variable in the presentation of the results. It is unclear to what extent the responses of the musically trained and untrained participants would be similar, and thus explainable by the same principles.

OVERVIEW

Our goals in this research are twofold. Most importantly, we are interested in the effect of tempo on perceived beat. The approach we have taken involves comparing the predictions of three models with data from listeners asked to perform a beat perception task at different tempos. Collectively, the models applied to the beat perception data will be referred to as *matching models* because they involve generating all possible beat alignments to a pattern, and then picking the best match, according to a heuristic. The instructive difference is the nature of the heuristic. The three models examined are the Povel and Essens' (1985) clock model, which determines the best match based on counter (negative) evidence, and two variations. The first is identical to clock model, except that it uses positive evidence instead of negative evidence. The other is a hybrid model that subtracts negative evidence from positive evidence to produce a combined measure (an H score). We refer to these three models as P&E, ~P&E, and the hybrid model (HM), respectively.

A secondary goal is to consider the additional variable of musical experience. This tests the generality of previous findings of the effect of tempo on perceived beat, reported by Parncutt (1994) as well as others (Duke, 1989; Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978). By comparing the model predictions with listeners responses, the differing heuristics allow us to characterise the extent to which musicians and nonmusicians weigh positive and negative evidence in their perception of the beat at different tempos.

Table 1
Binary Notation for the Six Repeating Temporal Patterns: Pulse, March, Waltz, Swing, Skip, and Cross

1. Pulse	1	1	1	1	1	1	1	1	1	1	1	1
2. March	1	0	1	1	1	0	1	1	1	0	1	1
3. Waltz	1	0	1	1	0	1	1	0	1	1	0	1
4. Swing	1	0	0	1	0	1	1	0	0	1	0	1
5. Skip	1	0	0	1	1	0	1	0	0	1	1	0
6. Cross	1	0	1	1	1	0	1	0	1	1	1	0

Note. The notation specifies a repeating sequence of elements marking out *fixed* inter-tone-onset-intervals equal to the base IOI (quarter-note). For each pattern, 12 elements are shown: 1s represent tones and 0s represent silences. There are six different base IOIs: 100, 200, 300, 400, 500, and 600 ms.

PATTERNS

Figure 1 and Table 1 describe musical and binary notation, respectively, for the six rhythmic patterns investigated in this study. These are identical to Parncutt (1994; Exp. 1). The first pattern (Pulse) is an isochronous rhythm. The next three (March, Waltz, and Swing) include silent elements, but are still relatively simple and metrically unambiguous. In musical terms, the March is in 4/4, the Waltz is in 3/4, and the Swing is in 6/4. The last two patterns (Skip and Cross) are more complex and metrically ambiguous. It is possible to hear each bar of either pattern as two groups of three, or three groups of two. For the binary representation of these patterns, the 1s abstractly correspond to sounds and 0s to silences. The time intervals between events (tones or silences) have a fixed duration, which we will refer to as the base Inter-event-onset-interval (IOI). The base IOI defines pattern *tempo* and, in musical terms, is equal to a quarter-note.

THREE MATCHING MODELS

The models considered in this article are based on the assumption that people perceive, remember, and reproduce temporal patterns by structuring their representation according to an internal clock (Povel & Essens, 1985). The Povel and Essens' conception of an internal clock refers to a discrete series of pulses ("ticks") that occur at regular time intervals. For our purposes, the clock time interval represents the beat period. The assumption is that the beat period establishes the time level of a metric hierarchy that is used to efficiently code the particular sequence of IOIs making up a pattern. Thus, some rhythmic patterns should be easier to encode than others, because they afford more efficient descriptions, in terms of simple subdivisions of the clock (Povel & Essens, 1985). Our particular interest is the clock/beat induction process (i.e., what beat period is most likely for a given temporal pattern).

The models share three stages. First, each assigns subjective accents to the elements of a pattern according to purely temporal principles. Accents are assumed to occur on (a) temporally isolated tones, (b) the second in a group of two tones, and (c) the first and last tone in a run of three or more elements (Povel & Essens, 1985; Povel & Okkerman, 1981). Second, all possible clocks are generated, allowing some restrictions on what would be considered viable responses. Finally, in the "matching" stage, the amount of evidence afforded by the pattern is calculated for each clock. The models differ by the heuristic used to determine the clock with the best score.

The P&E model

The Povel and Essens (1985) model uses counter-evidence to determine the best clock. The C score is determined by the number of clock pulses that must be aligned with silent elements (s) and unaccented elements (u) according to the following formula:

$C = (W\ s) + u$

For $W > 1$, silent elements contribute more strongly to the C score than do unaccented elements. The clock with the strongest induction strength (best match) is the one with the *least* amount of counter-evidence (lowest C score).

The P&E model has been used to generate predictions about pattern complexity (Essens, 1986; Essens, 1995; Essens & Povel, 1985; Povel & Essens, 1985). Patterns producing a low counter-evidence scores are predicted to be more easily reproduced and judged simpler than others, under the assumption that the induced clock facilitates a stronger coding of the pattern. Correlations between C scores, performance variability, and complexity judgments provide some support for the model, but the possible mediating effects of tempo were not considered.

The ~P&E model

The proposed ~P&E model is identical to the P&E model in all respects, except that it is based on positive evidence, instead of negative (counter) evidence. The analogous positive evidence score, P, is determined by the number of clock pulses (beats) that align with *accented* elements (a) as opposed to *silent* elements (s). It is based on the same formula as the P&E model, simply substituting a for s:

$P = (W\ a) + u$

The number of aligned unaccented elements (u) plays the same role in both models. The weight W is also the same, permitting reasonable comparisons between the two models. The clock with the strongest induction strength (best match) is the one with the *most* positive-evidence (largest P score).

