

Rate Limits of On-Beat and Off-Beat Tapping With Simple Auditory Rhythms: 1. Qualitative Observations

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The accuracy of on-beat and off-beat synchronized finger tapping was examined as a function of sequence rate in musically trained individuals. Auditory sequences consisted of cyclically repeated, underlyingly isochronous patterns of the form T0, TT0, or TTT0, where T denotes a tone onset and 0 denotes its absence. In different conditions, participants attempted to tap in synchrony with one of the possible T ("on-beat") or 0 ("off-beat") positions in each pattern while the sequence rate increased from trial to trial. It was hypothesized that on-beat tapping would be easier with tones that carry a rhythmic grouping accent (T_2 in TT0, T_1 and T_3 in TTT0) than with tones that do not (T_1 in TT0, T_2 in TTT0), according to findings of Povel and colleagues. The hypothesis was strongly supported for TTT0, but there were considerable individual differences with regard to TT0. Off-beat tapping was generally difficult and often switched to on-beat tapping at fast tempi. The findings reveal rate limits of sensorimotor coordination that may be relevant to music performance in ensembles.

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WHEN playing in an ensemble, musicians must coordinate their actions with great temporal precision. This can present challenges even to experienced artists. One type of challenge arises at very fast tempi, when even simple rhythms can become difficult to follow. The present article is concerned with the rate limits of several simple synchronization tasks. It presents detailed qualitative observations of individual participants' synchronization behavior, whereas a subsequent article (Repp, in press) presents quantitative estimates of rate limits obtained with a different method and also examines how the rate limits are affected by different types of accent.

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Musical ensemble playing is a form of sensorimotor synchronization. The laboratory paradigm commonly used to study sensorimotor synchronization is finger tapping to a computer-generated auditory sequence. Admittedly, these sequences are usually much simpler than real music. Moreover, visual cues, which can be important in ensemble playing, are typically excluded. Nevertheless, such simple stimuli and responses can serve as a starting point for investigating the complexities of coordination in musical ensemble performance.

Tapping in synchrony with isochronous sequences of identical clicks or tones has been studied extensively, and it is well known that on-beat (or in-phase) tapping, where the taps approximately coincide with tone onsets, is easier than off-beat (syncopated, anti-phase) tapping, where the taps fall between tone onsets (Engström, Kelso, & Holroyd, 1996; Fraisse & Ehrlich, 1955; Kelso, DelColle, & Schöner, 1990; Pressing, 1998; Volman & Geuze, 2000). When the sequence rate is fast, off-beat tapping is often observed to switch involuntarily to on-beat tapping. However, the maximal rates up to which off-beat synchronization can be maintained have never been determined precisely, it seems. In those studies that varied sequence rate, the focus was usually on the phase transition from off-beat to on-beat tapping, and participants were instructed not to resist the transition when it happened (e.g., Engström et al., 1996; Kelso et al., 1990). Also, participants in these studies were usually not musically trained and thus did not possess well-developed rhythmic skills. An exception is the late Jeff Pressing, an expert pianist and percussionist, who reported a tone sequence interonset interval (IOI) of 375 ms as being close to his own limit for prolonged off-beat tapping (Pressing, 1998). The rate limit for off-beat tapping is of theoretical interest because it is likely to reveal the temporal limit for the mental subdivision of an IOI, which in turn has a bearing on the fastest possible beat rate in music because, according to London (2002, 2004), a beat IOI must be divisible.

The rate limit for 1:1 on-beat tapping (one tap to each tone) does not seem to have been determined very precisely either. Studies of synchronization with selected tones in rapid isochronous sequences (Bartlett & Bartlett, 1959; Repp, 2003) have uncovered a perceptual or sensorimotor limit at sequence IOIs of 100–120 ms, which is below the maximal possible tapping rate, reported to be at intertap intervals (ITIs) of 150–200 ms (Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985; Peters, 1980, 1985; Todor & Kyprie, 1980; Truman & Hammond, 1990). Therefore, the rate limit for 1:1 on-beat tapping may simply be a biomechanical limit. Indeed, difficulties with this task have been observed to occur at IOIs of 170–180 ms (Peters, 1989; Wing & Kristofferson, 1973), although Peters thought this was still above the maximal tapping rate of some of his participants.

The main innovation of the present study was to extend the on-beat and off-beat tapping tasks to simple nonisochronous sequences, namely cyclically repeated groups of two or three tones, as illustrated schematically in Table 1. In this scheme, an isochronous sequence is considered as consisting of cyclic repetitions of T0, where T stands for a tone onset and 0 stands for the absence of a tone onset, occurring in successive temporal positions defined by an isochronous metrical grid. On-beat tapping then consists in tapping with every T, and off-beat tapping, with every 0. The additional sequences employed in this study were cyclic repetitions of TT0 and TTT0. For the former, there are two possible on-beat tapping tasks, either with the first tone (T_1) or with the second tone (T_2), and one off-beat tapping task (with 0). For the latter, there are three possible on-beat tapping tasks (with T_1 , T_2 , or T_3) and one off-beat tapping task (with 0). The terms "on-beat" and "off-beat" are used here to denote tapping with an auditory event (T) or with silence (0), respectively, regardless of where the main metrical beat (tactus) may be located. The sequence rate or tempo is represented by the inversely related variable of *metrical grid spacing* (MGS).¹

On-beat synchronization with TT0 and TTT0 sequences is theoretically interesting because Povel and coworkers have shown that temporal grouping causes certain tones to be perceived as accented. In groups of two tones (TT0), T_2 is usually perceived as accented (Povel & Okkerman, 1981). In groups of three tones (TTT0), both T_1 and T_3 are perceived to have such a *grouping accent* (Povel & Essens, 1985). One aim of the pres-

TABLE 1
Schematic Illustration of Metrical Grid, Sequence Types, and Tapping Tasks*

Metrical grid:										...
T0 sequence:	T		T		T		T		T	...
On-beat tapping (T):	t		t		t		t		t	
Off-beat tapping (0):		t		t		t		t		t
TT0 sequence:	T	T		T	T		T	T		...
On-beat tapping (T1):	t			t			t			
On-beat tapping (T2):		t			t			t		
Off-beat tapping (0):			t			t			t	
TTT0 sequence:	T	T	T		T	T	T		T	T
On-beat tapping (T1):	t				t				t	
On-beat tapping (T2):		t				t				t
On-beat tapping (T3):			t				t			
Off-beat tapping (0):				t				t		

*T = tone, 0 or blank = silence, t = tap.

