Perception and Production of Syncopated Rhythms

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THE PROCESSING OF COMPLEX, METRICALLY ambiguous rhythmic patterns, of the sort found in much popular music, remains poorly understood. We investigated listeners' abilities to perceive, process and produce complex, syncopated rhythmic patterns. Rhythmic complexity was varied along a continuum, quantified using an objective metric of syncopation suggested by Longuet-Higgins and Lee. Participants (a) tapped in time to the rhythms, (b) reproduced the same patterns given a steady pulse, and (c) recognized these patterns when replayed both immediately and after a 24-hour delay. Participants tended to reset the phase of their internally generated pulse with highly syncopated rhythms, reinterpreting or "re-hearing" the rhythm as less syncopated. High complexity in rhythmic stimuli can thus force a reorganization of their cognitive representation. Less complex rhythms were more robustly encoded than more complex syncopated rhythms in the delayed memory task. Syncopated rhythms provide a useful tool for future explorations of human rhythmic competence.

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RHYTHM PERCEPTION AND PRODUCTION is a pervasive and fundamental feature of human musical activities. Imitation of rhythms and entrainment to an external pulse are both complex sensorimotor abilities, with few parallels in animal behavior (Fitch, 2006; Merker, 2000). Many researchers have proposed theories to partially account for humans' ability to process rhythmic stimuli (Cooper & Meyer, 1960; Desain, 1992; Drake, 1998; Drake & Gérard, 1989; Drake, Jones, & Baruch, 2000; Fraisse, 1978; Large & Jones 1999; Lerdahl & Jackendoff, 1983; Longuet-Higgins & Lee, 1982; Martin, 1972; Parncutt, 1994; Povel & Essens, 1985; Steedman, 1977; Sundberg & Lindblom, 1976). There are also a growing number of empirical studies exploring phenomena of rhythm perception (see, for review, Desain & Windsor, 2000; Gabrielsson, 1987; Krumhansl, 2000). However, the role of syncopation in rhythm perception has received relatively little attention from researchers (Clarke, 1999; Gabrielsson, 1999; Longuet-Higgins & Lee, 1984; Sloboda, 1991; Temperley, 1999), despite a body of empirical work on production of syncopated rhythms and polyrhythms (Ding, Chen, & Kelso, 2002; Handel & Oshinsky, 1981; Mayville, Bressler, Fuchs, & Kelso, 1999; Mayville, Fuchs, Ding, Cheyne, Deecke, & Kelso, 2001; Pressing, 2002; Pressing, Summers, & Magill, 1996; Scholz & Kelso, 1990; Temprado, Zanone, Monno, & Laurent, 1999; Weaver, 1939). The present study examines both the perception and the production of syncopated rhythms as a means of exploring broader phenomena of temporal and rhythmic perception.

We define a rhythm as a temporal pattern of acoustic events "where the events occur with some repetitive structure" (following Windsor & Desain, 2000). In music these events are sounds, such as tones or percussive noises. Most music is organized around an abstract metrical structural framework consisting of strong (accented, or stressed) and weak (unaccented) events occurring at regularly spaced intervals (Handel, 1989). Rhythmic patterns, along with melodic and harmonic patterns, are superimposed on this underlying metrical structure. A rhythmic pattern whose strong accents coincide with the strong positions of the metrical framework is considered unsyncopated, or more colloquially, to be "with the beat." In contrast, a rhythmic pattern whose accented or strong events are placed at weak positions in the underlying metrical structure is termed syncopated or "off beat." Consequently, syncopated rhythms accent some weak positions in the metrical structure while leaving nearby strong positions "empty," or devoid of stress. In this study, which uses 4/4 or "common time" rhythms exclusively, the regular strong positions in the metrical framework are termed

"the pulse." This pulse is typically what listeners entrain to as they tap their foot or dance along with a piece of music (Handel, 1989), and is also colloquially termed the "beat," or more technically the "tactus" (Lerdahl & Jackendoff, 1983).