The Hybrid Model

The proposed hybrid model is based on a linear combination of positive and negative evidence. The H score of each clock is obtained by subtracting the C score of the P&E model from the P score of the ~P&E model:

$H = w_p P - w_c C$

The weights, w_p and w_c, in this formula, represent the relative weighting of positive and negative evidence, respectively. By making the assumption that the weights sum to 1, the two weights effectively collapse to a single free parameter: $w_p = 1 - w_c$. When $w_p > w_c$, positive evidence contributes more strongly to the H score than does negative evidence. In contrast, when $w_p < w_c$, positive evidence contributes less strongly than negative evidence to the H score. Thus, at one extreme ($w_p = 1.0$), the hybrid model reduces to the ~P&E model, while at the other ($w_p = 0.0$) it reduces to the P&E model. The original weight W of the P&E and ~P&E model effectively scales the similarity of the P and C scores contributing to the H score. Consider the limiting case when W = 0: for this weight value, the P score is equal to the C score for each clock, and the associated H score is zero. As W increases, the predictions of the three models become more differentiated. For the hybrid model, the best clock is determined by the largest H score.

Table 2
Example of the Clock Induction Process for the Three Models Applied to the Swing Pattern: The P&E Model, the ~P&E Model, and the Hybrid Model

Input	1 0 0 1 0 1 1 0 0 1 0 1 1 0 0 1 0 1 1 0 0 1 0 1							
Add accents	1 0 0 **1** 0 1 **1** 0 0 **1** 0 1 **1** 0 0 **1** 0 1 **1** 0 0 **1** 0 1							
Generate clocks	Period	Phase	A	U	S	C score	P score	H score
	1	0	8	4	12	52	**36**	0 (-8)
	2	0	4	0	8	32	16	0
	2	1	4	4	4	20	20	0
	3	0	8	0	0	**0**	32	**16**
	3	1	0	0	8	32	0	0
	3	2	0	4	4	20	4	0
	4	0	2	0	4	16	8	0
	4	1	2	2	2	10	10	0
	4	2	2	0	4	16	8	0
	4	3	2	2	2	10	10	0
	6	0	4	0	0	**0**	16	8
	6	4	0	0	4	16	0	0
	6	2	0	0	4	16	0	0
	6	3	1	0	0	**0**	4	2
	6	4	0	0	4	16	0	0
	6	5	0	4	0	4	4	0
	8	0	1	0	2	8	4	0
	8	1	1	1	1	5	5	0
	8	2	1	0	2	8	4	0
	8	3	1	1	1	5	5	0
	8	4	1	0	2	8	4	0
	8	5	1	1	1	5	5	0
	8	6	1	0	2	8	4	0
	8	7	1	1	1	5	5	0

Note. Evidence was considered for clocks with periods of 1, 2, 3, 4, 6, and 8 times the base IOI, corresponding to six response categories: 1:1, 1:2, 1:3, 1:4, 1:6, and 1:8. Scores were based on four repetitions of the six-element pattern (24 elements) so that all clocks divided evenly into the pattern length.

An Example

Table 2 illustrates the clock-induction process for the three models applied to four repetitions of the six-element repeating Swing pattern (100101). The model outputs are described at each stage of the algorithm.

Stage 1: Assign accents. In Stage 1, accents are assigned accordingly to the first element (the second of a group of two), and the third element (an isolated event having silent elements before and after) of the input pattern.

Stage 2: Generate clocks. In Stage 2, all clocks are generated. Each clock is specified by its period (the duration between clock pulses) and phase (how the pulses are aligned with the pattern). Periods and phases are restricted to multiples of the base IOI. The following notation is used. A 1-clock means that the clock period is equal to the base IOI. This is the minimum predicted beat period. For the 1-clock, there is only one phase alignment, referred to as Phase 0. For the 2-clock (one with a beat period equal to twice the base IOI), clock pulses occur every other element, and consequently, there are two distinct phase alignments (Phases 0 and 1). In the present study, evidence is considered for clocks that are 1, 2, 3, 4, 6, and 8 multiples of the base-IOI. This corresponds to six response categories: 1:1, 1:2, 1:3, 1:4, 1:6, and 1:8.

Stage 3: Determine best match. In Stage 3, matches are determined according to the appropriate model-specific heuristic. Four repetitions of the six-element pattern are used as input so that all clocks divide evenly into the pattern length. The P and C scores are obtained by calculating the amount of positive and negative evidence, respectively, for W = 4 (consistent with the original Povel and Essens model). The H score is obtained for $w_p = w_c = 0.5$. These values were chosen in order to specifically examine the case weighing positive and negative evidence equally. Negative H scores were set to zero (enforcing a lower limit).

The models make different predictions about the best clock. For the P&E model, there are two best clocks, each producing zero counter-evidence: the 3-clock at Phase 0, and two different alignments of the 6-clock (Phases 0 and 3). For the hybrid model, there is one best clock, the 3-clock. This clock affords both a high P score and a low C score, producing the maximal difference between the two. For the ~P&E model, the best clock is the 1-clock.