1. By this definition, MGS = IOI/2 in T0 sequences. For reasons of consistency in presenting the data, this will be assumed to be the case even for on-beat tapping with T0 sequences, although the 0 position has no functional significance in on-beat tapping. In TT0 and TTT0 sequences, MGS is equal to the within-group IOI.

ent experiment was to examine the implications of these perceptual results for on-beat tapping with rhythmic sequences. The hypothesis was that it should be easier to tap with tones that carry a grouping accent than with those that do not. Thus, tapping with T_2 of a TT0 sequence should be easier than tapping with T_1 , and tapping with T_1 or T_3 of a TTT0 sequence should be easier than tapping with T_2 . These differences should become increasingly manifest as the sequence rate increases and should be reflected in different rate limits for the different tasks.

A second aim was to explore the rate limit for off-beat tapping. Off-beat tapping was expected to be more difficult than on-beat tapping and equally difficult with all three sequence types, because the same underlying limit of mental subdivision may be involved. This difficulty should be reflected in breakdown of synchronization at a relatively high MGS value, compared to on-beat tapping.

Method

PARTICIPANTS

The eight participants (five women, three men) included six paid volunteers, a postdoctoral researcher, and the author. The author was 57 years old at the time; the ages of the others ranged from 18 to 31 years. Participants had at least 6 years of training on one or more musical instruments. They included one professional violist, one professionally trained but currently inactive trombonist, one active classical amateur pianist (the author), four currently inactive amateur pianists (all presumably classically trained), and one active pop musician. All had participated in numerous previous synchronization experiments and were highly motivated. All were right-handed.

MATERIALS

The sequences consisted of high-pitched digital piano tones (E_7 , MIDI pitch 100, about 2640 Hz) that were produced on a Roland RD-250s digital piano via an Opcode Studio Plus Two musical instrument digital interface (MIDI) translator under control of a MAX 3.0 program running on a Macintosh Quadra 660AV computer.² The tones had sharp onsets and decayed freely; no "note offset" was specified in the MIDI instructions. All tones were produced at the same nominal intensity (MIDI key velocity). Each sequence contained 29 cycles of the basic sequence pattern (T0, TT0, or TTT0). The sequence always started at the beginning of a cycle, regardless of the task. In the on-beat tapping tasks, 10 different sequences were used whose constant MGS durations ranged from 170 to 80 ms in 10-ms decrements. In the off-beat tapping tasks, because of their expected greater difficulty, 10 sequences with MGS durations ranging from 200 to 110 ms in 10-ms decrements were used.

2. Owing to a peculiarity of this setup, the tempo of the output was about 2.4% faster than specified in the MIDI instructions, and participants' taps were registered at a correspondingly slower rate. Throughout this article, all millisecond values are reported as they appeared in the MAX environment. To obtain the actual values, multiply by 0.976. Apart from this constant scaling factor, MAX was highly accurate (within 1 ms) in timing the sequences and registering the taps.

PROCEDURE

Participants sat in front of a computer monitor on which the current trial number was displayed, listened to the sequences over Sennheiser HD540 II earphones at a comfortable loudness level, and tapped on a Roland SPD-6 percussion pad that they held on their lap. They were allowed to use their preferred way of tapping, which they had employed in many previous experiments. The majority rested the wrist and other fingers of the right hand on the surface of the pad and tapped by moving the index finger only; one (J.S.), however, tapped "from above" by moving the wrist and elbow of the unsupported arm. The impact of the finger on the rubber pad provided some direct auditory feedback (a thud), in proportion to the tapping force.

The experiment was divided into two sessions, typically 1 week apart. The T0 and TT0 sequences were presented in successive parts of the first session, and the TTT0 sequences in the second session.³ For each type of sequence, all tasks were performed once (each task comprising one block of 10 trials of increasing tempo) and then repeated three times in the same order before proceeding to the next sequence type. The order of the tasks (tapping targets) was fixed: T, 0 for T0; T₁, T₂, 0 for TT0; T₁, T₂, T₃, 0 for TTT0. Participants started trials by pressing the space bar on the computer keyboard and started tapping in the third cycle of the sequence. A repeat button on the computer screen enabled them to repeat trials they had difficulty with. Participants were instructed to use the repeat button to get used to each task (i.e., to repeat the first trial as often as they liked), but to use it on subsequent trials only if they felt they had slipped into a wrong cognitive set or had started to tap at the wrong time. Only the final attempt of a repeated trial was analyzed. Movements of limbs other than the tapping hand were discouraged.

Results

The results are presented individually because averaging across participants would have led to variable and sometimes unrepresentative results. In calculating mean asynchronies and standard deviations for each trial, the first five taps were excluded, so that each value was based on 22 taps.

T0 SEQUENCES

The times of occurrence of on-beat (T) and off-beat (0) taps relative to their targets in T0 sequences (effectively, their asynchronies) are shown in Figure 1. All graphs in this article should be read from right to left, in the direction of decreasing MGS duration (i.e., increasing tempo), which corresponds to the order of presentation within the trial blocks. The solid horizontal line at time zero represents the tone onsets (i.e., T). The slanted dashed line represents the midpoint of the IOI (i.e., 0). The even more slanted solid line on top, of which only the beginning is shown, indicates the time of occurrence of T in the next cycle. The double standard error bars (equivalent to the standard deviation when $n = 4$) reflect the variability of the mean asynchrony across the successful trials for each MGS duration in each task. The small negative numbers next to data points indicate

3. One participant's (R.F.'s) data from the second session were accidentally not registered by the computer, so that the session had to be repeated.