Importantly, both pulse and meter are abstract concepts, not necessarily present in the auditory signal, but rather inferred by the listener. Thus, even though there is no acoustic event at some pulse locations, a pulse may be perceived. This is also true of the related concept of meter, which allows listeners to group and subdivide pulses into higher order structures. Even an isochronous sequence of identical sonic events (a perceptually "flat" structure) is often interpreted as having hierarchical structure, with some events being perceived as stronger than others (Bolton, 1894). Such cognitive hierarchies are pervasive in human cognition and perception (Simon, 1962, 1972), although this is not necessarily the case in animal cognition or perception (Fitch, 2006; Fitch & Hauser, 2004). Rhythm perception thus provides an interesting domain in which to explore participants' discovery and processing of abstract generalizations based on concrete, temporally organized acoustic stimuli.

The degree of syncopation of a pattern is a measure of the correspondence (or lack thereof) between an *inferred* pulse and *actual* acoustic events. Syncopation is a matter of degree: some patterns are more syncopated than others without there being any absolute categorical threshold when a pattern becomes syncopated. Varying the degree of syncopation thus provides a useful method for experimentally exploring how participants deal with varying degrees of congruity between their cognitive inferences and ongoing perceptual reality.

Longuet-Higgins and Lee (1984; LHL hereafter) proposed a theoretical model for defining syncopation in musical rhythmic patterns, which we adopt here as an objective, reproducible measure of rhythmic syncopation. LHL followed the Western musical tradition of dividing music into "measures," or groupings of pulses. In the present study, all stimuli are based on common time (4/4) measures with four pulses each. To compute the LHL syncopation measure, we first specify the "metrical units" of a 4/4 measure, the highest unit being four beats (a whole note), followed by the half-note division (2+2), then the quarter-note division (1+1+1+1), and so on (see Figure 1). At any of these metrical levels, tied notes or repeated rests are considered as a single longer note: any metrical unit that is made up of all rests, or exclusively of tied notes, is changed to a single rest or a single note, respectively. Each note is then assigned a perceptual "weight" based on its metrical unit. A note or
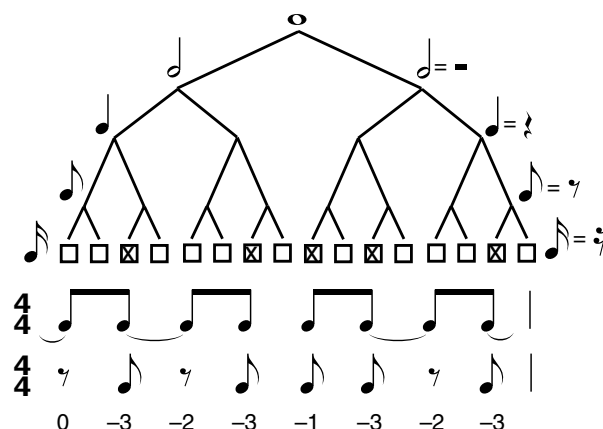

FIGURE 1. A Longuet-Higgins and Lee (1984) rhythm tree with an example rhythm and corresponding event weights. The rhythm has a moderate syncopation index of 5, and is indicated in two equivalent ways in standard musical notation and via Xs in the "box notation" above. The syncopation index value is calculated as follows (following Longuet-Higgins and Lee; see Appendix). Each "box" or event in the rhythmic tree has a pre-specified weight; the greatest weight (0) is assigned to the first event. The next strongest (–1) is on the "three," the "two" and "four" are assigned weights of –2, and each of the "ands" (the off-beat eighth notes) are given a weight of –3. Sixteenth notes receive weight –4, and so on. Syncopations occur when a rest (or tied note) "R" is preceded by a sounded note "N" of lower weight. The difference in weights (R–N) is the syncopation value for each such pair. When a rhythm is produced continuously, the values wrap. In this example, the unsounded first rest, of weight 0, is preceded by a sounded eighth note of value –3, giving the first note a syncopation value of 0 minus –3 or 3. The next sounded note, –3, precedes a rest of value –2, giving a syncopation value of –2 minus –3, or 1. The same applies to the rest on the final beat. Thus the total syncopation value for this rhythm is (–2 – –3) + (–2 – –3) + (0 – –3) = 5. See text and appendix for further details.

rest that initiates the highest metrical unit receives a weight of zero. In any 4/4 measure, this is the whole-note unit, initiated by the first note or rest of the measure. The weight decreases by one for each metrical subunit. Thus, the note or rest that initiates the second half of the measure is weighted –1, and the notes or rests that initiate the second and fourth beats of the measure each are weighted –2.