Summary

In summary, the models we have described assume that the mostly likely perceived beat for a rhythmic pattern is based on the best match of an internal clock. They differ according to the nature of the evidence used to determine the strength of the match. The P&E model uses negative evidence to determine the best match. It consequently tends to favour high metrical levels because they afford *less* opportunity to obtain negative evidence (e.g., the 6-clock in the Swing example). The ~P&E model uses positive evidence to determine the best match. Hence, it tends to favour low metrical levels because they afford *more* opportunity to obtain positive evidence (e.g., the 1-clock in the Swing example). By subtracting negative evidence from positive evidence, the hybrid model tends to favour intermediate metrical levels. Those producing relative high *and* low, P and C scores, respectively (e.g., the 3-clock in the Swing example).

METHOD

None of the above three models predicts an effect of tempo on perceived beat. However, if tempo and/or musical experience affect the weighting of positive and negative evidence in the induction of an internal clock, then we would expect a shift in the best fitting model with differences in pattern tempo tempos and/or differences in musical experience. This possibility was investigated by having listeners (with a range of musical experience) tap at periodic intervals in synchrony with what they perceived to be the most natural placement of accents for the six rhythmical patterns in Table 1 presented at six different tempos, ranging from fast to slow. These were the same six patterns examined in Parncutt (1994: Exp. 1). Fits of the P&E, hybrid, and ~P&E models were then performed to the distribution of listeners responses, in order to categorise the relative extent to which musicians and nonmusicians used positive and negative evidence in their assessment of the beat. The weight W of the P&E and ~P&E model was fixed at 4, and the relative weighting parameter of the hybrid model was fixed at 0.5, in order to consider the case where positive and negative evidence contribute equally.

Participants

Twenty eight individuals in a first-year psychology course at the University of Queensland participated in the experiment in return for course credit. The results for 5 participants had to be discarded due to equipment failure, an inability to comply with the experimenter's instructions, or incomplete data. Of the remaining 23 participants, 8 were male and 15 were female, 14 had considerable musical experience (> 5 years formal musical training), and the other 9 had no musical training.

Stimuli

Stimuli comprised temporal patterns of 40-ms 440-Hz sine tones. The six different rhythmic patterns in Table 1b were crossed with six different tempos, defined by the base IOI. The base IOIs were 100, 200, 300, 400, 500, and 600 milliseconds. The associated labels Pulse, Waltz, March, Swing, Skip, and Cross were not told to participants. For the Pulse pattern, the onset-to-onset time between two adjacent tones was always equal to the base IOI. The other five patterns included silent elements; thus, their construction involved simply removing tones from the Pulse pattern. The resulting patterns comprised repeating sequences of inter-onset-intervals that were always multiples of the base IOI (e.g., 200-100-100 for the March pattern). The number of IOIs in a cycle differed for each pattern.

Equipment

The stimuli were generated on a PC and delivered via a set of speakers positioned in front of each participant. The computer controlled all aspects of stimulus presentation and response collection. Each participant wore a loose-fitting wrist band (with copper insert) that was attached by flexibly insulated wire to a response board with two copper response plates. Responses were collected when participants tapped with their dominant-hand index finger on the corresponding copper plate. Tap onsets were recorded to the nearest millisecond.

Procedure

Participants were instructed to respond to each pattern by tapping what they perceived to be the most natural placement of accents ("beats"). They were instructed to respond at a constant rate and that different responses were possible to each pattern. The Pulse pattern was then presented, as an example, in order for participants to familiarise themselves with the equipment and the task. Testing began when the experimenter was certain that the participant understood the task.

During a trial, participants (tested separately) listened to one of the six patterns played at one of the six tested tempos and began tapping when they were ready. Listeners tapped out what they perceived the beat to be for 20 cycles (repetitions) of the patterns. All six patterns were tested in a block with tempo held constant. The presentation order of the blocks and of the patterns within each block was counterbalanced between participants. Three rest breaks were provided, each after approximately 10 minutes of testing. There were 36 total trials.

MODEL PREDICTIONS

There were six different ratios considered as viable responses: 1:1, 1:2, 1:3, 1:4, 1:6, and 1:8. The rationale was to limit the number of response categories to likely ratios, in order not to artificially inflate the correlations between the predicted and observed responses. The expected distributions of responses for each pattern were calculated as follows. First, matching strengths were generated for each response category (clock). Clock scores were then collapsed across phase (in a winner-take-all fashion), in order to obtain only a single score for each category. Tables 3a and 3b show the resulting matches according to the three different heuristics: the P&E model (based on negative evidence only), the ~P&E model (based on positive evidence only), and the hybrid model for $w_p = w_n = 0.5$ (positive and negative evidence weighted equally). The best clocks are highlighted here in bold. Three general features of these predictions are worth pointing out:

1. The P&E model predicts more than one best response for five out of six of the patterns. The most dramatic case is for the Pulse pattern, where it predicts that all responses categories are equally likely.
2. The predicted response for the ~P&E model is 1:1 in all cases.
3. The predicted response for the hybrid models varies with pattern, and is unique for five out of six of the patterns.

To obtain a distribution of responses to each pattern and to resolve the issue of having multiple "best" clocks, the matching strengths M^c for each clock C were converted to response probabilities according to the Luce choice rule (Luce, 1963):

$$Pr(C) = \exp(\xi M_c / \Sigma_n \exp(\xi M_i))$$

In this equation, the probability of responding at a particular clock interval C is determined by that clock's matching score M_c, relative to the sum of the matching scores for all of the clocks. Normalising by an exponential function guarantees that the sum of the response probabilities is 1.0. The parameter ξ is a scaling constant. These probabilities were then scaled according to the numbers of musician and nonmusician participants to obtain model predictions about the expected number of responses in each category.

