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ORIGINAL ARTICLE

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Staying offbeat: Sensorimotor syncopation with structured and unstructured auditory sequences

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Abstract Three experiments investigated whether adding metric (higher-order, periodic) structure to tone sequences stabilizes syncopated finger tapping. Participants tapped in antiphase with metronomic tone sequences in which accents—produced by sounding two tones simultaneously—occurred regularly every two, three, or four tones (metric), occurred unpredictably (irregular), occurred on every tone (heavy beat), or were absent (light beat). Tap timing variability, although commensurate with metric and light beat sequences, was lower with metric than with heavy beat and irregular sequences even when the instructions specified using metric grouping in all conditions. Higher-order periodic fluctuations (delays) in tap timing—found only in metric conditions—were associated with low overall tap timing variability, suggesting that a regularly applied, meter-based phase-resetting mechanism stabilizes syncopation.

Introduction

Timing one's behavior in relation to the behavior of others is a common requirement of everyday life. Sometimes the resulting temporal structures are relatively irregular and unpredictable, such as in animated conversations or in throwing and avoiding punches when boxing, whereas in other situations, e.g., music and dance, timing is more regular and predictable. Perhaps surprisingly, remarkable challenges arise, even in the case of some perfectly regular timing patterns. For instance, it is difficult to generate an isochronous movement sequence (e.g., a series of finger taps) whose period forms a fixed inharmonic ratio (e.g., 3:4 or 4:5) with the period of an isochronous stimulus sequence (e.g., an auditory metronome). Ensemble musicians are often required to perform such polyrhythms—with one individual pitting his or her sequence against that of another—although the phenomenon is typically studied in the context of a single individual performing the two conflicting sequences with separate limbs (Deutsch, 1983; Pressing, Summer, & Magill, 1996; Summers, Rosenbaum, Burns, & Ford, 1993). This article is concerned with an even simpler cooperative timing task—*sensorimotor syncopation*, specifically, tapping a finger at the midpoint between the ticks of an auditory metronome—which also proves to be challenging under certain circumstances.

A prototypical real-life example of sensorimotor syncopation is an ensemble musician performing a sequence of 'offbeats,' in such a way that he or she produces sounds at the midpoint between a series of beats articulated by another member of the ensemble. This task becomes notoriously difficult at moderately fast tempi (i.e., with beat intervals around 400 ms), where there is a tendency for people to make an abrupt transition from the intended antiphase relationship between sounds and beats to an in-phase relationship where sounds and beats coincide (Fraisse & Ehrlich, 1955; Fraisse & Voillaume, 1971; Kelso, DelColle, & Schöner, 1990; Semjen, 2000; Volman & Geuze, 2000). Indeed, such *phase transitions* have been observed in a wide variety of antiphase movement sequences outside the musical domain, including unimanual finger movements paced by auditory or visual metronomes (Carson, 1996; Kelso et al., 1990; Yamanishi, Kawato, & Suzuki, 1979), alternating bimanual finger movements (Kelso, 1984; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Semjen & Ivry, 2001), and the coordination of limb oscillations both within and between individuals (Beek, Rikkert, & van Wieringen, 1996; Schmidt, Carello, & Turvey, 1990).

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The mechanisms that underlie phase transitions have been studied extensively in the field of dynamical systems theory (Haken, Kelso, & Bunz, 1985; Kelso, 1995; Kelso et al., 1990). Researchers in this field have argued that the tendency to shift from the antiphase to the in-phase coordination mode indicates that the latter is the more stable one (i.e., resistant to perturbation) at fast rates. Stability is determined by the strength of the coupling between oscillatory processes occurring within an individual (e.g., the internal timing mechanism that drives finger tapping) and his or her environment (e.g., a metronomic tone sequence). Coupling strength is influenced by the frequency of the oscillators, decreasing as frequency increases (Haken et al., 1985; Large & Jones, 1999; Peper, Beek, & van Wieringen, 1995; Sternad, Turvey, & Schmidt, 1992; Treffner & Turvey, 1993). Although in-phase coordination remains stable with weak coupling, antiphase coordination becomes unstable. Thus, the in-phase mode serves as an attractor state to which movements are drawn during sensorimotor syncopation at fast rates, ultimately leading to a transition from antiphase to in-phase coordination. Such phase transitions are usually preceded by increased variability in the cycle-to-cycle relative phase relationship between the coupled oscillators (Kelso, Scholz, & Schöner, 1986; Schmidt et al., 1990).

Alternatives to the dynamical approach identify factors besides oscillator coupling strength that can affect the stability of sensorimotor syncopation. Interval-based approaches to sensorimotor timing postulate that instability during syncopation at fast rates arises due to factors such as rate limits in cognitive-motor processing. Thus, pinpointing the temporal goal (i.e., the midpoint between beats) of the movement may become difficult due to insufficient processing time (e.g., Semjen, Schulze, & Vorberg, 1992). Related arguments have been made in the context of alternating bimanual hand movements (Semjen & Ivry, 2001).

The challenge for musicians performing offbeats is to prevent transitions from antiphase to in-phase coordination. One possible strategy by which to achieve this goal is to reset the relative phase (i.e., the placement of the sequence of one's movements relative to the external sound sequence) once an increase in variability is detected. This would involve stopping the internal timekeeper that underlies movements, and then restarting it at the appropriate time, i.e., at the midpoint between the next two beats. (Another possibility that will be addressed later in the "General discussion" involves locally changing the period of the internal timekeeper.) However, this reactive type of strategy, which requires the musician to detect an increase in movement variability, may not be optimal because such increases in variability occur suddenly and are followed abruptly by phase transitions (Wimmers, Beek, & van Wieringen, 1992). Therefore, it may be preferable to employ an anticipatory strategy in which the relative phase is reset routinely at periodic intervals, i.e., even when no noticeable increase in variability has occurred. Furthermore, imposing a regular higher-order structure on the beat sequence may assist this process by allowing the musician to prepare to engage the phase-resetting mechanism. Specifically, structural boundaries between higher-order structural groups could serve as predictable anchor points at which to reset the phase. Metric frameworks may provide the basis for such a process.

Metric frameworks are cognitive/motor schemas that guide musical rhythm in perception and action. Listeners and performers experience these frameworks as series of pulsations in which every *n*th pulse is accented (i.e., perceived to be stronger than its neighbors). Psychological approaches to rhythm claim that the presence of these periodic accents indicates that metric frameworks comprise hierarchically arranged levels of pulsation, with pulses at the 'beat level' nested within those at the 'bar level' in simple integer ratios such as 2:1 (duple meter), 3:1 (triple), or 4:1 (quadruple; Drake, Jones, & Baruch, 2000; Lerdahl & Jackendoff, 1983; Palmer & Pfordresher, 2003). Metric frameworks are readily induced by isochronous auditory sequences containing salient events that occur periodically (within certain temporal limits; see Parncutt, 1994). Such events, which include pitch changes and relatively loud tones, endow these sequences with regular higher-order structure. However, even in the case of unstructured sequences consisting of isochronous, undifferentiated tones, it is possible to impose higher-order structure in a top-down fashion by proactively generating a metric framework. Indeed, it has long been known that when listening to unstructured metronomic sequences people often perceive every second, third, or fourth tone as accented, in effect grouping the tones according to a duple, triple, or quadruple meter respectively (Bolton, 1894). Moreover, evidence of such metric grouping has been observed in finger tapping. Vorberg and Hambuch (1978) augmented the standard synchronization–continuation paradigm—in which people are required first to tap in synchrony with a metronome and then to continue tapping at the same rate when the metronome is turned off—by asking their participants to group their taps mentally into twos, threes, or fours. When the inter-tap intervals (ITIs) produced during continuation tapping were examined, Vorberg and Hambuch (1978) observed higher-order dependencies in tap timing that reflected the prescribed metric grouping. Furthermore, Nagasaki (1987) found that duple, triple, and quadruple periodicities can actually emerge spontaneously in fast tapping.

Numerous empirical studies have shown that metric frameworks facilitate the accurate perception and production of rhythm patterns (e.g., Bharucha & Pryor, 1986; Essens, 1995; Franks & Canic, 1991; Keller, 1999; Povel & Essens, 1985). It has been argued that these benefits arise because metric structure allows reliable predictions to be made about the occurrence of future, structurally important events. Based on these predictions, or 'expectancies,' a listener or performer can prepare to attend to, or act at, the temporal locations where these events should occur (Large & Jones, 1999).

Thus, the predictability of metric structure may also play a role in stabilizing off-beat performance. The higher-order periodicities inherent in metric frameworks may provide a basis for regularly adjusting the phase relationship between the external sound sequence and the timing mechanism that guides performance, thereby minimizing movement timing variability and transitions from antiphase to in-phase coordination. This hypothesis was tested in three experiments that required sensorimotor syncopation with structured and unstructured auditory sequences.