Once these weights have been assigned, a "syncopation" can be defined. A syncopation occurs when a rest or tied note is preceded by a sounded note of lower weight. The degree of syncopation is equal to the difference in weight between the rest or tied note and the preceding sounded note (Longuet-Higgins & Lee, 1984), and the local syncopation values can be summed to obtain a global measure of syncopation for a rhythmic pattern. This system is able to quantify the degree of syncopation of a rhythm in general accordance with

musicians' intuitions, and thus provides a quantitative framework within which we can empirically examine the effect of syncopation on rhythm perception.

Even without training, humans are, at some level, sensitive to the abstract metrical framework of strong and weak events underlying music (listeners generally tap naturally with the strong events or "on the beat"). When humans hear a passage of music for the first time, they are often able to tap their foot along with the music, or dance to it, whether or not they are musically trained (Drake, Penel, & Bigand, 2000). Syncopated rhythm patterns, by definition, partially conflict with this basic inferred pulse and thus may perturb listeners' cognitive representations of the pulse. When a syncopated pattern is introduced after listeners have already established an internal pulse, they could adopt one of several possible cognitive strategies to process this conflicting information. They could maintain the inferred pulse while simultaneously processing the opposing accent pattern of the syncopated rhythm, maintaining distinct cognitive representations of both patterns as separate "streams" (Bregman & Campbell, 1971). This possibility will be referred to here as "coexistence." Alternatively, listeners might integrate or combine the two patterns into a single, coherent stream. This strategy is termed "assimilation," and is akin to Temperley's (1999, 2001) notion of metrical "deep structure" and the syncopation shift rule: as listeners perceive a syncopated musical passage, they may "form a 'deep structure' representation" that shifts syncopated events forward to unsyncopated positions. This deep structure allows a consistent metrical interpretation of the passage to be maintained, despite a "surface" syncopation (Temperley, 1999). A third possibility is that high levels of syncopation will cause listeners to "reset" their internal representation of the accent pattern in accordance with the accents of the syncopated rhythm, so that the new inferred internal pulse coincides with the strong beats of the syncopated pattern: that is, they "rehear" or reinterpret the pattern as less syncopated by shifting the inferred pulse. This third option is labeled "resetting." The present study was designed to determine if and when these three cognitive strategies are used to process rhythmic stimuli ranging from simple, unsyncopated rhythms to complex, highly syncopated patterns. To address the questions concerning the perception and salience of syncopated rhythmic figures, we implemented two experimental tasks: (1) pulse-tracking and (2) rhythm reproduction.

Syncopated patterns are popular across many musical traditions despite the rhythmic complexity and cognitive conflict these patterns may create. To better understand this popularity, we further investigated the memorability of rhythms varying along the syncopation continuum in two memory tasks: (1) a short-term or "immediate recognition" task and (2) a 24-hour "delayed recognition" task.

In all tasks, participants were presented with rhythm patterns ranging along a continuum from unsyncopated to highly syncopated. In the pulse-tracking task participants heard a pattern, initially accompanied by a pulse, and were asked to continue tapping out the pulse to the pattern after the computer generated pulse ceased. Next, in the rhythm reproduction, task participants tapped the rhythmic patterns just heard, while listening to a computer generated pulse. These two tasks were interleaved, such that pulse-tapping to a particular rhythm was always followed by reproduction of that same rhythm. After completing these tasks for all the study rhythms, the immediate recognition task required participants to listen to rhythm patterns from the previous two tasks as well as similar but novel "foil" rhythms, and to respond whether or not they had heard the pattern previously. Finally, the delayed recognition task was identical to the immediate recognition task, except that it was administered approximately 24 hours after the previous three tasks.

Method

Participants

Sixteen undergraduates (mean age 21.4 years; *SD* = 0.89) participated in all portions of the experiment (six females and ten males; 15 right-handed, 1 left-handed based on administration of the Oldfield, 1971, questionnaire). Participants' musical experience ranged from 0 to 15 years of music training, with 6 participants currently involved in serious regular musical activities. Four additional pilot participants' results (mean age 20 years, *SD* = 0.95; three females and one male; all right-handed) were used to calibrate the difficulty level of the tasks and were excluded from further analysis. All participants signed informed consent forms before participating in the experiment and received either partial credit in an introductory psychology course or $12 in exchange for their participation. The experiments were approved by the Harvard University Committee on the Use of Human Subjects in Research.