DATA ANALYSES

All inter-response-intervals (IRIs) deviating from the mean IRI by less than or more than 50% were assumed to be tapping errors and were removed from subsequent data analysis (Helmuth & Ivry, 1996; Wing & Kristofferson, 1973). Tapping errors occurred for two readily identifiable reasons: insufficient contact with the response plate or accidental "double

Table 3a
Clock-induction Strengths for the Pulse, March, and Waltz Patterns for the P&E, ~P&E, and Hybrid Models

Ratio	Pulse			March			Waltz		
	P&E	~P&E	HM	P&E	~P&E	HM	PE	~P&E	HM
1:1	0	24	12	30	54	12	40	40	0
1:2	0	12	6	0	48	24	20	20	0
1:3	0	8	4	10	18	4	0	32	16
1:4	0	6	3	0	24	12	10	10	0
1:6	0	4	2	0	16	8	0	16	16
1:8	0	3	1.5	0	12	6	5	5	0

Note. The best clocks according to each model are highlighted in bold.

Table 3b
Clock-induction Strengths for the Swing, Skip, and Cross Patterns for the P&E, ~P&E, and Hybrid Models

Ratio	Swing			Skip			Cross		
	P&E	~P&E	HM	P&E	~P&E	HM	PE	~P&E	HM
1:1	52	36	0*	52	36	0*	36	52	8
1:2	20	20	0	16	32	8	0	48	24
1:3	0	32	16	4	20	8	4	20	8
1:4	10	10	0	8	16	4	0	24	12
1:6	0	16	8	0	16	16	0	16	8
1:8	5	5	0	4	8	2	0	12	6

Note. The best clocks are highlighted in bold. The asterisks mean that the H score is negative in these cases, but the reported value is bounded by a zero minimum.

taps" (contact with the response plate twice in quick succession). The adjusted mean inter-response-interval was then rounded to the nearest multiple or subdivision of the base IOI to obtain an estimate of the perceived beat period. In the presentation of the results, we examined both the beat period and response category (1:1, 1:2, 1:3, 1:4, 1:6, or 1:8), but not the phase of each response.[1]

RESULTS AND DISCUSSION

Most all of the responses fell into one of the six responses categories (1:1, 1:2, 1:3, 1:4, 1:6, and 1:8). Figure 2 plots the mean beat period (collapsed across participants) as a function the base IOI, for the six different rhythmic patterns, for the musicians and nonmusicians, respectively. Tables 4 to 9 report the number of participants responding in each category for the six base IOIs (100 ms, 200 ms, 300 ms, 400 ms, 500 ms, and 600 ms), as well as the predicted number of responses according to the three models: P&E, ~P&E, and the hybrid model. Individual tables separate the responses for the different patterns and also permit distinctions according to musical training.

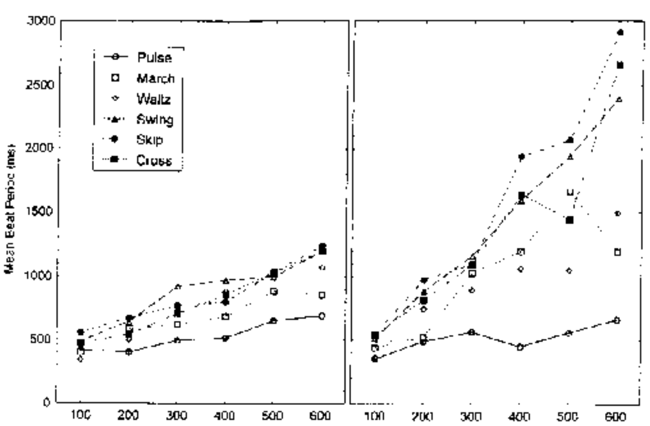

Figure 2
Mean beat period in milliseconds (collapsed across participants) as a function the base IOI, for the six different rhythmic patterns, for the musicians, and non-musicians, repectively.

There was a clear effect of tempo on absolute beat period: longer beat periods were observed at slower tempos. The mean beat periods for the six base IOIs (collapsed across response category, pattern, and musical training) were 449, 629, 815, 982, 1135, and 1,357 milliseconds.

As can be seen in Figure 2, tempo effects on absolute beat period were mediated by both pattern and musical training. Beat period lengthened more for the nonmusicians than for the musicians, and more for the complex rhythmic patterns than for the simple rhythmic patterns. An ANOVA revealed a significant three-way interaction between musical training, base IOI, and pattern ($p < 0.01$). To further examine this interaction, linear regressions were performed on the base IOI and the mean beat period, collapsing across pattern to focus on the musical training distinction, and collapsing across musical training to focus on the pattern distinction. All regressions were highly significant ($p < 0.001$), with at least 80% of the variance accounted for in all cases. The obtained slopes were larger for the nonmusicians than for the musicians (2.75 versus 1.2), and larger for the complex rhythms (Swing 2.53, Skip 2.9, and Cross 2.6) than for the simple rhythms (Pulse 0.55, March 1.5, and Waltz 1.72). Notice that the two highest slopes obtained for the two ambiguous rhythms (Skip and Cross), indicating that the beat period lengthened the most for these patterns.