Experiment 1: Metrically structured vs. unstructured sequences

Experiment 1 assessed the stability of sensorimotor syncopation with three types of metrically structured sequence and two types of unstructured sequence (see Fig. 1). In each metrically structured sequence—duple, triple, and quadruple—a beat was articulated by an isochronous series of high-pitched tones, which were accompanied by lower-pitched tones occurring every two, three, or four beats. These low tones were intended to encourage the perception of duple, triple, and quadruple meter respectively, and thereby assist participants in following instructions to use metric grouping strategies while tapping. Unstructured sequences consisted of beats articulated either by only the high tone (light beat) or by the high and low tones (heavy beat) sounding simultaneously on each beat. Participants were explicitly instructed to avoid the use of grouping strategies while tapping with these unstructured sequences. Thus, we were able to compare the stability of sensorimotor syncopation in the presence and absence of metric structure. Performance stability was assessed by examining the variability of asynchronies between taps and the midpoints between tones. (The size of these asynchronies varies with changes in relative phase.) We also counted the number of errors—i.e., omitted taps and taps that were placed closer to tones than to the midpoint between tones—although we did not expect to observe transitions from antiphase to in-phase coordination because participants were instructed to avoid such transitions. In order to manipulate task difficulty, all sequences were presented at two rates: either slow or fast relative to each participant's own estimate of his or her just-manageable rate for sensorimotor syncopation. In addition, auditory feedback was varied across experimental sessions in such a way that taps either did or did not produce tones.

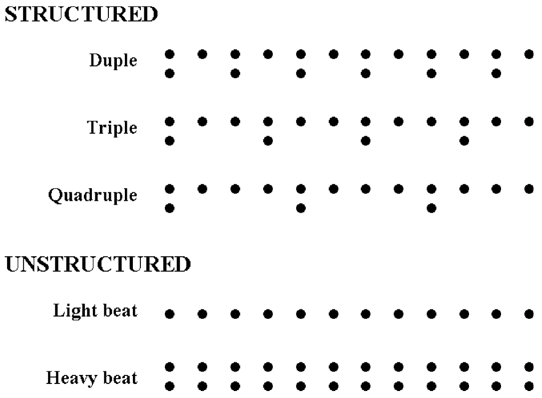

Fig. 1 Schematic examples of the structured (*duple*, *triple*, and *quadruple*) and unstructured (*light beat* and *heavy beat*) sequences used in Experiment 1. In the depiction of the structured and heavy beat unstructured sequences, the *upper row of dots* symbolizes high-pitched tones and the *lower row of dots* symbolizes low-pitched tones. The light beat unstructured sequences consisted of high-pitched tones only

The main prediction was that if metric frameworks facilitate stable syncopation, tap timing variability should be greater with unstructured sequences than with metrically structured sequences. Furthermore, it was expected that this effect would be more evident at fast rates, which make syncopation difficult, than at slow rates. It was also considered possible that there would be a reduction in tap timing variability following strong beats, due either to phase resetting or the use of a hierarchical timekeeper (see Vorberg & Hambuch, 1984). We were unsure whether to expect that stability would vary across the three metrically structured conditions or between the two unstructured conditions. Likewise, no specific predictions were made about the effects of auditory feedback, which was manipulated for reasons of generality. Feedback tones occur in musical contexts, but not typically in studies of finger tapping. Nevertheless, auditory feedback might facilitate performance by making it easier to integrate tones and taps into a single auditory stream.

Methods

Participants

Five females and three males participated ($N=8$).[1] The average age of participants was 25 years (range 21–28 years). All were trained amateur musicians (average experience 11.5 years; range 4–21 years) who were recruited from the Yale University international student community and paid in return for participation. One participant preferred to tap with the left hand; all others preferred to tap with the right hand.

Design

A $2 \times 2 \times 5$ repeated measures design was employed, with factors *rate* (slow, fast), *feedback* (present, absent), and *sequence* (duple, triple, quadruple, light beat, heavy beat).

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[1] Six additional potential participants (five of whom had no musical training) indicated that they were interested in taking part in the experiment, but were unable to do so after experiencing difficulty with sensorimotor syncopation, even at a very slow rate (beat interval = 800 ms).

Materials

Stimuli consisted of sequences of piano tones produced on a Roland RD-250 s digital piano under control of MAX (version 3.0) software running on a Macintosh Quadra 660AV computer.[2] All tones had a nominal duration of 80 ms plus natural damped-string decay. Each sequence contained an isochronous series of high-pitched tones (C6, 1046 Hz) that was intended to mark the beat. In three metrically structured sequences, a lower tone (C4, 262 Hz) sounded simultaneously with the high tone every two (duple), three (triple), or four (quadruple) beats. In two unstructured sequences, tones were either all relatively accented (high and low tones sounded simultaneously, producing a heavy beat) or all unaccented (only high tones sounded, producing a light beat). Sequence length was determined by when the participant started tapping and presentation rates were set relative to each participant's estimate of his or her own just-manageable rate (see below).

Procedure

Participants sat in front of the Macintosh computer, listened to the sequences over Sennheiser HD540 II earphones at a comfortable intensity, and tapped on a Roland SPD-6 electronic percussion pad, which was held on the lap. The sensitivity of the pad was set to the manual (as opposed to drumstick) mode. Each participant tapped with the index finger of his or her preferred hand. Some participants rested their hand on the pad and tapped by moving only the index finger; others tapped 'from above' by moving the wrist and/or elbow joints of the free arm.

The experiment was run across two 1-h sessions separated by approximately 1 week. Auditory feedback was present only during the first session, in which each tap on the pad produced a high-pitched piano tone that was higher in pitch (E^b6, 1,245 Hz) than the high sequence tone. At the start of the first session, the participant was required to estimate his or her syncopation threshold by tapping in antiphase with, and adjusting the presentation rate of, a light beat sequence. The participant started the sequence by pressing the spacebar on the computer keyboard. Initially the sequence had a rate where the inter-onset interval (IOI) was 800 ms. The participant began tapping, and then adjusted the rate by pressing the 'up' and 'down' arrow keys on the computer keyboard. Pressing the 'up' key shortened the IOI by a constant 20 ms, resulting in a rate increase, while pressing the 'down' key lengthened the IOI by 20 ms, resulting in a rate decrease. The participant was instructed to increase the rate of the sequence until he or she could no longer tap along in antiphase, and then to decrease the rate gradually until antiphase tapping was just manageable. The sequence played continuously until it was stopped by the participant clicking a virtual button on the computer screen, at which point the current IOI value was recorded by MAX. Sequences in the remainder of the experiment were presented at tempi 9% faster and 9% slower than this personalized just-manageable rate. The average rate selected by participants had a beat interval of 410 ms (range 340–480 ms).

Each experimental session consisted of 6 blocks of 10 randomly ordered trials. A different one of the 10 (rate × sequence) conditions was presented in each of these trials. At the start of a trial, the participant pressed the spacebar on the computer keyboard to begin the sequence, which continued to play until the participant had made 74 taps. The participant was instructed to move only his or her tapping finger during trials. Instructions also specified that the participant should just listen to the sequence at first, and then begin tapping once the identity of the sequence—duple, triple, quadruple, light beat, or heavy beat—was clear to him or her. The participant was told to resist the tendency to shift onto the beat, and to make corrections as quickly as possible (without stopping) if this occurred. Instructions also informed the participants that "When all tones are equal in accent [i.e., in the light beat and heavy beat sequences], you should think of them as one long on-beat/off-beat sequence. Please try to avoid grouping the tones in any way. On the other hand, when tones are differentiated in terms of accent, think of them as making up a continuous string of short sequences, each initiated by an accented tone. When tapping along with these sequences, you should attempt to use grouping strategies that are consistent with the accent pattern."

After each trial, a message appeared on the computer screen prompting the participant to press the space bar to initiate the next trial. At the end of each block, the participant called the experimenter (from an adjacent room) to save the data and to open the file for the next block. The second session was similar to the first, with the exception that taps on the percussion pad no longer produced tones. However, the impact of the finger on the pad provided some auditory feedback (a thud), in proportion to the tapping force.

Dependent measures

Asynchrony from the mathematical midpoint between tones was measured (in ms) for 60 consecutive taps per trial—from all but the first (practice) block of each session—starting at a point:

a) After at least 12 taps had been made
b) Such that the first tap followed an accent in metric conditions

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[2] Due to a peculiarity of MAX, sequences were presented 2.4% faster than specified in the program, and tap timing was recorded 2.4% slower than it actually occurred. Actual timing values can be obtained by multiplying the reported values by .967. Apart from this constant scaling factor, timing in MAX is accurate to within 1 ms.

Skipped taps and asynchronies greater than one quarter of the target IOI were counted as errors, and the latter were removed from the time series data from each trial and their frequency of occurrence was analyzed. Performance stability was indexed by calculating the coefficient of variation (CV) for the asynchrony series (with errors deleted) from each trial (i.e., the standard deviation of asynchronies was divided by the mean within-trial ITI, and then multiplied by 100). Arcsine-transformed error rates, mean asynchronies, and CVs of asynchronies were analyzed in separate Rate × Feedback × Sequence repeated measures analyses of variance (ANOVAs). Within each ANOVA, four planned orthogonal contrasts tested for effects of the sequence factor. The first contrast tested our main hypothesis by comparing performance between structured (duple, triple, and quadruple) and unstructured (light beat, heavy beat) sequences. The remaining contrasts were more exploratory in nature. The second contrast tested whether variability differed when tapping with the light beat sequence and heavy beat sequence. The third and fourth contrasts explored whether the type of metric structure has any effect on variability. One compared performance with binary (duple and quadruple combined) vs. ternary (triple) structure, and the other compared duple and quadruple performance.Autocorrelation coefficients were computed (up to lag 4) for the series of asynchronies from each trial in order to test for higher-order periodicities in tap timing. We analyzed asynchronies rather than ITIs (see Vorberg & Hambuch, 1978) because the latter are not informative about how accurately taps are placed relative to the sequence, which is the primary concern in syncopation. The analysis of autocorrelation coefficients is described in more detail in the 'Higher-order dependencies' subsection of the following "Results" section. The criterion for statistical significance was set at $p < .05$ for all analyses reported in this article.