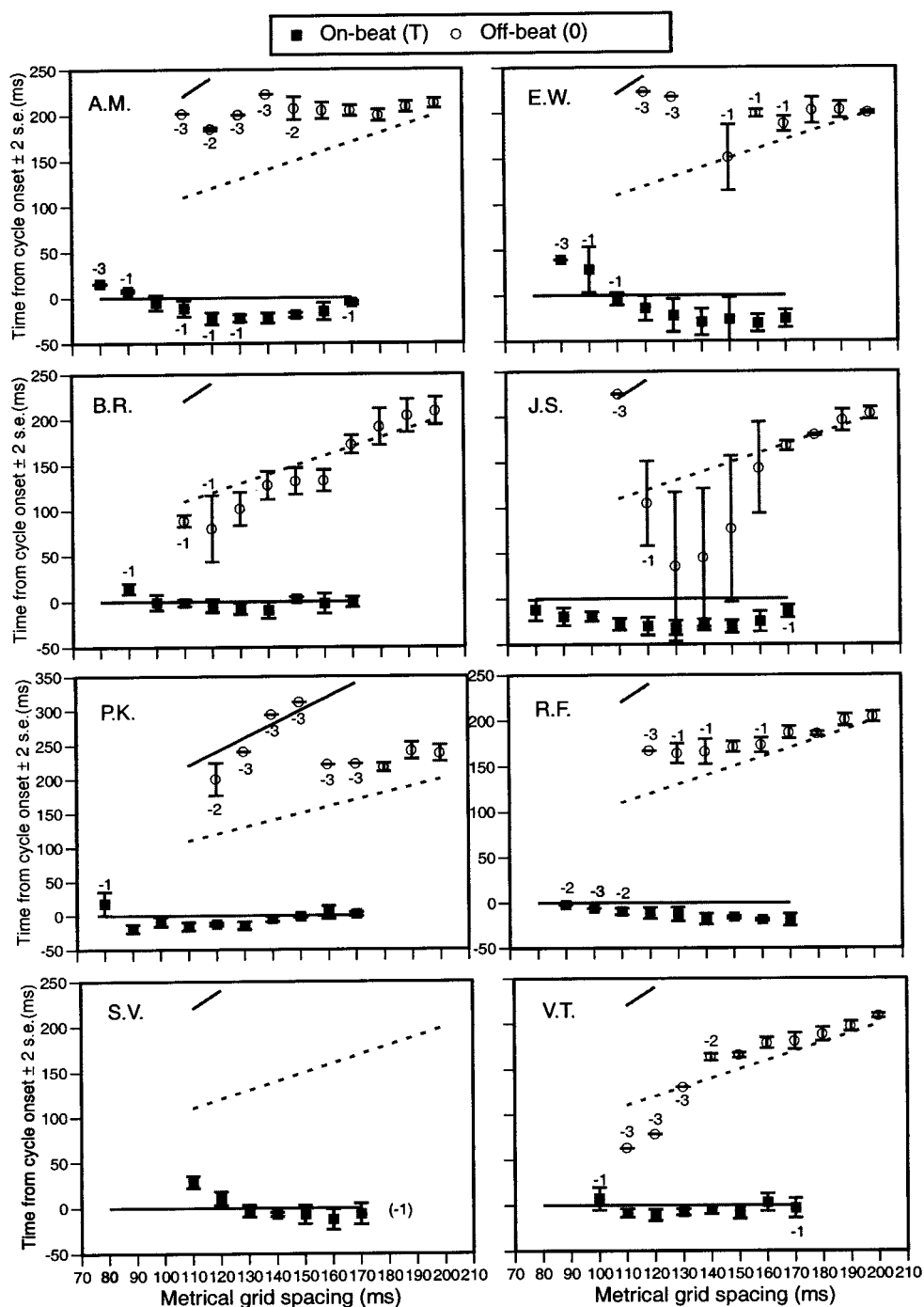


Fig. 1. Times of occurrence of taps relative to target positions as a function of metrical grid spacing (MGS) duration in the on-beat and off-beat tapping tasks with T0 sequences. Negative numbers indicate omitted trials (out of 4).

how many trials (out of four) were excluded because synchronization was unsuccessful. In general, this means that progressive phase drift occurred because participants tapped at a tempo different from that of the sequence. In the T0 on-beat tapping condition, however, it usually means that participants could not tap fast enough and omitted many taps. Occasionally, trials were rejected for other reasons such as exceptionally large variability or a highly atypical mean asynchrony relative to the other trials. Basically, entries of -1 represent just occasional failures, which occurred sometimes even at the beginning of the first block. Entries of -2 and -3 , however, indicate increasingly serious difficulties with the task, culminating in the absence of a data point when all four attempts were unsuccessful. One participant (S.V.) felt unable to carry out the off-beat tapping task even at the slowest rate, and his on-beat tapping data are based on only three trial blocks because one block of data was lost, as indicated by " -1 " in the panel.

Consider first the on-beat tapping results. All participants found this task rather easy initially (MGS = 170 ms, IOI = 340 ms), which is reflected in small mean asynchronies and low variability across trials. Asynchronies were either close to zero or slightly negative (i.e., taps preceded tones), as is commonly found in on-beat synchronization tasks (see, e.g., Aschersleben, 2002). As the tempo increased, the asynchronies changed little at first. At the fastest rates, however, or just before synchronization broke down because of motoric limits, an upturn toward positive asynchronies can be seen for most participants. This is an indication that the taps started to lag behind the tones because it was difficult to keep up with the sequence. Only three participants (A.M., J.S., P.K.) were able to synchronize successfully in at least one trial at the fastest rate (MGS = 80 ms, IOI = 160 ms). One of them (J.S.) tapped out of her wrist/elbow, but the other two tapped with the finger only. Three others (E.W., B.R., R.F.) were unsuccessful at the fastest rate but managed to hang on at the next-slower rate (MGS = 90 ms, IOI = 180 ms). The limit for the remaining two participants (V.T., S.V.) was at IOIs of 200 and 220 ms, respectively. These results are in agreement with the range of fastest tapping rates cited in the literature (see above), and they also reveal considerable individual differences in finger mobility. None of the participants experienced any difficulties with on-beat synchronization, as long as they could tap fast enough.