If people choose the same ratio (response category) independent of tempo, then we would necessarily expect a lengthening of the beat period with base IOI, with the slope of the linear relationship determined by the preferred ratio. However, close inspection of the pattern of responses in Tables 4 to 9 reveals that this is not the case. Instead, consistent with previous findings, the preferred ratio tends to shift towards lower levels in a metric hierarchy with slower tempos, especially with

Table 4a
Pulse Data for the 14 Musicians: Predicted and Actual

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	2.33	11.74	7.26	0	7	7	10	10	11
1:2	2.33	1.07	2.19	2	3	5	4	2	2
1:3	2.33	0.48	1.47	2	1	2	0	1	0
1:4	2.33	0.32	1.20	8	3	0	0	0	0
1:6	2.33	0.22	0.98	0	0	0	0	0	0
1:8	2.33	0.18	0.89	2	0	0	0	0	0

Note. For each base IOI, the number of responses in each category is shown; 97.6% of the observed responses fit into one of the six categories. The two exceptions were one participant who selected the 1:5 category at the 500-ms base IOI, and another participant who chose to subdivide the 600-ms base IOI (tapping approximately every 300 ms in a 2:1 fashion).

Table 4b
Pulse Data for the 9 Nonmusicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	1.67	7.55	4.67	1	6	7	7	7	8
1:2	1.67	0.68	1.40	3	0	1	1	1	1
1:3	1.67	0.31	0.94	1	0	0	0	0	0
1:4	1.67	0.21	0.77	1	2	0	0	0	0
1:6	1.67	0.14	0.63	1	0	0	0	0	0
1:8	1.67	0.11	0.57	1	1	1	0	0	0

Note. 94.4% of the responses fit into one of the six categories. The exceptions were a 1:11 response at the 100-ms base IOI and two decisions to subdivide at the 400- and 500-ms base IOIs.

musicians. Examination of the distribution of responses for all six patterns supports an interaction between tempo and musical experience.

Pulse

The most striking feature of the Pulse data (Tables 4a and 4b) is the relatively broad spread of different responses at the fastest tempo, compared with the slower tempos. At the 100-ms base IOI, 9 (out of all 23) participants (mainly musicians) grouped the tones by fours, 5 participants grouped by twos, and 3 each grouped by threes and eights. However, as the tempo slowed, the 1:1 category gradually became the dominant response. For the 600-ms base IOI, 19 out of the 23 participants tapped in a 1:1 fashion (i.e., reproducing the base IOI). These results are consistent with those of Duke (1989) and Parncutt (1994: Exp. 1), as well as early studies by Bolton (1894) and Woodrow (1909), who found grouping by twos, threes and fours at fast tempos (with threes less common than twos or fours).

March

Consistent with a 4/4 meter, the most common responses to the March pattern (Tables 5a and 5b) were 1:1, 1:2, 1:4, and 1:8, replicating Parncutt (1994: Exp. 1). Overall, the musicians preferred the 1:4 (measure-level) response at the 100-ms base IOI, the 1:2 (half-note) response at the 200-, 300-, and 400-ms base IOIs, and the 1:1 (quarter-note) response at the 500- and 600-ms base IOIs. The nonmusicians contrasted the performance of the musicians by preferring the 1:4 (measure level) response at all six tempos.

Waltz

Consistent with a 3/4 meter, the responses to the Waltz (Tables 6a and 6b) were mainly 1:1 and 1:3, replicating Parncutt (1994: Exp. 1). Overall, the majority of musicians selected the 1:3 (the measure level) response at the 100-, 200-, 300, and 400-ms base IOIs. However, at the 500 ms base IOI, they distributed their responses between 1:1 (quarter-note), 1:3 (dotted half-note), and 1:2 (half-note). At the 600-ms base IOI, they most selected the 1:1 (quarter-note) response. The majority of the nonmusicians, in contrast, selected the 1:3 (measure-level) response, independent of tempo. The 1:2 response by some of the musicians at the 500-ms base IOI is somewhat surprising, as it does not typically fit with a waltz rhythm, and requires alternating the placement of beats between bars.

Swing

Consistent with a 6/4 meter, the main responses to the Swing pattern (Tables 7a and 7b) were 1:1, 1:2, 1:3, and 1:6, replicating Parncutt (1994: Exp. 1). The most pronounced differences were observed between the 100- and 200-ms base IOIs. At the 100-ms base IOI, 9 out of the 14 musicians and 5 of the 9 nonmusicians selected the 1:6 (measure-level) response, tapping once for each repetition of the pattern. At the 200-ms base IOI (a small 100 ms per quarter-note difference) only 1 musician selected the same response. At the same time, the number of nonmusicians in the 1:6 (measure-level) category remained the same.

Skip

Most people found the Skip pattern to be the most difficult one to tap to. Common responses shown in Tables 8a and 8b were 1:6, 1:3, and 1:1. These are similar in distribution to those reported by Parncutt (1994: Exp. 1). At the 100-ms base IOI, the majority of listeners (19 out of 23) preferred the 1:6 (measure-level) response. Similar to the results for the previous five patterns, the musicians tended to switch their preferences with changes in tempo, while the nonmusicians tended

Table 5a
March Data for the 14 Musicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.01	10.72	1.00	0	1	3	6	5	10
1:2	3.38	3.23	11.04	0	6	9	7	7	3
1:3	0.46	0.01	0.20	0	0	0	0	0	0
1:4	3.38	0.02	1.00	14	7	2	1	1	1
1:6	3.38	0.01	0.45	0	0	0	0	0	0
1:8	3.38	0.00	0.30	0	0	0	0	0	0

Note. 98.9% of the responses were 1:1, 1:2, or 1:4. One participant chose a 2:1 response at the 500-ms base IOI.