Results

Errors

Errors (omitted taps and asynchronies exceeding ± .25*IOI) represent failures to maintain the prescribed antiphase relationship between taps and the pacing sequence. A higher percentage of errors was observed at fast (5.63%)[3] than at slow (2.18%) rates, $F(1, 7) = 14.27$, $p < .01$, and when auditory feedback was present (5.58%) than when it was absent (2.23%), $F(1, 7) = 20.19$, $p < .01$ (which may also be due to practice, as the order of feedback conditions—present followed by absent—was not counterbalanced). None of the four planned contrasts revealed a significant effect of type of pacing sequence on error rate, and there were no significant interactions between rate, feedback, and/or sequence, *p*s > .2.

Asynchronies

Here we report results pertaining both to mean asynchronies and to the variability of asynchronies. Mean asynchronies reflect how early or late taps occur, on average, relative to the midpoint between pacing sequence tones. The usual tendency for taps to occur early—revealed in negative asynchronies (see Aschersleben, 2002)—was observed, and was more pronounced at slow (−10.76 ms) than at fast (−1.69 ms) rates, $F(1, 7) = 14.98$, $p < .01$. However, there were no significant main effects of feedback or sequence (on any of the four contrasts), and no significant interaction effects involving these variables, on mean asynchronies, *p*s > .1.

The variability (CV) of asynchronies data—shown in Fig. 2—are informative about performance stability. The ANOVA on these data revealed a significant main effect of rate, $F(1, 7) = 24.97$, $p < .01$, indicating that variability of asynchronies was—as expected—greater at fast (7.93) than at slow (5.27) rates (which is opposite to what is found in synchronized tapping, see Peters, 1989). The effect of feedback, and the interaction between rate and feedback, were not significant, *p*s > .4. In the ANOVA, the first planned contrast addressing the effects of sequence type tested our main hypothesis that variability would be lower with structured (duple, triple, and quadruple) than with unstructured (light beat, heavy beat) sequences. In support of this hypothesis, CVs were higher with unstructured than with structured sequences, $F(1, 7) = 23.87$, $p < .01$, and, furthermore,

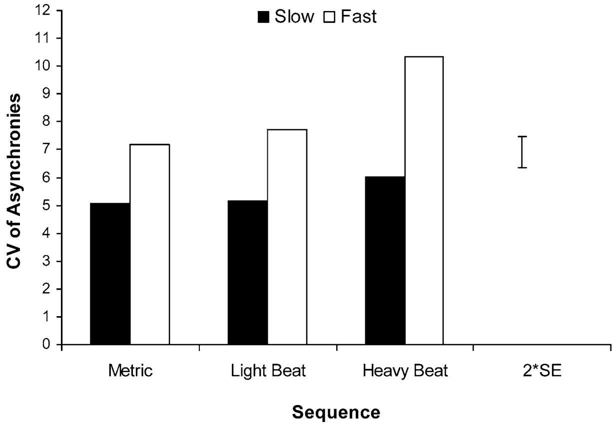

Fig. 2 Coefficient of variation (CV) of asynchronies in metric (duple, triple, and quadruple combined), light beat, and heavy beat conditions from Experiment 1. The *error bar on the right*—labeled *2*SE*—represents double the standard error of the mean

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[3] Error rates are reported here without the arcsine transformation. Note that this error rate is quite low considering that fast rates were set to be 9% faster than individual participants' subjective limits, indicating that these limits were rather conservative. The magnitude of the asynchrony for erroneous taps was not analyzed due to the low error rates.

this effect was more pronounced at fast than at slow rates, $F(1, 7) = 6.43$, $p < .05$. The second contrast—which was more exploratory—tested whether variability differed when tapping with the light beat sequence and heavy beat sequence. Although CVs were higher in the heavy beat condition than in the light beat condition, this difference fell short of statistical significance, $F(1, 7) = 5.23$, $p = .056$. Indeed, a follow-up test revealed that CVs in the light beat condition alone were not reliably larger than those in structured (metric) conditions, $p > .6$, which is an unexpected result that is followed up in Experiments 2 and 3. The third and fourth contrasts revealed that CVs in the duple, triple, and quadruple conditions did not differ significantly from one another, *p*s > .3.

Higher-order dependencies

Autocorrelation coefficients were computed for lags 1–4 for the series of asynchronies from each trial. The statistical significance of these coefficients was assessed using confidence limits based on double the standard error (2*SE) of the estimates, calculated across participants and trials within each experimental condition (cf. Vorberg & Hambuch, 1978). Average lag 1, 2, 3, and 4 autocorrelation coefficients from the five sequence type conditions are shown in Fig. 3. Lag 1 autocorrelations were on average positive and moderate in strength (mean $r = .48$, 2*SE = .025), indicating that adjacent asynchronies were dependent upon one another. This may reflect the presence of drift in the time series. Drift arises when accelerations or decelerations in tapping lead to slight departures from the prescribed anti-phase relationship between taps and tones. Such drift can distort the autocorrelation estimates at larger lags (2–4), which are of interest here because they provide evidence of higher-order dependencies—i.e., periodic structure—in the asynchrony series. Therefore, we performed two separate analyses on the autocorrelation estimates at lags 2, 3, and 4.[4] The first analysis included only the trials for which the lag 1 autocorrelation coefficient was not statistically significant (i.e., trials with no significant drift), amounting to about 20% of the (5 repeats × 8 participants =) 40 trials from each of the 20 rate × feedback × sequence conditions. In addition, these trials contained no errors, i.e., no data points were missing from the time series. The second analysis included all trials from each structured condition.[5] In this second analysis, missing data points (which were very rare) were dealt with by inserting blank cells at the appropriate location/s in the time series before running the autocorrelation analyses.

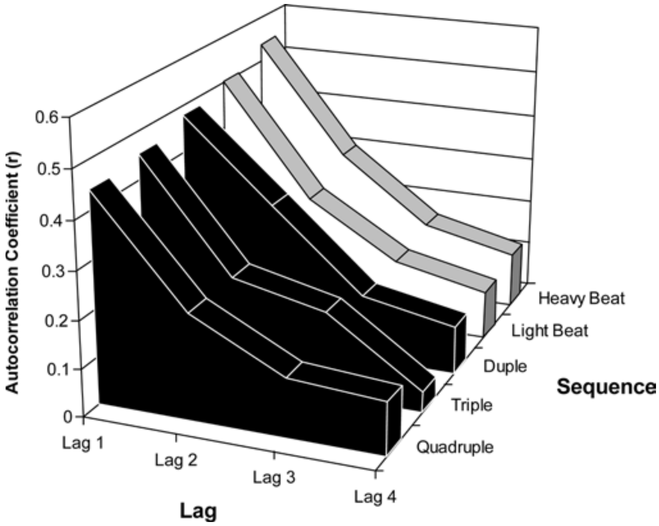

Fig. 3 Autocorrelation coefficients (r) at lags 1–4 in duple, triple, quadruple, light beat, and heavy beat conditions from all trials in Experiment 1

The results of the first analysis are straightforward. Lag 2, 3, and 4 autocorrelation coefficients—only for trials with nonsignificant lag-1 autocorrelation values, determined based on 2*SE estimates from individual trials—from the five sequence type conditions are shown in Fig. 4 (averaged across participants as well as the rate and feedback factors). In the three metric conditions, positive peaks in the autocorrelation function occurred at lags that correspond to the accent structure of the pacing sequences. Thus, there was significant lag 2 (and lag 4, a higher harmonic of lag 2) autocorrelation in the duple condition, significant lag 3 autocorrelation in the triple condition, and significant lag 4 autocorrelation in the quadruple condition. None of the remaining autocorrelation coefficients—including those in the unstructured conditions—are statistically significant.

The results of the second analysis are basically consistent with those of the first. Average lag 2, 3, and 4 autocorrelation coefficients—for all trials—from the three metric sequence type conditions can be seen in Fig. 3. Note that in the current analysis we focus on relative, rather than absolute, values of the autocorrelation coefficients because the latter are somewhat distorted due to the presence of drift in the asynchronies

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[4] Note that this is a different measure to lag 1 autocorrelation in ITIs, which is conventionally examined in studies of self-paced (metronome absent) tapping, and is typically found to be negative (see Vorberg Wing, 1996; Wing, 2002). Also note that drift arises during sensorimotor syncopation because the task involves making taps simultaneously with imagined events (IOI midpoints) rather than with physical events in the pacing sequence. However, drift during syncopation is typically not as large in magnitude as drift during self-paced tapping due to the presence of the pacing sequence.