Equipment

All stimuli were presented on an Apple Macintosh PowerMac G3 computer (MacOS 9). The pulse-tracking, rhythm reproduction, and recognition tasks were

implemented using custom software written in the freely available SuperCollider (SC 2.2.13) programming language (www.audiosynth.com). Stimuli were output through the computer's built in loudspeaker. Participants' responses were made by tapping on a keypad of a drum machine (Roland TR-505 Rhythm Composer) interfaced with the computer via MIDI (an Apple MIDI interface and Opcode OMS). The programs recorded the timing of participants' responses as well as that of the stimuli to an accuracy of 1 millisecond. The participants' yes/no responses on the recognition tests were made using the mouse to push an onscreen button, and were recorded by the program.

The rhythm subtest of Gordon's (1989) *Advanced Measures of Music Audiation* (AMMA) was administered from a portable compact disc player. Participants recorded their responses to the rhythm subtest by marking a paper answer sheet.

Stimuli

All stimuli were purely synthetic, computer generated sounds. The rhythmic patterns utilized in all portions of the experiment consisted of a single measure of common time (4/4 meter) music containing either four or five notes, where each note was an impulsive, nontonal "click" sound of 20 ms duration (see Figure 1). All rhythm patterns were rated using a "syncopation index" based on the metric described by LHL (Longuet-Higgins & Lee, 1984). The only change to the metric of LHL, made for clarity, is that we stipulate that a completely unsyncopated rhythm receives a syncopation value of zero (in LHL, such a rhythm would receive no value, because it has no tied notes or rests).

The rhythmic patterns were composed manually to give a wide range of syncopation values (0-15). Thirty target rhythms were created ranging from syncopation index zero to fifteen, and these were utilized in the pulse-tracking and rhythm reproduction tasks (see Figure 2 for sample rhythms[1]). For the recognition tasks, fifteen of these familiar target rhythms were selected, as well as fifteen new foil rhythms with syncopation indices that matched the fifteen target rhythms.

In the pulse-tracking task, target rhythms were played with a synthesized midrange "woodblock" sound. Initially, a steady pulse was provided by a low frequency "bass drum" sound while participants' taps were played as a synthesized high frequency "hi-hat." In the rhythm

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[1]All rhythms are available in various forms on TF's website: http://www.st-andrews.ac.uk/~wtsf/rhythmFiles/RhythmFiles.html

reproduction task, the steady pulse was played as the hi-hat, (thus continuing the pulse that the subject had just been tapping), while participants' reproductions of the target rhythms were played using the woodblock sound (as they had been played before, by the computer).

To increase the generality of our findings, three different tempi were utilized for all tasks (either 75, 90, or 105 beats per minute, or in musical terms, *andante*, *moderato*, and *allegretto*). After assessing pilot participants' performance at various tempi, this range of tempi was chosen to determine whether tempo affects perception of syncopation. At 75 bpm the inter-onset interval (IOI) of the pulse is 800 ms (16th note subdivision = 200 ms); at 90 bpm the pulse IOI is 667 ms (16th note IOI = 167 ms); at 105 bpm the pulse IOI is 571 ms (16th note IOI = 143 ms).

Procedure

The experiment was divided into two sessions occurring on two different days (see Figure 3). During the first session, participants completed the pulse-tracking, rhythm reproduction, and immediate recognition tasks. The second session occurred on the following day and included the delayed recognition task and the rhythm subtest of the AMMA. Both rhythms and tempos were presented in randomized orders.

SESSION 1

Participants first read a description of the study outlining the procedure of the two sessions. Participants were allowed to put the book sized MIDI drum pad wherever was most comfortable and to tap with whichever hand they preferred in all portions of the experiment.

In the first portion of the experiment, each trial included both a pulse-tracking, or "beat-tapping," segment and a rhythm reproduction segment. Before beginning the full length task, participants performed two practice trials of these tasks. The experimenter addressed any questions about the pulse-tracking and rhythm reproduction tasks at this point and participants were allowed to repeat the practice trials until they felt comfortable enough with the procedure to begin the full set of trials. No subject repeated the practice trials more than twice.