Table 5b
March Data for the 9 Nonmusicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.01	6.90	0.64	0	1	1	2	2	4
1:2	2.18	2.07	7.09	0	4	1	1	0	3
1:3	0.29	0.01	0.13	1	0	0	0	0	0
1:4	2.18	0.02	0.64	6	3	7	5	7	2
1:6	2.18	0.00	0.29	0	0	0	0	0	0
1:8	2.18	0.00	0.19	1	0	0	0	0	0

Note. 94.4% of the responses were 1:1, 1:2, 1:3, 1:4, or 1:8 (a slightly broader range than observed for the musicians). The remaining responses were 1:14 at 100 ms, 1:11 at 200 ms, and 2:1 at 400 ms.

Table 6a
Waltz Data for the 14 Musicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.00	11.36	0.42	0	3	2	4	5	7
1:2	0.10	0.21	0.42	1	1	3	3	4	3
1:3	5.55	2.29	10.26	10	10	9	7	5	4
1:4	0.75	0.03	0.42	1	0	0	0	0	0
1:6	5.55	0.09	2.07	2	0	0	0	0	0
1:8	2.04	0.01	0.42	0	0	0	0	0	0

Note. All of the observed responses could be classified as 1:1, 1:2, 1:3, 1:4, or 1:6.

Table 6b
Waltz Data for the 9 Nonmusicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.00	7.30	0.27	0	0	0	3	4	2
1:2	0.07	0.13	0.27	0	0	0	0	0	0
1:3	3.57	1.47	6.59	5	6	9	5	5	6
1:4	0.48	0.02	0.27	1	0	0	0	0	0
1:6	3.57	0.06	1.33	2	2	0	1	0	0
1:8	1.31	0.01	0.27	0	0	0	0	0	0

Note. 94.4% of the observed responses were 1:1, 1:2, 1:3, 1:4, and 1:6. The three exceptions were a 1:24 response at the 100-ms base tempo, a 1:12 response at the 200-ms base IOI, and a 2:1 response (subdivision) at the 600-ms base IOI.

to make the same choice (usually at the level of pattern repetition) independent of tempo. The musicians, in contrast, tended to prefer the 1:3 (dotted half-note) response at the 200-ms base IOI, the 1:2 (half-note) response at the 300-, 400-, and 500-ms base IOI, and the 1:1 (quarter-note) response at the 600-ms base IOI.

Cross

The primary responses to the Cross pattern (Tables 9a and 9b) were 1:1, 1:2, 1:4, and 1:6. This set of responses is also consistent with that reported in Parncutt (1994: Exp. 1). For the Cross pattern, the musicians preferred the 1:4 or 1:6 response at 100 ms, the 1:2 response between 200 and 500 ms, and the 1:1 response at

Table 7a
Swing Data for the 14 Musicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.00	9.24	0.09	0	0	2	3	5	6
1:2	0.10	0.38	0.43	1	0	1	2	4	5
1:3	5.55	4.15	10.51	4	13	9	9	5	2
1:4	0.75	0.05	0.43	0	0	0	0	0	0
1:6	5.55	0.17	2.12	9	1	2	0	0	1
1:8	2.04	0.02	0.43	0	0	0	0	0	0

Note. All of the responses could be classified as 1:1, 1:2, 1:3, or 1:6.

Table 7b
Swing Data for the 9 Nonmusicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.00	5.94	0.06	0	0	2	2	3	3
1:2	0.07	0.24	0.28	0	2	0	0	1	0
1:3	3.57	2.67	6.75	2	2	3	2	0	1
1:4	0.48	0.03	0.28	0	0	0	0	0	0
1:6	3.57	0.11	1.36	5	5	4	5	5	5
1:8	1.31	0.01	0.28	0	0	0	0	0	0

Note. 96.3% of the responses were 1:1, 1:2, 1:3, or 1:6. Two participants chose a 1:12 response at the 100-ms base IOI.

Table 8a
Skip Data for the 14 Musicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.00	9.15	0.15	0	0	1	5	5	6
1:2	0.27	4.11	3.69	0	2	8	7	6	4
1:3	2.94	0.37	3.69	2	7	3	1	2	3
1:4	1.32	0.17	1.66	0	4	1	0	0	0
1:6	6.54	0.17	3.69	12	1	1	1	1	1
1:8	2.94	0.03	1.11	0	0	0	0	0	0

Note. All of the responses fit into one of the six response categories.

Table 8b
Skip Data for the 9 Nonmusicians

Ratio	Predicted			Actual					
	P&E	~P&E	HM	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
1:1	0.00	5.88	0.10	0	2	1	0	1	0
1:2	0.17	2.64	2.37	1	0	4	2	2	2
1:3	1.89	0.24	2.37	0	0	0	0	0	0
1:4	0.85	0.11	1.07	0	0	0	0	0	0
1:6	4.20	0.11	2.37	7	7	4	5	4	5
1:8	1.89	0.02	0.71	0	0	0	0	0	0

Note. 87% of the responses were 1:1, 1:2, or 1:6. The main exceptions were 2:1 responses (2 each) at the 400-ms, 500-ms, and 600-ms base IOIs. One participant selected a 1:24 response at the 100-ms IOIs.

600-ms tempo. The majority of the nonmusicians preferred the 1:6 (measure level) response, independent of tempo.