[5] De-trending the time series did not seem like the best option because inspection of the data revealed that the most prominent component of the drift was non-monotonic (i.e., gradual slowing down *and* quickening across runs of taps within trials) rather than monotonic (i.e., slowing down *or* quickening within a trial). Although it has been shown that monotonic (linear) trends can be removed without introducing statistical artifacts into the time series, it remains an "open question" whether this holds for non-monotonic trends (Vorberg Wing, 1996, p. 199).

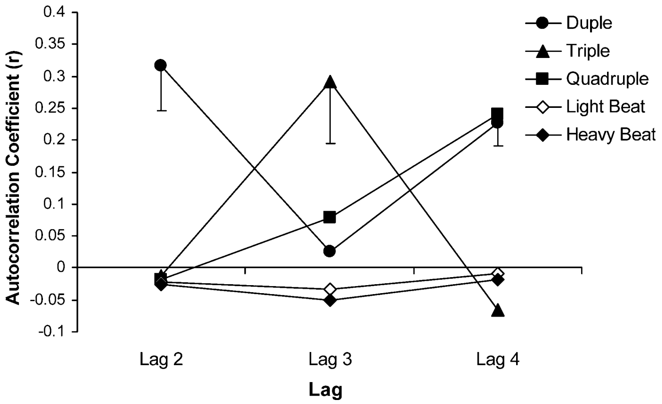

Fig. 4 Autocorrelation coefficients (*r*) at lags 2–4 in duple, triple, quadruple, light beat, and heavy beat conditions from non-drift trials in Experiment 1. *Error bars* show double the standard error of the autocorrelation estimates at the lag/condition combinations of primary interest

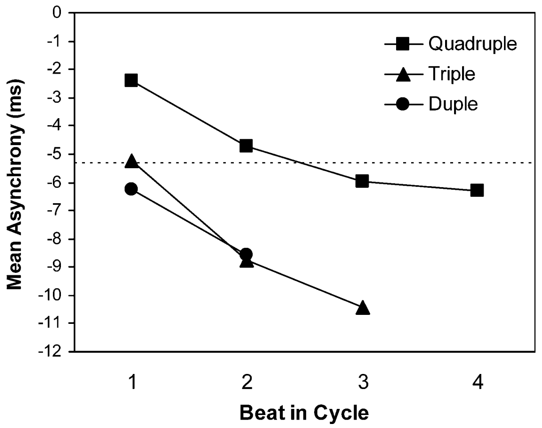

Fig. 5 Mean asynchronies as a function of beat number within (duple, triple, and quadruple) metric beat cycles from Experiment 1. Note that beat 1 is *accented* and beats 2–4 are *unaccented.* The *horizontal dotted line* represents mean asynchrony from the light beat conditions

series. This drift is presumably responsible for the relatively large positive autocorrelation values obtained across lags in the unstructured conditions, in which participants were instructed to avoid metric grouping.

The strength of correlation at each lag was compared across metric conditions in three separate 2 (rate: fast vs. slow) × 2 (feedback: present vs. absent) × 3 (sequence: duple, triple quadruple) ANOVAs (one per lag). A single, unique planned contrast tested the effect of sequence type in each of the three ANOVAs:

1. Duple vs. triple and quadruple combined for lag 2
2. Triple vs. duple and quadruple combined for lag 3
3. Quadruple vs. duple and triple combined for lag 4

All ANOVAs yielded evidence of higher-order dependencies in asynchronies. Lag 2 autocorrelation coefficients are higher in the duple condition than in the triple and quadruple conditions combined, $F(1, 7) = 19.33, p < .01$; lag 3 coefficients are higher in the triple condition than in the duple and quadruple conditions combined, $F(1, 7) = 7.37, p < .05$; and lag 4 coefficients are higher in the quadruple condition than in the duple and triple conditions combined, $F(1, 7) = 11.91, p = .01$. These results indicate that tap timing characteristics are similar for the taps following every second (accented) tone in the duple condition, for taps following every third tone in the triple condition, and for taps following every fourth tone in the quadruple condition. The above effects occurred independently of feedback and rate, *p*s > .1.

Overall, these results suggest that asynchronies were modulated by metric structure. We attempted to learn more about this modulation by comparing mean asynchronies associated with taps that occurred immediately after accented beats (when high and low tones sound simultaneously) with asynchronies following unaccented beats (with the low tone absent). Figure 5 shows the mean asynchronies for taps following each beat in the metric cycles of duple, triple, and quadruple sequences, in which beat 1 is always accented and the subsequent beat(s) is(are) unaccented.

These mean asynchronies were analyzed in a $2 \times 2 \times 2 \times 3$ ANOVA, with factors accentuation (accented vs. unaccented), rate, feedback, and (metric) sequence. The analysis yielded a main effect of accentuation, $F(1, 7) = 11.96$, $p = .01$, but no significant interactions between accentuation and the other factors, *p*s > .2. The main effect of accentuation indicates that mean asynchronies following accented tones were less negative than mean asynchronies following unaccented tones (see Fig. 5). Thus, taps following accents were delayed.[6] The results with quadruple metric sequences are particularly interesting. It can be seen in Fig. 5 that after becoming less negative following the first (accented) beat, the asynchronies settle back gradually rather than suddenly. The horizontal dotted line in the figure represents mean asynchrony from the light beat conditions, which may be considered as a sort of 'baseline' for taps following unaccented beats. It is unclear why mean asynchrony with duple and triple sequences appears to be at baseline following accented beats, and then becomes more negative following unaccented beats. The CVs of asynchronies data were subject to a similar analysis as the mean asynchronies, but no significant main effect of accentuation or interactions between accentuation and the other factors were found, *p*s > .09.

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[6] To address whether accentuation modulates tap timing indirectly by affecting tapping force, we computed correlations between asynchronies and MIDI velocities (measured on a scale—ranging from 0 to 127—that is, monotonically related to how hard the percussion pad is struck) in each trial from the metric conditions. Velocity and asynchrony are essentially uncorrelated (mean $r = .08$, n.s.), which suggests that accentuation affects timing directly.

Discussion

The main findings are consistent with the hypothesis that metric frameworks can be used to stabilize sensorimotor syncopation. There was less variability in asynchronies with metrically structured sequences than with unstructured sequences—in particular, the heavy beat sequence. Performance with structured sequences was also characterized by higher-order dependencies in asynchronies, indicating that tap timing was influenced by metric structure. No such higher-order dependencies were found with unstructured sequences. With metrically structured sequences, taps that were made immediately after accented beats were delayed relative to taps following unaccented beats. Note that the delays appear, at first glance, to be inconsistent with the results of a study by Billon, Semjen, and Stelmach (1996). They found that when participants were instructed to accent a single tap during unpaced tapping, the interval preceding the accented tap was shortened and the interval that immediately followed the accent was lengthened; in other words, the forceful tap was made relatively early. However, it is difficult to compare the results of Billon et al. (1996) with those of the current study due to considerable procedural differences between the studies; most notably the use of short, unpaced tap sequences and explicit instructions to produce accented taps in Billon et al. (1996) but not in the current study.

Although it is not possible at this stage to identify with certainty the underlying cause of the regular delays in tap timing that we observed, they may be a consequence of a phase-resetting mechanism that serves to curtail transitions from antiphase to in-phase coordination. This interpretation is invited by the fact that the momentary delay in tap timing, followed by a gradual return to baseline in the case of quadruple sequences, bears a qualitative resemblance to the phase correction response elicited by the early or late arrival of a single pacing tone, or a change in tempo, during both sensorimotor synchronization and syncopation (see Repp, 2001a). However, before seriously entertaining the notion of regular phase resetting, it will be necessary to demonstrate that the observed higher-order dependencies in tap timing reflect an anticipatory meter-based process rather than simply a reflexive response to accented tones. We investigated this issue in Experiment 2 by including sequences in which accents occur unpredictably.

Further questions are raised by our finding that performance stability (variability in asynchronies) was similar with the light beat unstructured sequence and the metrically structured sequences. This may be indicative of a trade-off in which any advantage of metrical conditions over the light beat condition is counteracted by a general disadvantage associated with the presence of accented tones in the former. Another possibility is that participants were unable to resist imposing metric structure(s) on the light beat sequences—as in the subjective rhythmization phenomenon described in the "Introduction"—albeit not consistently enough to be detected in autocorrelation functions. Thus, the same phase-resetting mechanism that we claim assisted performance with sequences containing regular accents may have been engaged in light beat conditions. Such metric interpretations may have been relatively difficult to impose in the case of heavy beat sequences if, for instance, generally increasing the salience of sequence tones increases the potency of the in-phase attractor and thus decreases the stability of antiphase coordination (see the "General discussion"). The issues of beat salience and the disruptive effects of accentuation are addressed in Experiment 2 and the question of how consistently participants are able to impose metric interpretations on unstructured sequences will be pursued in Experiment 3.