Turning now to the off-beat tapping results, it can be seen that none of the participants (except for S.V.) had any difficulty at the slowest rates. Mean asynchronies relative to the IOI midpoint (dashed line in Figure 1) were close to zero or slightly positive, and variability across trials was low in most cases. As the tempo increased, however, the task soon became more difficult, often quite abruptly so. Abrupt transitions from good to poor performance can be seen for participants A.M., E.W., J.S., and P.K. Their

difficulties, which were reflected in unsuccessful trials, increased variability, and greatly deviant asynchronies, commenced at MGS durations of 170–150 ms (IOIs of 340–300 ms). In the few trials at faster rates in which these four participants succeeded in tapping at the correct tempo, they tended to tap in phase with the following tone, or at least were strongly attracted to it. One participant (J.S.) was attracted to the preceding tone in some trials and to the following tone in others, hence the very large error bars. Participants R.F. and V.T. did better but failed at MGS durations of 120 and 130 ms (IOIs of 240 and 260 ms), respectively. Only B.R. was able to tap in approximate anti-phase up to the fastest tempo (MGS = 110 ms, IOI = 220 ms). These results reveal large individual differences in off-beat tapping ability, even among musically trained participants.

Figure 2 shows the average within-trial standard deviations of the asynchronies, with the error bars (single standard errors here) reflecting the variability of this measure across successful trials. The variability of on-beat tapping was generally low (often in the vicinity of 10 ms) and did not change systematically as MGS duration decreased. The variability of off-beat tapping was initially low also, often as low as that of on-beat tapping, but then increased abruptly. This increase occurred around MGSs of 170–160 ms (IOIs of 340–320 ms) for most participants, V.T. being the main exception (MGS = 130 ms, IOI = 260 ms).

TT0 SEQUENCES

The average asynchronies for the three tasks with TT0 sequences are shown in Figure 3. The four lines of increasing slant indicate the onsets of T_1 (solid), T_2 (dashed), 0 (dotted), and T_1 in the next cycle (solid), respectively. Consider first the two on-beat tapping tasks. Only two participants, B.R. and V.T., were able to carry out both tasks accurately, with near-zero asynchronies and low between-trial variability at all rates. The other six participants had difficulties with one or the other task, but not with both. Three (A.M., E.W., S.V.) had trouble tapping with T_1 , as predicted on the basis of grouping accent. One of them (E.W.) felt totally unable to synchronize with T_1 and defaulted. Another one (A.M.) was strongly attracted to T_2 and produced virtually the same behavior as in the T_2 tapping task. The third one (S.V.) was attracted to T_2 as the tempo increased, but suddenly reverted to T_1 at the fastest tempo. Three other participants (J.S., P.K., R.F.) unexpectedly had trouble with the T_2 task. One (J.S.) was attracted to T_1 at all tempi and produced behavior similar to that in the T_1 task. The other two were attracted to T_1 at fast tempi only. These results were surprising because it had been predicted (from Povel & Okkerman, 1981) that only the T_1 task would be difficult. These results may reflect individual differences in the tendency to perceive one or the other tone in a group of two tones as accented.

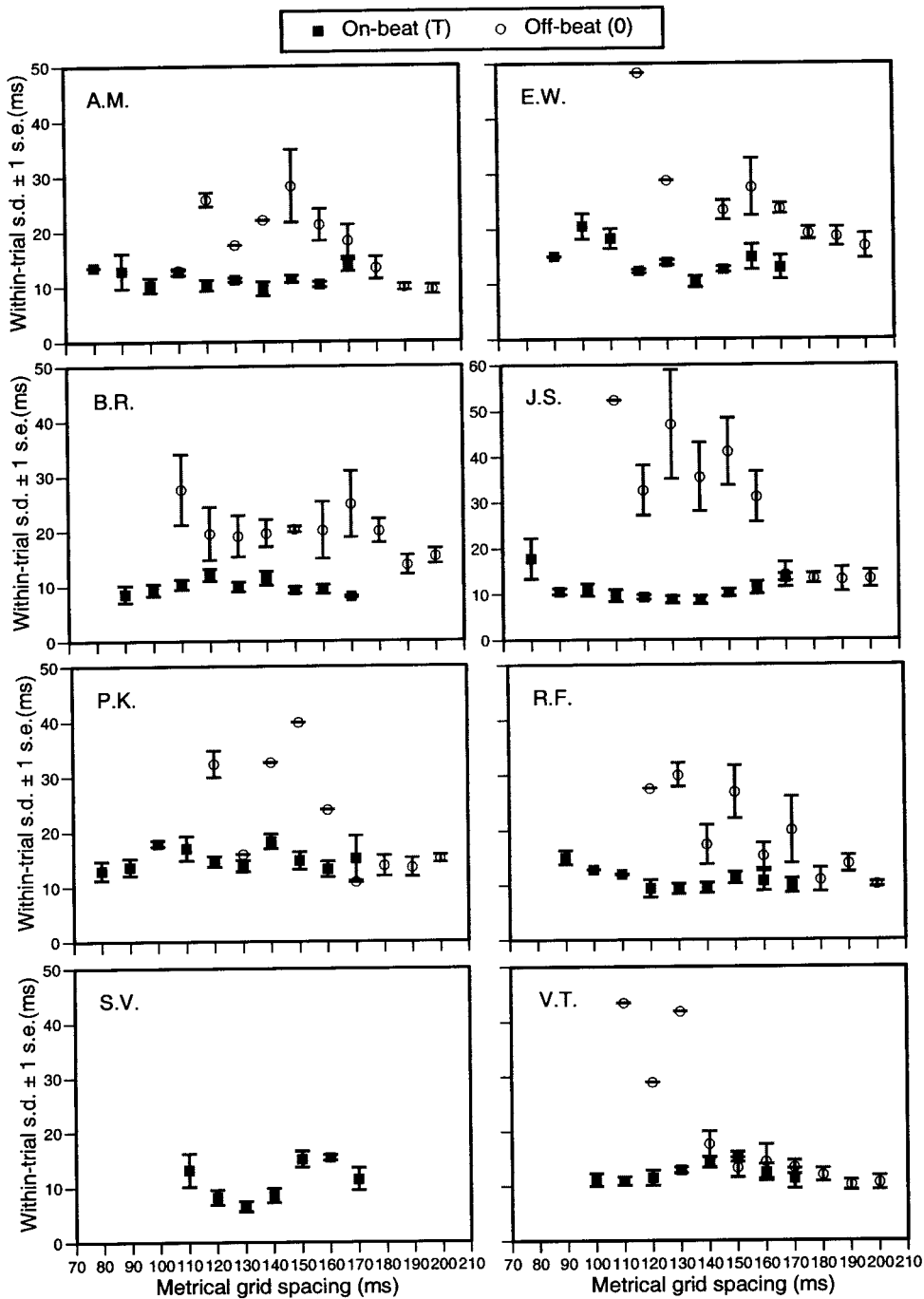


Fig. 2. Within-trial standard deviations of asynchronies as a function of the metrical grid spacing (MGS) duration in the on-beat and off-beat tapping tasks with T0 sequences.