Model Fits

In sum, perceived beat was found to depend on both tempo and musical experience. To characterise these effects, model fits were performed by calculating the root-mean squared error (RMSE) between the expected and actual values reported in Tables 4 to 9. The best-fitting models (i.e., the ones with the smallest RMSE) are reported in Table 10. Fits were performed separately at each base IOI, for the musicians and nonmusicians, respectively, in order to interpret the effect of tempo on response category in terms of the relative use of positive and negative evidence.

Table 9a
Cross Data for the 14 Musicians

Ratio	Predicted P&E	Predicted ~P&E	Predicted HM	Actual 100 ms	Actual 200 ms	Actual 300 ms	Actual 400 ms	Actual 500 ms	Actual 600 ms
1:1	0.00	9.62	0.46	0	0	1	3	3	6
1:2	3.15	4.32	11.28	1	10	11	9	10	4
1:3	1.41	0.02	0.46	0	0	0	1	0	2
1:4	3.15	0.04	1.02	7	3	1	0	0	0
1:6	3.15	0.01	0.46	6	1	1	1	1	1
1:8	3.15	0.00	0.32	0	0	0	0	0	0

Note. 98.8% of the responses were 1:1, 1:2, 1:3, 1:4, or 1:6. The single exception was a 2:1 response at the 600-ms base IOI.

Table 9b
Cross Data for the 9 Nonmusicians

Ratio	Predicted P&E	Predicted ~P&E	Predicted HM	Actual 100 ms	Actual 200 ms	Actual 300 ms	Actual 400 ms	Actual 500 ms	Actual 600 ms
1:1	0.00	6.18	0.30	0	1	1	1	4	2
1:2	2.02	2.77	7.25	0	3	4	3	2	1
1:3	0.90	0.01	0.30	1	0	0	0	0	0
1:4	2.02	0.02	0.66	1	0	0	0	0	0
1:6	2.02	0.00	0.30	6	5	4	5	3	6
1:8	2.02	0.00	0.20	0	0	0	0	0	0

Note. 98.1% of the responses were 1:1, 1:2, 1:3, 1:4, or 1:6. One participant chose a 1:24 response at the 100-ms base IOI.

Table 10a
Model Fits to Musicians Responses for All Six Patterns

Pattern	Best model (musicians) 100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
Pulse	P&E	Hybrid	Hybrid	~P&E	~P&E	~P&E
March	P&E	Hybrid	Hybrid	~P&E	~P&E	~P&E
Waltz	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	~P&E
Swing	P&E	Hybrid	Hybrid	Hybrid	~P&E	~P&E
Skip	P&E	Hybrid	Hybrid	~P&E	~P&E	~P&E
Cross	P&E	Hybrid	Hybrid	Hybrid	~P&E	~P&E

Note. The best model at each base IOI was the one that produces the lowest root-mean squared error between the predicted and actual distribution of responses.

Table 10b
Model Fits to Nonmusicians Responses for All Six Patterns

Pattern	Best model (musicians) 100 ms	200 ms	300 ms	400 ms	500 ms	600 ms
Pulse	Hybrid	~P&E	~P&E	~P&E	~P&E	~P&E
March	P&E	Hybrid	P&E	P&E	~P&E	Hybrid
Waltz	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Swing	P&E	P&E	P&E	P&E	P&E	P&E
Skip	P&E	P&E	P&E	P&E	P&E	P&E
Cross	P&E	P&E	P&E	P&E	~P&E	P&E

Note. The best model at each base IOI was the one that produced the lowest root-mean squared error between the predicted and actual distribution of responses.

For the most part, the nonmusicians data were best fitted by the original P&E model, independent of tempo and pattern. The two main exceptions are the Pulse pattern, where the ~P&E provided the best fit at five out of six tempos, and the Waltz pattern, where the hybrid model provided the best fit at all six tempos. In contrast to the nonmusicians, the best fitting models to the musicians' data depended systematically on tempo. The original P&E model best fitted the musicians' responses only at the 100-ms (fastest) tempo. The hybrid model provided the best fit of the musicians' responses at the 200- and 300-ms tempos, either the hybrid or the ~P&E model provided the best fit of the musicians' responses at the 400-

and 500 ms tempos, while the ~P&E model (based on positive evidence only) gave the best fit of the musicians' responses at the 600-ms (slowest) tempo. Thus, musicians seemed to be less affected by negative evidence overall, compared with nonmusicians. Moreover, negative evidence seemed to have less of an effect on the perceived beat period as the tempo of a pattern slowed.

GENERAL DISCUSSION

There are three main findings in this research: (a) Perceived absolute beat periods are longer at slow tempos than at fast tempos. (b) Perceived relative beat periods are at lower metrical levels (ratios closer to 1:1) at slow tempos than at fast tempos. (c) Musical experience seems to mediate performance; nonmusicians tend to prefer longer absolute beat periods than musicians and the same metrical level independent of tempo. Many of the nonmusicians in the present study often tapped in synchrony with each pattern repetition.

These first two findings mirror those reported in Parncutt (1994: Exp. 1) and are consistent with most previous studies examining the rhythmic interpretation of simple and complex temporal patterns (Duke, 1989; Handel & Lawson, 1983; Handel & Oshinsky, 1981; Oshinsky & Handel, 1978). The third finding identifies musical experience as a mediating variable. The observed interaction between tempo and musical experience on perceived beat is consistent with related research on time discrimination showing that nonmusically trained listeners are less likely to subdivide a base time interval to make duration judgments than are musically trained listeners (Jones & Yee, 1997; Yee, Holleran, & Jones, 1994).