Experiment 2: Regular, irregular, and unstructured sequences

The main aim of Experiment 2 was to investigate whether the higher-order dependencies in tap timing that were observed in Experiment 1 are anticipatory or reflexive in nature. To examine this issue, participants were required to tap in antiphase with the three metrically structured, regular sequences used in Experiment 1 and with three new sequences containing irregular, hence unpredictable, accents. In order to allow performance with the regular and irregular sequences to be compared, the ratio of accented to unaccented tones was matched across both sets of sequences: that is, one irregular sequence contained accents that could occur either on adjacent tones or on every second or third tone, so that on average half of the sequence tones were accented (as in the duple regular sequence); in another irregular sequence, either every second, third, or fourth tone was accented, so that a third of the sequence tones were accented (as in the triple sequence); and in the final irregular sequence, either every third, fourth, or fifth tone was accented, so that a quarter of the sequence tones were accented (as in the quadruple sequence). If the delaying of taps following accented tones that was found in Experiment 1 was reflexive, then similar delays should occur in the context of both regular and irregular sequences in the current experiment. However, if the delays were anticipatory rather than reflexive, they should occur only for regular sequences. We favored this second outcome. We also expected that performance would be generally more stable in metric conditions than in irregular conditions.

A further aim of Experiment 2 was to examine the effects of beat salience on the stability of sensorimotor syncopation. To this end, an unstructured sequence composed of beats articulated by three simultaneous tones—high, intermediate (mid), and low in pitch—was included in addition to the light beat and heavy beat unstructured sequences used in Experiment 1. Thus, the set of three unstructured sequences used here represents a variety of beat saliences: Light (high tones only), heavy (high and low tones), and extra heavy (high, medium, and low tones). If increased beat salience leads to greater instability in antiphase tapping, variability in asynchronies should increase from light, through heavy, to extra heavy unstructured sequences.

Finally, based on the results of Experiment 1, we expected that performance stability would be greater in metric conditions than in the heavy and extra heavy beat conditions. However, given issues such as the potential trade-off between the advantage of metric structure and the disadvantage of the presence of physical accents that was identified earlier, we were less sure whether or not stability would differ in metric and light beat conditions.

Methods

Participants

Eight females and four males participated ($N = 12$). The average age of the participants was 26 years (range 21–57 years). Three had participated in Experiment 1 and the rest were trained musicians who had participated in other finger-tapping experiments. All participants preferred to tap with the right hand and were paid for participation.

Design

The sole variable that was manipulated in Experiment 2 was *sequence*, with nine types: duple, triple, quadruple; irregular-2, irregular-3, irregular-4; and light beat, heavy beat, extra heavy beat (see below). In contrast to Experiment 1, the presentation rate was held constant for each participant at a value slightly faster than the rate that he or she deemed manageable (see below). Also, the auditory feedback variable from Experiment 1 was not included in the current design because it did not previously affect performance stability differentially in structured and unstructured conditions.

Materials

Stimuli consisted of nine sequences of piano tones. The tone duration was 80 ms plus natural damped-string decay. All sequences contained an isochronous series of 74 high-pitched tones (C6, 1,046 Hz) that was intended to mark the beat. In three metrically structured sequences, lower tones (C4, 262 Hz) sounded simultaneously with the high tone either every two (duple), three (triple), or four (quadruple) beats. In three unstructured sequences, tones were either all relatively unaccented (light beat), all of intermediate accentuation (heavy beat; as in Experiment 1), or all strongly accented (extra heavy; with a medium pitched tone—C5, 523 Hz—being added to the high and low tone complex used to create accents previously). Finally, three irregularly structured sequences were generated by first segmenting the high-pitched tone series (starting from the second tone) into cycles of 6, 9, or 12 beats, and then placing accents within these cycles either:

a) Every 1, 2, or 3 beats (termed *irregular-2*, because accents occur on average every two beats)
b) Every 2, 3, or 4 beats (*irregular-3*)
c) Every 3, 4, or 5 beats (*irregular-4*) respectively

Within-cycle accents occurred in random order. Thus, these irregularly structured sequences are matched with the metrically structured sequences in terms of the ratio of accented to unaccented tones that they contain. Segmentation into cycles allowed us to control the ratio of accented to unaccented tones while avoiding runs of regular accents. Six different exemplars of each type of irregular sequence were created, across which accent location varied but the ratio of accented to unaccented tones was constant. In all sequences containing accents, the accents started from the second tone of the high-pitched tone series (i.e., the first tone served as an upbeat), and the last tone of the series was always accented. The presentation rate was set relative to each participant's estimate of his or her own just-manageable rate (see below). The apparatus was identical to that used in Experiment 1.

Procedure

The testing environment and general set-up were identical to those used in Experiment 1. However, testing for the current experiment required only a single 1-h session per participant. The session started with the participant finding his or her just-manageable syncopation rate using the threshold estimation task from Experiment 1 (except taps on the percussion pad no longer triggered tones). Sequences in the remainder of the experiment were presented at a tempo 9% faster than this subjectively just-manageable rate. The average rate selected by participants had a beat interval of 463 ms (range 380–580 ms).

The experiment proper consisted of nine blocks of six trials, with the stimulus sequence varying between blocks while remaining constant across the one practice and five test trials within each block (in contrast to the randomized design employed in Experiment 1). In blocks with trials consisting of irregular sequences, different exemplars of the relevant type of irregular sequence were presented from trial to trial so that accent location remained unpredictable. Blocks were presented in six different counterbalanced orders. The participant pressed the spacebar on the computer keyboard to begin the sequence at the start of each trial. The instructions specified that the participant should begin tapping between the second and third beat of the sequence. As in Experiment 1, the participant was asked:

a) To resist the tendency to shift onto the beat
b) To avoid grouping the tones in the case of unstructured sequences

c) To use (unspecified) grouping strategies in the case of metric sequences

The participant was told simply to ignore the accents in irregularly structured sequences. Taps on the percussion pad did not trigger tones.

Dependent measures

Asynchrony from the midpoint between tones was measured (in ms) for taps produced between the 14th and 74th (final) tone of each sequence in test trials. As in Experiment 1, error rates (indicating the arcsine-transformed proportion of skipped taps and asynchronies greater than one quarter of the target IOI), mean asynchronies, and CVs of asynchronies were calculated, and then analyzed in separate ANOVAs. Also, as in the previous experiment, the issue of higher-order dependencies in tap timing was examined by computing autocorrelation coefficients for the asynchrony series from each trial.

Results

Errors and asynchronies

Within each of the separate ANOVAs on error rates, mean asynchronies, and CVs, seven planned orthogonal contrasts tested for effects of sequence type. The results of Experiment 1 motivated the first two contrasts, which compared performance in metric conditions (duple, triple, and quadruple combined) with performance in the heavy beat conditions (heavy and extra heavy beat combined), and in the light beat condition respectively. The next contrast compared performance for metric and irregular conditions. Two further contrasts—also motivated by the results of Experiment 1—tested for differences between the three unstructured conditions: Light beat performance vs. heavy beat and extra heavy beat performance combined, and heavy beat vs. extra heavy beat performance. Finally, two (more exploratory) contrasts tested whether performance was affected by the proportion of tones that were accented in the metric and irregular sequences (half in duple and irregular-2, a third in triple and irregular-3, and a quarter in quadruple and irregular-4 sequences): Duple/irregular-2 and quadruple/irregular-4 combined vs. triple/irregular-3, and duple/irregular-2 vs. quadruple/irregular-4.

The analysis of error rates—which were generally low ($M = 3.91\%$, without the arcsine transformation)—revealed a significant effect of sequence for the first contrast, $F(1, 11) = 9.07$, $p = .01$, indicating that the mean error rate was higher in the heavy beat condition (4.65%) than in the metric conditions combined (3.67%). None of the remaining contrasts yielded a significant difference for errors, *p*s > .1.

Mean asynchrony was positive on average (4.36 ms), which is not uncommon with syncopation (e.g., Keller & Repp, 2004). Two of the contrasts in the ANOVA revealed unexpected effects of sequence type on mean asynchrony. First, the mean asynchrony was smaller in the light beat condition (1.73 ms) than in the heavy and extra heavy beat conditions combined (11.43 ms), $F(1, 11) = 7.04$, $p < .05$. Second, the mean asynchrony was smaller—and negative—in the duple and irregular-2 conditions (−1.61 ms) than in the quadruple and irregular-4 conditions (6.49 ms), $F(1, 11) = 9.66$, $p = .01$. The mean asynchrony in the triple and irregular-3 conditions (2.46 ms) was intermediate. Thus, it appears that taps occur increasingly earlier in time as the ratio of accented to unaccented tones in structured sequences is increased. The above results for mean asynchrony will not be discussed further because their causes remain unclear. None of the other contrasts yielded a significant difference, *p*s > .09.

Average CVs of asynchronies are displayed in Table 1. The ANOVA on these data revealed that, as expected, CVs of asynchronies were larger in heavy beat conditions than in metric conditions, $F(1, 11) = 6.22$, $p < .05$, and that CVs in the light beat condition were not significantly different from CVs in metric conditions, $p > .8$. So far these results corroborate the findings of Experiment 1. Furthermore, in accordance with predictions, the current analysis yielded the new finding that CVs were larger in irregular conditions than in metric conditions, $F(1, 11) = 8.51$, $p < .02$. This indicates that the variability of asynchronies was increased by accents that occurred unpredictably, relative to regular (metric) accents.

The present results proved to be inconclusive—as was the case in Experiment 1—with regard to the question whether or not performance stability varies for the different types of unstructured sequence. Although CVs were higher in the heavy and extra heavy beat conditions than in the light beat condition, this difference once again fell short of statistical significance, $F(1, 11) = 3.38$, $p = .09$. Moreover, the difference in CVs in the heavy beat and the extra heavy beat conditions (10.86 vs. 10.47, respectively) was negligible, $p > .7$.