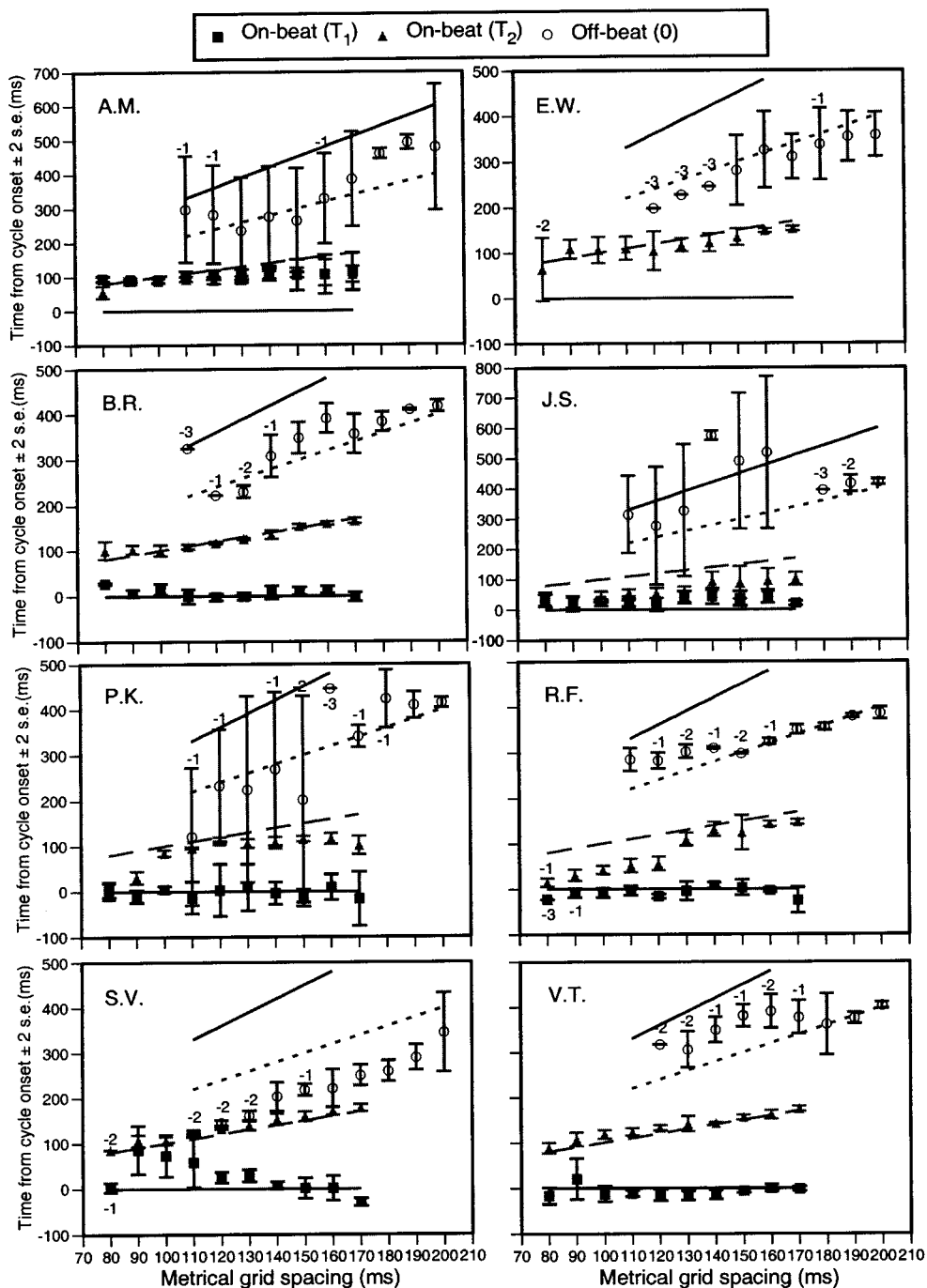


Fig. 3. Times of occurrence of taps relative to target positions as a function of metrical grid spacing (MGS) duration in the on-beat and off-beat tapping tasks with TT0 sequences. Negative numbers indicate omitted trials (out of 4).

The TT0 off-beat tapping task was manageable initially for the majority of participants, but quickly increased in difficulty as the rate increased. Only one participant (R.F., the professional violist) was moderately successful across the whole range of tempi, although her taps were attracted to the following tone at fast tempi. B.R. also did reasonably well, except at the fastest tempo. Two other participants were strongly attracted either to the preceding tone (S.V.) or to the following tone (V.T.). One participant (E.W.) was quite variable and faltered when the MGS reached 140 ms. The remaining three participants (A.M., J.S., P.K.) tended to synchronize with either the preceding or the following tone (in different trials) as the tempo got fast, which resulted in the very large error bars in the figure.

The within-trial standard deviations of successful trials are shown in Figure 4. There were no systematic differences between the T_1 and T_2 on-beat tapping tasks; only S.V. showed lower variability in the T_2 task. Variability in the off-beat tapping task was clearly higher than in the on-beat tapping tasks for all participants, although occasionally there were off-beat tapping trials with low variability. There were no systematic changes in on-beat tapping variability with tempo, and even off-beat tapping variability showed no clear trends. Variability in the TT0 on-beat tapping tasks tended to be larger than in the T0 on-beat tapping task (Figure 2). Because on-beat tapping variability did not change with tempo, the difference across sequence types is probably due to the presence of two tones in a cycle versus one (i.e., greater rhythmic complexity) and not to the slower tapping speed in the TT0 condition (mean ITI = $3 \times \text{MGS}$) than in the T0 condition (mean ITI = $2 \times \text{MGS}$).