Our interpretation of the observed effects of tempo and musical experience on perceived beat is that it reflects differential weighting of positive and negative evidence in the induction of an internal clock ("the beat"). For the nonmusicians, we found that most of the pattern responses were best fitted by the original P&E model at all six tempos, implying that these listeners relied primarily on negative evidence at all six tempos. Exceptions were found for the simple rhythms (the Pulse and Waltz patterns in particular), with the hybrid and ~P&E models providing better overall fits. For the musicians, on the other hand, we observed a systematic shift in the best-fitting model with differences in tempo. Although the original P&E model provided the best overall fit at the fastest tempo, the ~P&E model provided a better fit at the slowest tempo, with the hybrid model providing better fits at intermediate tempos. In sum, negative evidence, as proposed in the original P&E model, seems to be the best predictor of the induced beat for (a) listeners without musical training and for (b) fast tempos independent of musical experience. Why might this be the case?

Minimising negative evidence to induce an internal clock means that "beats" (measured in the present study as taps) are preferred when they coincide with as few silent elements (rests) in the pattern as possible. In the best case (a C score of zero), taps are only aligned with accented elements. Maximising positive evidence means, on the other hand, that beats are preferred when they coincide with as many sounded elements (notes) as possible, without paying a penalty for placing beats on rests. The best case is when taps occur in synchrony with the onset of every note. A shift from a negative-evidence-based clock to a positive-evidence-based clock model thus means that it becomes less important whether *every* beat/tap coincides with the onset of a note. This suggests greater flexibility in the rhythmic interpretation of a pattern, which conceivably may develop with formal musical training, and be easier when the tempo of a pattern is slow.

Supporting evidence for the differential weighting of positive and negative evidence by musically trained and untrained participants comes from Povel and Essens (1985). In their original model, Povel and Essens argued that timing variability in a reproduction task is least for patterns that induce a strong negative-evidence-based clock. One unexplained finding, worthy of note here, is that mainly the nonskilled participants showed a significant correlation between timing variability and pattern complexity (as defined by their negative evidence score). In light of the present results, one possibility for the observed skill differences in the original Povel and Essens study is that the experienced participants were perhaps coding the temporal patterns using a clock induced by positive evidence, instead of negative evidence.

One possibility that we have thus far not considered is that tempo effects in beat perception, especially those involving tapping tasks, may be simply due to motor factors. In the present study, this seems unlikely, except perhaps at the fastest tempo (100 ms per quarter note). At the 100-ms base IOI, 1:1 tapping is still reasonable, although possibly difficult for some people. However, ratios other than 1:1 at this rate (not at the level of pattern repetition) should not present motor difficulties.

A second question that arises concerns the extent to which the reported data are consistent with the concept of a preferred tempo. The explanation of tempo effects on beat perception proposed by Parncutt (1994) involves calculating the salience of each metrical level a rhythmic pattern with respect to a distribution of *preferred* absolute time intervals. Based on his data, Parncutt (1994) proposes an existence region for the perceived beat, centred around a 710-ms time interval. This value was obtained by a log-normal fit to the distribution of beat periods for all responses. The present results are consistent with such a preferred tempo explanation, although we obtained different distributions of beat periods for the musician and nonmusician participants; the mean produced time intervals for the musicians and nonmusicians, respectively, were 745 ms and 1139 ms. It is unclear to what extent the responses separated according to musical experience are explainable within the formal framework outlined by Parncutt (1994), but the present data do not necessarily rule out a preferred tempo hypothesis. The differential-weighting hypothesis that is proposed in this article is intended simply as an alternative explanation of these data.

In listening to musical performance, the perception of a recurring beat helps the listener to track and interpret the unfolding temporal pattern. Studies of music performance have shown that the *intended* beat of the performer (i.e., choice of tactus) affects structural aspects of the performance, such as expressive variations in note-to-note timing and global variations in tempo (Meyer & Palmer, 1999). The present results show that the perceived beat depends on tempo and therefore, in some cases, may make it difficult for a performer to communicate a particular beat period at a particular tempo (e.g., a waltz can be played only so slowly before it is no longer a waltz). Moreover, the success with which a performer is able to communicate a particular beat period may depend on nonstimulus factors, such as the musical experience of the audience.

In broader terms, the ability to perceive musical beat suggests a general ecological advantage. An internalised beat can be used to predict *when* the next event in any environmental pattern (music or otherwise) is likely to occur (Jones, 1976). Emphasising positive evidence, listeners maximise their ability to predict the online timing of events in the environment. The lower the metrical level of the induced beat, the less likely a listener will be surprised by the timing of an event; however, a penalty is incurred in the generation of false expectations. When emphasising negative evidence, false expectations are reduced, but the penalty is in the form of more frequent "surprises". For music listening, temporal surprise is of often the intent of the performer or composer, and contributes to our musical enjoyment, but, in other instances of temporal tracking, it is better not to be surprised. In speech, for example, being able to predict when the next word will occur is important for effective communication. Clarifying the nature of perceived beat in music potentially aids our understanding about the more general mechanisms involved in predicting timing in the environment.

Footnote

1. We chose not to report phase for two reasons. Given the anticipations that frequently occur in synchronised tapping, and the overall tap-to-tap variability in peoples' responses, the calculation of phase proved ambiguous at fast tempos, and we were concerned about the validity of this measure. Secondly, the present design did not counterbalance the start part of each pattern, introducing a potentially confounding factor in the reported phase; previous studies have shown that the placement of beats in a cyclical pattern is biased towards events that start the pattern (Garner & Gottwald, 1968).

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