Participants completed 30 trials of the pulse-tracking and rhythm reproduction task sequence (see Figure 3), each trial with a unique target rhythm. The target rhythms varied in syncopation index from zero to fifteen with each level of syncopation represented at least once. At the start of each pulse-tracking segment, the computer
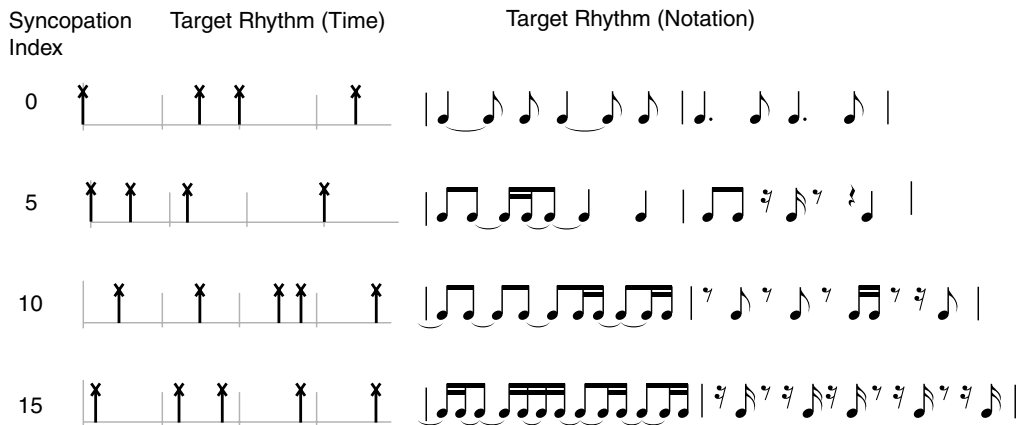
FIGURE 2. Examples of some of the 30 target rhythms used in the tasks, illustrating rhythms at several syncopation indices. On the left the rhythms are notated as events in time, starting at zero seconds (left), with each crossed stick representing a note. The gray timeline indicates the timing of the underlying regular pulses. The same rhythms are presented on the right in music notation in two fashions. Because the acoustic events used to represent these rhythms are percussive and of short, fixed durations, these representations are exactly equivalent.

monitor displayed the instruction to "tap the beat until the rhythm stops." Then participants heard the steady pulse by itself for two measures (eight bass drum beats), after which a target rhythm began. Participants were asked to begin tapping as soon as the pulse began. The pulse and target rhythm continued together for two measures, at which point the computer-generated pulse ceased. Participants continued tapping the pulse until the repeating target rhythm stopped after 46 pulses had elapsed (from 25.7 to 36.0 seconds, depending on the tempo). These durations were chosen, based on the pilot study results, to provide sufficient data and avoid subject fatigue, while maintaining an equal number of data points for each trial.

Next, in the rhythm reproduction segment of each trial, participants read an on screen instruction to "tap the rhythm you just heard" at the tempo of the pulse provided by the computer. Tempos were identical for the target rhythm on the pulse-tracking segment and the immediately following rhythm reproduction segment. Participants then heard the steady pulse for 15 seconds, and were asked to tap the target rhythm for this entire 15 seconds, generating a minimum of two reproduced measures per rhythm per subject.

For each trial, participants' tapping times were digitally recorded for the entire period during which either the pulse or target rhythm was being played.
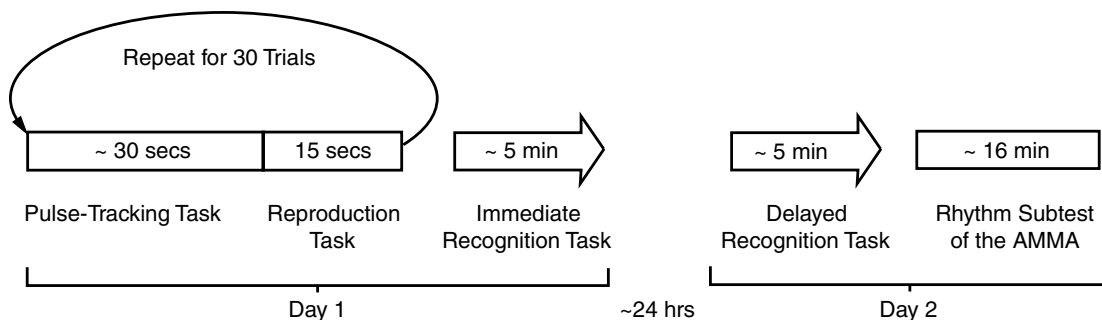

FIGURE 3. Time course of the experiment: Day 1 includes 30 trials of the pulse-tracking and reproduction tasks, plus the immediate recognition task. On Day 2, participants returned to complete the delayed recognition task and the rhythm subtest of the Advanced Measures of Music Audiation.