TTT0 SEQUENCES

The mean asynchronies for the four tasks with TTT0 sequences are shown in Figure 5. The T_1 tapping task was predicted to be easy, and so it was for six participants. Two participants, however, were strongly attracted to later tones as the tempo increased, one (P.K.) to T_2 and the other (J.S.) to T_3 , it seems. Because T_2 is an unlikely attractor, the taps of P.K. may reflect attraction to T_3 as well. The T_3 tapping task, too, was predicted to be easy. Again, six participants performed well at all tempi. One (P.K.), however, showed strong negative asynchronies initially, as if his taps followed T_1 with a fixed latency of about 200 ms, and at the fastest tempo he actually synchronized with T_1 instead of T_3 . Participant R.F.'s T_3 taps also shifted forward in time at the fastest tempi.

The T_2 tapping task was predicted to be more difficult than the other two on-beat tapping tasks, and this was confirmed by the results. Most participants were quite accurate initially (i.e., at the slowest tempo), but

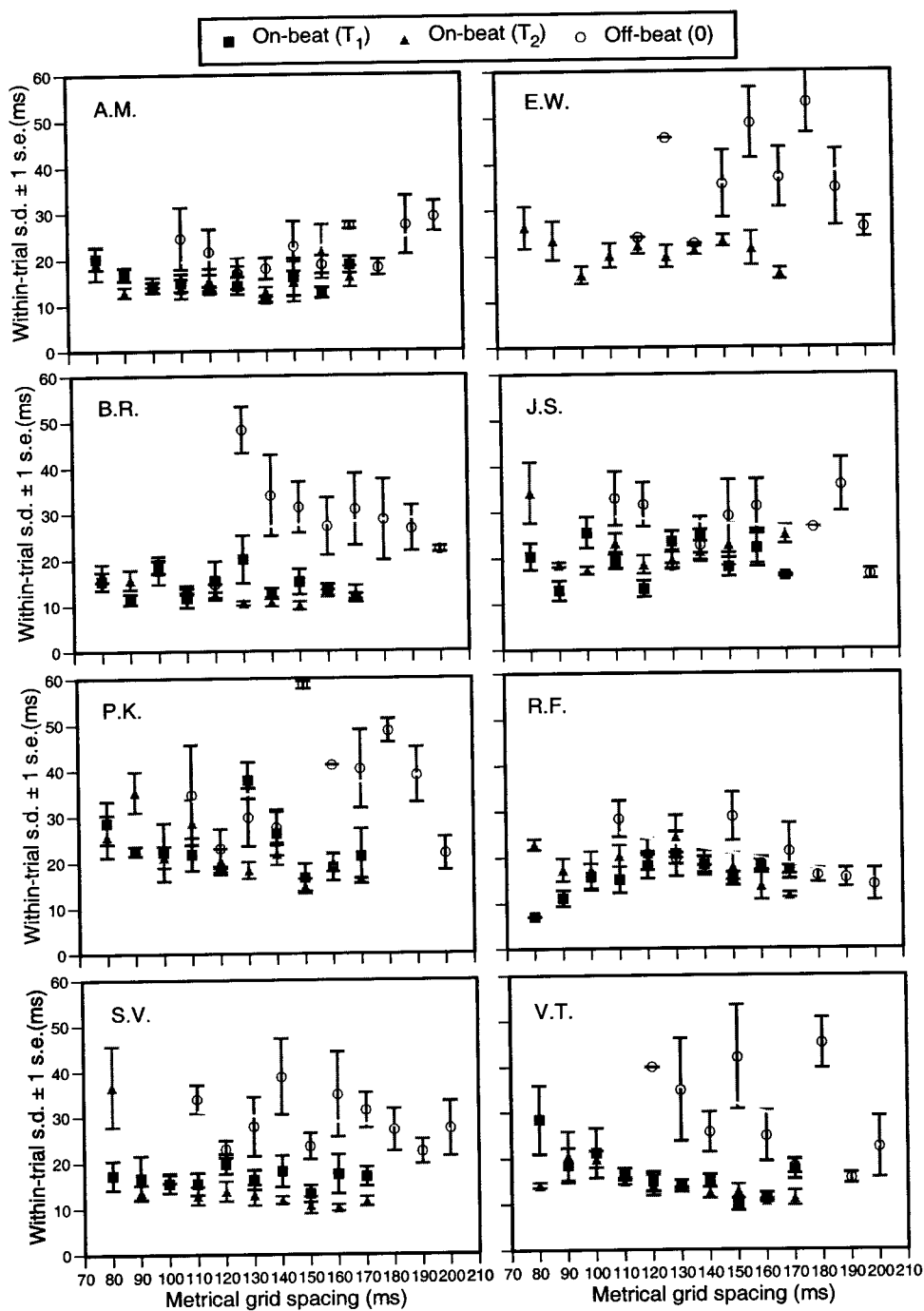


Fig. 4. Within-trial standard deviations of asynchronies as a function of the metrical grid spacing (MGS) duration in the on-beat and off-beat tapping tasks with TT0 sequences.