Finally, the contrasts testing for effects of the proportion of accented tones in the metric and irregular sequences revealed that CVs were larger in the duple and irregular-2 conditions ($M = 12.03$) than in the quadruple and irregular-4 conditions ($M = 9.67$), F(1,

Table 1 Average coefficients of variation (CVs) of asynchronies in the different sequence type conditions from Experiments 2 and 3: Metric (duple, triple, and quadruple combined), light beat, heavy beat (heavy and extra heavy combined in Experiment 2), and irregular (irregular-2, irregular-3, and irregular-4 combined). Standard deviations are shown in parentheses

Experiment	Sequence type			
	Metric	Light beat	Heavy beat	Irregular
2	8.48 (4.28)	8.34 (3.91)	10.66 (5.63)	12.48 (7.62)
3	4.99 (1.61)	4.97 (1.67)	6.87 (2.77)	6.56 (2.48)

11) = 6.49, $p < .05$. CVs in the triple and irregular-3 conditions (M = 9.75 ms) were numerically close to those in the quadruple and irregular-4 conditions. These results suggest that the high proportion of accented tones in duple and irregular-2 sequences was disruptive.

Higher-order dependencies

As in Experiment 1, autocorrelation coefficients were computed for lags 1–4 for the series of asynchronies from each trial. Once again, positive lag 1 autocorrelations (mean r = .52, 2*SE = .029) revealed the presence of drift in the time series. Therefore, we again performed two separate analyses on the higher-order autocorrelation estimates at lags 2, 3, and 4. The first analysis included only the trials in which no significant drift was detected, amounting to about 10% of the (5 repeats × 12 participants =) 60 trials from each of the nine sequence type conditions. In the three metric conditions, positive peaks in the autocorrelation function occur at lags that correspond to the accent structure of the pacing sequences: Lag 2 (r = .37, 2*SE = .095) and lag 4 (r = .33, 2*SE = .057) in the duple condition, lag 3 (r = .23, 2*SE = .149) in the triple condition, and lag 4 (r = .23, 2*SE = .207) in the quadruple condition. None of the remaining autocorrelation coefficients—including those in the unstructured and irregular conditions—approached statistical significance.

The second analysis on lag 2, 3, and 4 autocorrelation coefficients included all trials from each of the three metric conditions. This analysis also revealed meter-based periodicities in tap timing, though the evidence for such higher-order dependencies found here is somewhat weaker than the evidence yielded by the corresponding analysis in Experiment 1. Using the same planned contrasts as employed in Experiment 1, an ANOVA on lag-3 autocorrelation coefficients revealed that coefficients were higher in the triple condition (mean r = .20) than in the duple and quadruple conditions combined (mean r = .06), $F(1, 11) = 6.43$, $p < .05$. None of the remaining contrasts revealed significant effects. Nevertheless, as was the case in Experiment 1, further analysis of mean asynchronies revealed that asynchronies associated with taps that occurred immediately after accented beats (i.e., when high and low tones sound simultaneously) in metric sequences were, on average, more positive compared with asynchronies following unaccented beats (with the low tone absent). However, as can be seen in the left panel of Fig. 6, the 'return to baseline' (the horizontal dotted line represents mean asynchrony in the light beat condition) for taps following accents is not as gradual in the current experiment as it was in Experiment 1. This feature—which is possibly related to the sole use of fast rates in the current experiment—may have contributed to the weakness of the present results through its effects on autocorrelation. Specifically, meter-related autocorrelation structure may have been obscured by other serial dependencies arising because the phase-resetting process was still in progress beyond the first (accented) beat.

Most importantly, the results of the current experiment provide evidence of a dissociation between the effects of accents in metric and irregular conditions. As can be seen in the right panel of Fig. 6, whereas taps following accented beats were delayed relative to taps following unaccented beats in metric conditions, accentuation had no such effect in irregular conditions (where there appears to be a slight tendency for the opposite to occur). The reliability of this result is confirmed by the significant interaction of accentuation and regularity in a 2 (accented vs. unaccented) × 2 (metric vs. irregular) ANOVA, $F(1, 11) = 5.68$, $p < .05$.

Discussion

The main findings of Experiment 2 are that:

a) Asynchronies were less variable—and error rates lower—in metric conditions than in heavy beat

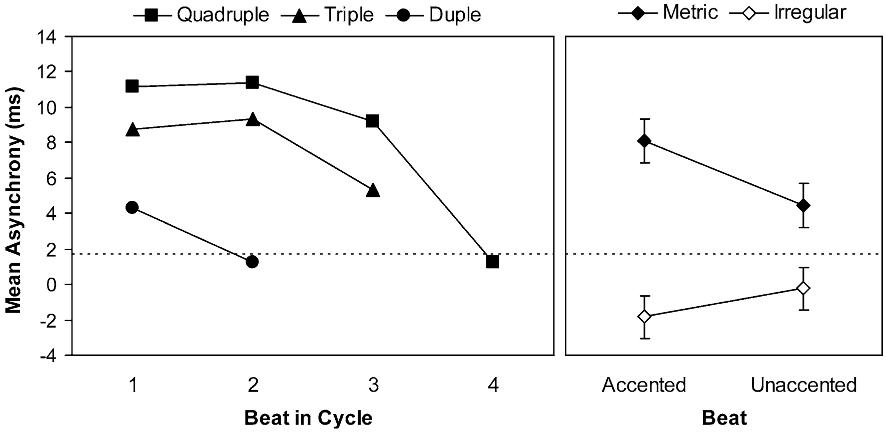

Fig. 6 Mean asynchronies in the metric and irregular conditions from Experiment 2. *Left panel*—asynchronies as a function of beat number within (*duple*, *triple*, and *quadruple*) metric beat cycles (only beat 1 is accented). *Right panel*—asynchronies as a function of whether the preceding beat was accented or unaccented in the metric and irregular conditions (with *error bars* representing double the standard error of the mean). The *dotted line* represents mean asynchrony from the light beat conditions

conditions (i.e., the heavy beat and extra heavy beat conditions, for which performance did not differ reliably)

b) The variability of asynchronies was commensurate in metric and light beat conditions

c) The variability of asynchronies was lower in metric conditions than in irregular conditions

d) Accentuation affected mean asynchrony differentially in the metric and irregular conditions

Leaving aside the commensurate variability in metric and light beat conditions for now, these findings indicate that greater stability in sensorimotor syncopation was achieved with metric sequences than with (heavy and extra heavy beat) unstructured sequences and irregularly structured sequences. Recall that participants were instructed to group their taps in metric conditions and to avoid such grouping in unstructured and irregular conditions. To the extent that these instructions were followed, the above results are consistent with the results of Experiment 1 in suggesting that metric frameworks help to stabilize sensorimotor syncopation. It was proposed in the "Introduction" that such benefits may be due to regular phase resetting based on metric structure. Partial support for this proposal (the present data do address it directly) is offered by the finding that the observed delays in tap timing that occur immediately after regularly placed accents do not occur following irregular accents, suggesting at least that the tap timing fluctuations with metric sequences are anticipatory rather than reflexive.

There is possibly an alternative, psychoacoustic-based explanation for the observed timing fluctuations. Tekman (2001, Experiment 1) has demonstrated—using sequences with alternating runs of loud and soft tones—that IOIs preceding loud (accented) tones are perceived to be longer than IOIs preceding soft (unaccented) tones, and, furthermore, that this effect occurs when accents occur regularly but not when they occur irregularly. This finding raises the possibility that the timing delays observed following accents in the current study were simply adaptive reactions to perceptually longer IOIs preceding accented tones. However, Tekman (2001, Experiment 2) also observed that when accents were produced by changes in pitch rather than loudness, the opposite tendency occurred: IOIs preceding accents were perceived to be shorter than the other sequence IOIs. This suggests that such psychoacoustics effects may have played only a limited role in the current study, because accents were produced by combined loudness and pitch changes, making it likely that the opposing loudness- and pitch-based psychoacoustic effects on IOI perception cancelled out one another. Moreover, Repp (2003) found that the presence of a single, predictable, accented (relatively loud) tone does not affect timing during synchronized tapping.

We turn now to the results for the light beat sequences, which were associated with similar levels of performance stability to those observed with metric sequences (as was the case in Experiment 1). Once again, this might be taken to suggest that any advantage associated with the use of metric frameworks is offset by a disadvantage caused by the presence of strong beats, or, more precisely, the presence of louder, more spectrally complex beat signals (i.e., chords composed of high and low tones). However, whether it is the mere presence of strong beats that causes problems is presently unclear because the difference in performance stability with heavy beat sequences vs. light beat sequences fell short of statistical significance (as it did in Experiment 1), and performance was commensurate for heavy beat and extra heavy beat sequences. Indeed, it may be the case that the interference produced by physical accents is most profound when these accents are inconsistent with a metric structure that the performer has in mind. A related issue that makes it difficult to assess the influence of strong beats per se is that, in both Experiments 1 and 2, the metric conditions differed from the other conditions not only in terms of containing sequences with regular accents, but also in terms of task instructions: Participants were told to use metric grouping strategies only in the former. We redressed this confound (which had been introduced deliberately in an attempt to maximize effects) in the next experiment by instructing participants to impose the same metric structures mentally in all conditions, i.e., regardless of sequence structure. In other words, participants were asked to engage in top-down metric framework generation.

Experiment 3: Imposing structural regularity

In Experiment 3, participants were required to invoke metric frameworks while tapping along in antiphase with sequences that were regular, irregular, or unstructured (light and heavy beat; the extra heavy beat sequence was dropped because it was uninformative in Experiment 2). In the case of unstructured sequences, this involves mentally imposing a metric structure in the absence of physical cues to such structure. Requirements are even more extreme in the case of irregular sequences: Metric structure has to be imposed in the face of cues that violate such structure. To assist participants in their task, each sequence was composed of two sections. The first section contained a short induction sequence that defined either a duple, triple, or quadruple meter (as in the regular sequences from Experiments 1 and 2). The second, longer section of the sequence was regularly structured, irregularly structured, or unstructured (as in Experiment 2). Participants were instructed to start tapping with the induction sequence and then to continue tapping throughout the second section with the induced meter in mind. This task allows us to compare how the deliberate use of metric frameworks affects performance stability for sensorimotor syncopation with regular, irregular, and unstructured (heavy vs. light beat) sequences. Furthermore, the task allows us to gauge the degree to which the physical accents—especially those that occur irregularly—interfere with the use of meter-based periodic grouping strategies. We expected that performance would be more stable:

a) In metric than in heavy beat conditions
b) In metric than in irregular conditions
c) In light beat than in heavy beat conditions

Moreover, there should be stronger evidence (in autocorrelation structure) of metric grouping in metric and light beat conditions than in irregular and heavy beat conditions.

Methods

Participants

Nine musically trained participants (five females and four males; age range = 21–57 years), including the two authors, one participant from Experiment 1, and two participants from Experiment 2, took part in Experiment 3.

Design

A 3 × 4 repeated measures design was employed, with factors *invoked meter* (duple, triple, quadruple) and *sequence* (metric, irregular, light beat, heavy beat).

Materials

The 12 sequences used as stimuli were created by prefixing the metric, irregular, light-beat, and heavy-beat sequences from Experiment 2 with three different types of metric induction sequence. Thus, all sequences had two sections, induction and main. In the induction sections—which consisted of 13 beats—low-pitched tones were presented simultaneously with every second, third or fourth high tone (starting on beat two) so as to induce a duple, triple, or quadruple meter respectively. Each of these three types of induction section was followed by four types of main section—each consisting of 73 beats —in which the low-pitched tones either:

a) Continued as in the preceding induction section (metric)
b) Began to occur unpredictably, while preserving the ratio of accented to unaccented tones from the induction section (irregular)
c) Occurred with every high tone (heavy beat)
d) Ceased altogether, leaving only the high tones (light beat)

The presentation rate was dependent upon individual participants' objective thresholds for sensorimotor syncopation (see below). The pitch and duration of the high and low tones, as well as the apparatus used for testing, were the same as in Experiments 1 and 2.

Procedure

Participants were presented with 12 blocks of six (one practice and five test) trials; one per invoked meter (duple, triple, quadruple) × sequence (metric, irregular, light-beat, heavy-beat) condition. The blocks were run in six counterbalanced orders. Each trial consisted of a single presentation of one of the stimulus sequences, triggered by pressing the spacebar on the computer keyboard. For irregular blocks, different exemplars of the relevant type of irregular sequence were presented from trial to trial. The presentation rate was set to be 15% slower than the participant's threshold for sensorimotor syncopation (which had been determined in a previous experiment).[7] The beat intervals used ranged from 338 to 446 ms across participants. As in Experiment 2, the participant was instructed to begin tapping in antiphase with the sequence after the second beat, to continue tapping until the sequence ended, and to resist the tendency to shift into an in-phase relationship between taps and tones. However, in Experiment 3 the participant received an additional instruction specifying that he or she should keep in mind the metric grouping suggested by the regular accents that were present during induction for the entire duration of the sequence. It was emphasized to the participant that he or she should try to maintain this grouping even in the face of contradictory cues such as the irregular accents. Taps on the percussion pad did not produce tones.

Dependent measures

Asynchrony from the midpoint between tones was measured for taps produced between the 13th and 73rd (final) tone of the main section of each sequence in test trials. Skipped taps and asynchronies greater than one quarter of the target IOI were counted as errors, and trials with more than five consecutive errors were removed from the data set (such error runs did not occur in Experiments 1 and 2; it is not known why they occurred here). Performance stability was indexed by the CV of asynchronies, and higher-order dependencies in tap timing were examined by estimating autocorrelation in the asynchrony series.

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[7] The procedure for measuring syncopation thresholds involved finding the maximum rate at which the participant could produce a consecutive series of 24 syncopated taps that fell within the 26–74% region of each IOI defined by the pacing sequence tones (50% representing the midpoint). After starting at a slow rate selected by the participant, the rate was increased from trial to trial in 4% steps until one or more errors occurred in three consecutive trials. At this point the rate was decreased by 4% and then progressively increased by 1% until another three consecutive error trials occurred. The rate of the final error-free trial was defined as the threshold. The participant completed this procedure with metric (duple, triple, quadruple), irregular (irregular-2, irregular-3, irregular-4), light beat, and heavy beat sequences. The thresholds from these conditions (eight in total) were then averaged to yield the participant's overall syncopation threshold.

Results

Errors and asynchronies

The effects of invoked meter (duple, triple, quadruple) and sequence (metric, irregular, light beat, heavy beat) upon error rate, mean asynchrony, and CVs of asynchronies were analyzed in separate 3 × 4 ANOVAs. Two planned orthogonal contrasts tested for effects of invoked meter: Duple and quadruple combined vs. triple, and duple vs. quadruple. Three further orthogonal contrasts tested our predictions about the effects of sequence type: Metric vs. heavy beat, metric vs. irregular, and light beat vs. heavy beat. Finally, three contrasts tested for interactions between invoked meter and sequence type.

Before analyzing (arcsine-transformed) error rates, trials with more than five consecutive errors were removed from the data set (4.38% of all trials). In the remaining trials, the error rate (.9%, without the arcsine transformation) was not affected reliably by invoked meter, type of sequence, or their interaction on any contrast, *p*s > .1. Likewise, these factors did not have reliable effects on mean asynchrony (12.82 ms), *p*s > .1. However, in accordance with predictions, CVs of asynchronies—displayed in Table 1—were found to be smaller in metric than in heavy beat conditions, $F(1, 8) = 6.23$, $p < .05$, in metric than in irregular conditions, $F(1, 8) = 11.01$, $p = .01$, and importantly in the light beat than in the heavy beat condition, $F(1, 8) = 6.34, p < .05$. The contrasts testing for main effects of invoked meter and interactions between invoked meter and sequence type produced no statistically significant results, *p*s > .5.

Higher-order dependencies

As in Experiments 1 and 2, there was significant drift in the asynchrony series (mean lag 1 $r = .44$, 2*SE = .027). Lag 2–4 autocorrelation coefficients were first computed for trials without drift—about 11% of the (5 repeats × 9 participants =) 45 trials from each of the 12 invoked meter × sequence conditions. As in the previous experiments, significant positive peaks in the autocorrelation function were found only for metric sequences: lag 2 ($r = .27$, 2*SE = .015) for duple sequences, lag 3 ($r = .25$, 2*SE = .126) for triple sequences, and lag 4 ($r = .34$, 2*SE = .165) for quadruple sequences. Surprisingly, despite instructions to use metric grouping, none of the remaining autocorrelation coefficients—including those in the unstructured (light beat and heavy beat) and irregular conditions—were statistically significant.

In a second, more exhaustive analysis using all trials, separate ANOVAs were used to compare the effects of invoked meter (duple, triple, or quadruple) on autocorrelation at lags 2, 3, and 4 in each of the four sequence conditions (metric, light beat, heavy beat, and irregular). In each of the 12 ANOVAs—one per lag × sequence combination—the effects of invoked meter were tested using the same planned contrasts used in Experiments 1 and 2. Only the analysis of lag-3 autocorrelation in the metric condition revealed evidence of higher-order dependencies in asynchronies. Consistent with the results of Experiments 1 and 2, lag-3 autocorrelation coefficients were significantly higher in the condition where the invoked meter was triple (mean $r = .18$) than in the duple and quadruple invoked meter conditions combined (mean $r = .09$), $F(1, 8) = 6.77$, $p < .05$ (other *p*s > .07 in metric conditions). As was the case in the analysis of non-drift trials, no evidence of meter-based higher-order periodicities in tap timing was found in the light beat (*p*s > .2), heavy beat (*p*s > .1), or irregular (*p*s > .4) conditions.

Discussion

The current experiment yielded two main sets of results. First, performance was more stable for syncopation with metric sequences than with heavy beat and irregular sequences, even though participants were under instructions to use specific metric grouping strategies in all conditions. This finding suggests that participants either had trouble imposing metric structure on the heavy beat and irregular sequences or that such top-down applied structure did not benefit performance with these particular types of sequence. The failure to find evidence of meter-based higher-order autocorrelation structure in heavy beat and irregular conditions implies that the former was the case (assuming that imposed metrical structure is necessarily reflected in the autocorrelation structure of timing, see Vorberg & Hambuch, 1978).