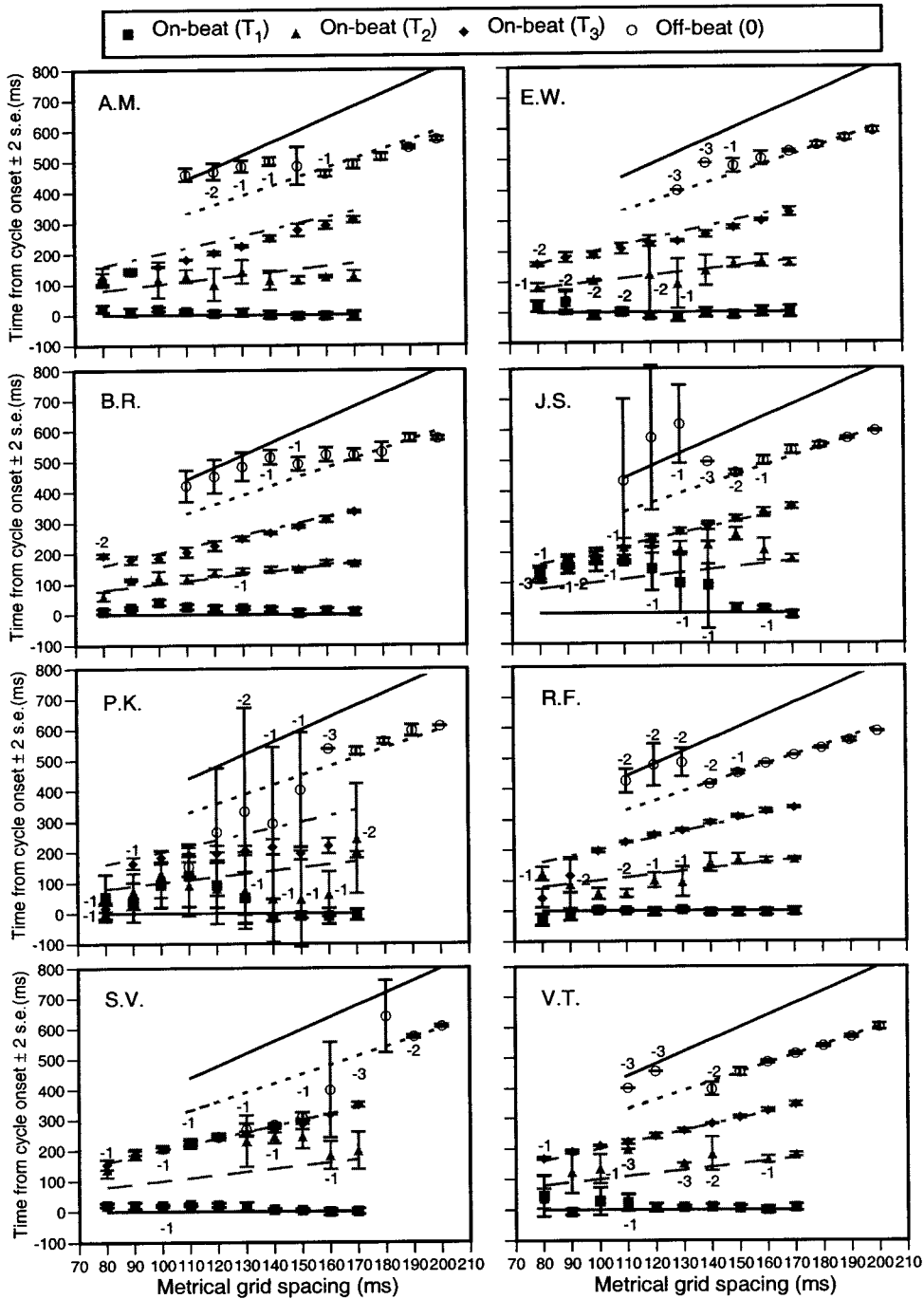


Fig. 5. Times of occurrence of taps relative to target positions as a function of metrical grid spacing (MGS) duration in the on-beat and off-beat tapping tasks with TTT0 sequences. Negative numbers indicate omitted trials (out of 4).

only three (A.M., B.R., R.F.) were able to stay with T_2 , more or less successfully, at all tempi.⁴ Two participants (E.W., V.T.) showed considerable variability and many unsuccessful trials in the T_2 tapping task. Two others (J.S., S.V.) synchronized with T_3 instead of T_2 at faster tempi. One participant (P.K.) was attracted to T_1 and showed large between-trial variability throughout.

In the TTT0 off-beat tapping task, all participants were very accurate at first but sooner or later ran into difficulties. No participant was able to carry out the task successfully at MGSs of less than 140 ms (i.e., tapping at the midpoint of an IOI of 280 ms). Starting at MGSs between 180 and 140 ms, the taps were attracted to either the preceding or the following tone and usually ended up being in phase with it. Four participants (A.M., B.R., R.F., V.T.) were always attracted to the following tone, one (S.V.) always to the preceding tone, and two (J.S., P.K.) alternated across trials. One participant (E.W.) avoided such unintended on-beat tapping by letting her relative phase drift instead.

The within-trial standard deviations are shown in Figure 6. There were no systematic differences in variability between the T_1 and T_3 tasks, whereas variability was clearly higher in the T_2 task (except in B.R.'s case) and the off-beat tapping task. No systematic trends as a function of tempo were evident.

Discussion

One hypothesis underlying the present research was that perceived grouping accent is the reason for the relative ease or difficulty of different on-beat synchronization tasks. The results of this experiment confirm some of the predictions. Clearly, off-beat tapping was generally more difficult than on-beat tapping, except for tapping with T_2 in TTT0, which was similarly difficult. The prediction, derived from Povel and Essens (1985), that tapping with T_2 would be much harder than tapping with either T_1 or T_3 in TTT0 thus was strongly confirmed. However, the prediction derived from Povel and Okkerman (1981) that tapping with T_1 in TT0 would be more difficult than tapping with T_2 in TT0 was not supported. Although three participants performed in accord with the predic-

4. In one case (B.R.), this involved a number of trial repetitions, especially at intermediate tempi. My experience was that the subjective downbeat on T_2 tended to shift spontaneously and involuntarily to T_3 , with the taps following suit. (This issue of subjective downbeat location will be dealt with in much greater detail in Repp, in press.) Interestingly, once that hurdle was overcome, the task seemed to get easier at faster tempi. Other participants repeated trials only rarely, either because they did not experience these cognitive difficulties or because they monitored them less carefully.

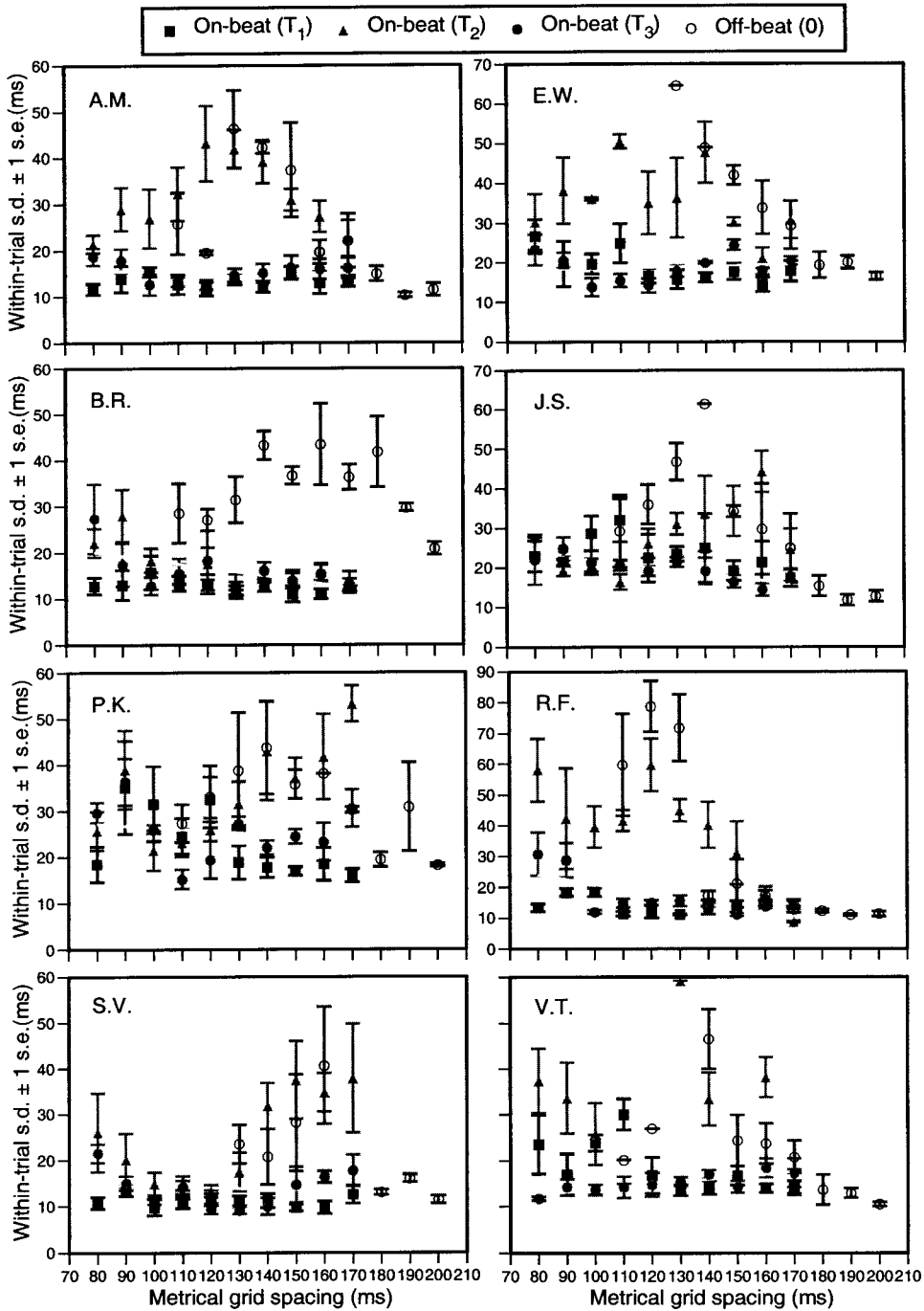


Fig. 6. Within-trial standard deviations of asynchronies as a function of metrical grid spacing (MGS) duration in the on-beat and off-beat tapping tasks with TTT0 sequences.

tion, three others showed the reverse pattern, and two found neither task difficult. Thus, there seem to be individual differences with regard to which of two tones in a group is perceived as more accented. Alternatively, if all participants perceived T_2 as accented and hence presumably as the metrical downbeat, it would have to be the case that some people find it easier to tap on an upbeat than on a downbeat.

The metrical interpretation of the sequences was not controlled in this study. It may be that tones that are perceived as accented are easier to synchronize with not because they are accented but because it is natural to think of them as the metrical downbeat of the rhythmic pattern and because it is easier to tap on a downbeat than on a weak beat. Conversely, tones that are perceived as unaccented and missing beats (0) may be difficult to synchronize with because they are not easily conceptualized as downbeats in a metrical structure.⁵ Thus, grouping accent may have its effect on synchronization difficulty either directly or via metrical interpretation. Possibly, grouping accent and metrical interpretation have separate and independent effects. Subsequent experiments have attempted to address this issue (Repp, in press).

In real music, of course, there are many other factors that could affect synchronization difficulty, such as variations in intensity, duration, pitch, and timing of tones. Moreover, metrical interpretation can be primed by preceding musical context and by notation. Obviously, the present study is just a first exploration with very simple materials.

Regarding the rate limits of synchronization, London (2002) speculated that the shortest MGS (i.e., the shortest possible interbeat interval at the lowest level of a metrical structure) in music is 200–250 ms because it still allows for simple subdivision into intervals of 100–125 ms duration. These subdivision intervals represent the shortest IOIs at which synchronization with selected events in an isochronous sequence is possible (Repp, 2003), and hence they perhaps also correspond to the shortest intervals that can be imagined in mental subdivision of IOIs. The present results suggest, however, that the shortest possible subdivisions may be a bit longer than 100–125 ms. To the extent that the off-beat tapping tasks reflect IOI subdivision, they suggest a limit of 150–170 ms for people with moderate to high amounts of musical training, and this corresponds to IOIs of 300–340 ms. This would be in agreement with the lower limit of the IOI distribution for the beats of dance music, as estimated by van Noorden and Moelants (1999).

5. The participants were not interviewed about how they conceptualized the metrical structure of the rhythmic sequences, and it is possible that different strategies were adopted by different participants. For me (B.R.), the target tone always constituted the downbeat of my subjective metrical structure, and the task became difficult when the downbeat spontaneously moved to an adjacent tone, seemingly out of my control. In off-beat tapping, however, I always thought of the immediately preceding tone (T_2 in TT0, T_3 in TTT0) as the downbeat.

It is possible that individuals with exceptional rhythmic skills (e.g., percussionists) exhibit lower limits than were observed here, and indeed London's estimates agree with the lower limit of van Noorden and Moelants's distribution of beat intervals in a larger sample of music of different styles, including jazz, where probably the fastest beat rates are to be found. It might be noted, however, that the present estimates are already considerably below an expert drummer's stated personal limit of 375 ms (Pressing, 1998), although that estimate presumably pertained to prolonged off-beat tapping. In any case, the rate limits in the present study were based merely on qualitative observations, and more precise quantitative estimates will soon be available (Repp, in press).⁶

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