The second set of results revolves around the finding that syncopation was more stable with light beat sequences than with heavy beat sequences. The corresponding difference only approached statistical significance in the previous two experiments, in which participants were instructed to avoid metric grouping in the unstructured sequence conditions. It is not entirely clear whether the effect was precipitated in the current experiment by the metric grouping instructions, as the experiments also differed in several other respects (e.g., sequence presentation rates). In any case, it is puzzling that the autocorrelation analyses unearthed no evidence of higher-order periodicities in the tap series from the light beat conditions. Perhaps participants' attempts to use metric grouping strategies in the absence of regular physical accents were susceptible to problems such as 'losing count,' leading to occasional runs of irregular group lengths. Performance may have been relatively immune to disruption by these (subjective) irregular groups because they were predictable for the participant who generated them. Alternatively, it may be the case that the higher-order dependencies that were once again observed in metric conditions are anticipatory but not entirely intentional, i.e., they rely on the presence of regular physical accents. This issue is addressed in more detail in the "General discussion."

General discussion

The hypothesis that metric frameworks stabilize sensorimotor syncopation was tested in three experiments that required participants to tap their finger in antiphase with structured and unstructured metronomic tone sequences. The structured sequences contained accents that occurred regularly (in accordance with various metric schemes) or irregularly, and the unstructured sequences were composed exclusively of heavy (accented) or light (unaccented) beats. Greater performance stability—i.e., lower tap timing variability—was observed when tapping with metric sequences than when tapping with heavy beat (Experiments 1 and 2) and irregular sequences (Experiment 2). The detrimental effects of heavy beats and irregular accents persisted even when participants were instructed to use metric grouping strategies under these conditions (Experiment 3). Furthermore, evidence of meter-based higher-order periodicities in tap timing were found only with metric sequences. Although these findings are consistent with the hypothesis that metric structure facilitates stable syncopation, questions are raised by the additional findings that performance was similarly stable in metric and light beat conditions (Experiments 1 and 2) and more stable in the light beat condition than in the heavy beat condition (Experiment 3; and tendencies toward this in Experiments 1 and 2). We address these questions before discussing the proposed relationship between metric frameworks and stable syncopation.

Regarding the commensurate levels of performance stability for metric and light beat sequences, it was already argued in the context of each experiment that the presence of physical accents may have generally augmented tap timing variability, thus counteracting the benefits of metric structure somewhat. Another possibility, also mentioned earlier in brief, is that a latent metric grouping process may have surreptitiously benefited syncopation with light beats. However, this proposal is challenged by the finding that the explicit instructions to use metric grouping in Experiment 3 left no trace of meter-based higher-order periodicities in the autocorrelation structure of the tap series. To account for this absence, it was suggested that metric grouping may have been applied too inconsistently—due to problems such as losing count—to be picked up by the autocorrelation analysis. Indeed, syncopation is a relatively difficult motor task that is attentionally demanding (Mayville, Jantzen, Fuchs, Steinberg, & Kelso, 2002) and, hence, may interfere with the ability to keep count.

The advantage observed with light over heavy beats in Experiment 3 is potentially interesting in its own right (although the corresponding effect fell short of statistical significance in Experiments 1 and 2). The light beat advantage implies—along with the finding that tap timing was more variable with heavy beats than with metric sequences—that increased beat salience leads to unstable syncopation. Heavy beats were created by sounding a low-pitched tone (or two such lower tones in Experiment 2) simultaneously with the high tone used to articulate light beats. This manipulation affects several parameters of the sound signal, making heavy beats louder, more spectrally complex, and lower in fundamental frequency than light beats. It is conceivable that any one of these qualities serves to increase the perceptual intensity of the signal, thereby enhancing beat salience and the potency of the in-phase mode as a dynamical attractive state. In any case, the present findings imply that stability of syncopation is jointly influenced by whether or not physical accents are present, and, if they are, whether or not these accents occur regularly.

We now turn to the hypothesized relationship between metric frameworks and stable syncopation, which is the main topic of the current study. The two major findings that are relevant to this issue are that performance was more stable in metric than in heavy beat and irregular conditions, and that higher-order periodicities reflecting the metric grouping of taps were found only in metric conditions. So far we have described these results separately, which begs the question: How directly is high performance stability related to the use of metric grouping? We address this question now by describing the results of an inter-experiment analysis that examined the degree of correlation, across individual participants, between tap timing variability and evidence of meter-based grouping. This analysis included data only from Experiments 1 and 3 because there is little overlap between the participant samples from these experiments (the exception being one participant, whose data from Experiment 3 were excluded).

Before conducting the correlational analysis, the degree to which individual participants employed metric grouping strategies was estimated by developing an index based on the autocorrelation coefficients from the metric conditions in Experiments 1 and 3. This index was calculated in two steps. The first step followed the logic behind the contrasts used in the ANOVAs reported in the context of the experiments. For each participant:

a) The mean lag-2 coefficient in the triple and quadruple conditions was subtracted from the mean lag-2 coefficient in the duple condition
b) The mean lag-3 coefficient in the duple and quadruple conditions was subtracted from the mean lag-3 coefficient in the triple condition
(c) The mean lag 4 coefficient from the duple and triple conditions was subtracted from the mean lag-4 coefficient in the quadruple condition

In the second step, the resultant three values were averaged to give an overall metricality index, reflecting how much autocorrelation evidence of metric grouping each participant showed. The relationship between metric grouping and performance stability was then assessed by measuring the strength of the correlation between participants' metricality indices and their mean CV of asynchronies from metric conditions. The result of this analysis is clearly in favor of a direct relationship between metric grouping and performance stability. Metricality indices and the mean CV of asynchronies are negatively correlated ($r = -.52$, $N = 16$, $p < .05$), indicating that participants whose tapping contained more evidence of metric grouping had lower overall timing variability. As pointed out earlier, this result is remarkable because metric grouping introduces variability of its own. This systematic form of variability is discussed next, with particular emphasis on how it may provide clues leading to the mechanism that underpins the relationship between meter and stable syncopation.

The higher-order periodicities observed in syncopated tapping with metric sequences indicate that taps following accented tones were delayed relative to taps following unaccented tones. It is an interesting question whether these momentary fluctuations in tap timing reflect the operation of a regular phase-resetting mechanism. One finding that supports the idea of phase resetting based on higher-order periodicities is that the observed timing delays rely on an anticipatory process: They occurred when accents were regular, hence predictable, but not when accents were irregular, i.e., unpredictable. However, although anticipatory, these meter-based timing deviations appear not to be based entirely on participants' intentions, as they did not occur under instructions to use mental grouping in the absence of physically accented tones (i.e., in the light beat conditions in Experiment 3).

The notion of a phase-resetting process that is not entirely intentional is consistent with a growing body of research on both synchronization and syncopation with pacing signals that contain subliminal timing deviations (e.g., Hary & Moore, 1987; Repp, 2001a, 2001b; Repp & Keller, 2004; Thaut, Tian, & Azimi-Sadjadi, 1998). In general, this work has shown that the phase relationship between taps and the pacing signal can be adjusted automatically and without arousing awareness. Here we propose that metric structure may provide the basis of a regular phase-resetting process that operates intermittently to counteract performance instability.

Note that it would be possible to propose an alternative account based on regular adjustments to the *period* of the internal timekeeper underlying movements (see Thaut & Kenyon, 2003). In fact, the higher-order dependencies during continuation tapping observed by Vorberg and Hambuch (1978) demand such an account because of the absence of a pacing signal by which to measure phase. Nevertheless, we favor an account based on phase resetting over one based on timekeeper period adjustment for the current findings (cf. Mayville et al., 2002). Period correction is necessary if a person intends to maintain synchrony with a pacing signal that changes in rate, or if one wants to avoid drift during self-paced tapping. Indeed, it has been shown empirically that the adjustment of timekeeper period—in contrast to phase adjustment—is an intentional process that requires attention (Repp, 2001b; Repp & Keller, 2004). Period correction was not necessary in the current study because tapping was paced by sequences that did not contain rate changes. Furthermore, contrary to Vorberg and Hambuch's (1978) findings with continuation tapping, the intention to use metric grouping strategies was not sufficient to yield evidence of higher-order dependencies in tap timing; regular accents had to be physically present in the tone sequence as well. Note that this carries the implication that phase resetting is more effective with predictable salient (accented) events than with other events. Finally, increasing the timekeeper period at regular intervals would alone be insufficient to maintain antiphase coordination: After making the final tap in one metric cycle, information about relative phase would be required for the system to 'know' by what amount to adjust the timekeeper period in order to produce the first tap of the next cycle at the right time (i.e., the midpoint between the first and second beat). A mechanism that controls relative phase is necessary for stable performance during sensorimotor syncopation; a worthwhile question for future research is whether or not it is also sufficient.

To conclude, we claim that when metric frameworks are invoked during syncopated tapping with regularly structured sequences, higher-level metric group boundaries come to serve as anchor points at which the phase relationship between taps and tones is reset. This routine of regular phase resetting appears to promote relatively stable syncopation by keeping movement timing variability in check. Such a process may help musicians to stay offbeat in contexts that require antiphase coordination between performers.

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