The complete pulse-tracking and rhythm reproduction portion of the experiment contained thirty trials, one for each rhythm, alternating between the two tasks. Between tasks, and also between trials, there was a one second pause. Participants were informed that there were 30 trials and the current trial number was displayed on the screen. The order of target rhythms and their tempos were selected randomly and were different for each subject. This portion of the session lasted approximately 25 minutes.

After participants completed the first portion of the experiment they began the "immediate recognition" experiment. This consisted of thirty trials, including fifteen familiar rhythms (target rhythms experienced in the previous portion of the experiment) and fifteen foil rhythms. The syncopation indices of the foil rhythms were matched to the syncopation indices of the familiar target rhythms. Each familiar rhythm was played back at the identical tempo at which it was played in the pulse-tracking and rhythm reproduction tasks; the tempi of the unfamiliar foil rhythms were randomly assigned. When the test began, participants read on screen instructions explaining that the computer would play a rhythm for several repetitions. The on screen instructions also asked participants to use the mouse to "click the FAMILIAR RHYTHM button if you recognize the rhythm from the first experiment or click the NEW RHYTHM button if you do not recognize the rhythm." No feedback was given. Again, the trial number was posted on the screen during each trial. Each rhythm was repeated for thirty seconds, or until the subject used the mouse to identify the rhythm as familiar or novel. Because of this self paced element, the duration of the immediate recognition task varied between participants, but generally took no more than six minutes to complete.

SESSION 2

The second session of the experiment took place from 20 to 28 hours after each subject's first session.[2] The first part of this session consisted of the delayed recognition task. The format of this task was identical to that of the immediate recognition task. The same fifteen familiar rhythms (target rhythms from the pulse-tracking task) were used, along with fifteen new foil rhythms with corresponding syncopation indices. The order of the rhythms was again randomized. Tempos of the familiar

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[2]The only exception to this was participant number 11, who completed the second session of the experiment approximately 52 hours after the first session.

rhythms were again consistent with the tempos they had been played at in earlier tasks, while the tempos of foil rhythms were randomly selected. Participants again responded to the rhythms by choosing "familiar rhythm" or "new rhythm" on the screen using the mouse, and their responses were recorded. The delayed recognition task also took about six minutes to complete.

The second part of this session consisted of the rhythm subtest of Gordon's (1989) *Advanced Measures of Music Audiation* (AMMA), designed to assess students' capacity for achievement in music, independent of their musical training or experience. The rhythm subtest of the AMMA consists of 30 paired comparisons of approximately 10-second, computer generated musical excerpts. Participants must decide whether the second excerpt in each pair differs from the first in melody, in rhythm, or not at all. The instructions for the rhythm subtest were on a compact disc, followed by the actual trials of the test. Each subject was given an answer sheet for the rhythm subtest and then followed the instructions given on the compact disc. The entire rhythm subtest took approximately sixteen minutes to complete.

DATA ANALYSIS

Data analysis required some relatively complex preprocessing of the input data, accomplished using a custom comparison and alignment software framework (hereafter, "analysis software") implemented in Hypertalk (Hypercard, Apple Computer) by the authors.

PULSE-TRACKING TASK

The experimental program generated a file with two columns of times for each trial: the "correct" time as predicted by the computer, and the actual time at which the subject tapped. Each tap occupied a single row. The times of participants' taps were first aligned with the temporally closest computer generated pulse by the analysis software. The algorithm shifted the two data columns relative to each other by adding empty rows until each tap was in the same row as the nearest computer pulse. An empty row was left in the column of computer pulses if the subject added an extra pulse, while an empty row was left in the column of subject taps if the subject missed a pulse. Because our interest is in participants' temporal accuracies for correct notes, these missed and extraneous taps were ignored in the subsequent temporal error analysis. For each tap, the error was calculated by comparing the time of the subject's tap and the time of the computer generated pulse (see Figure 4), and then took the absolute value of the difference between these two times. This error was normalized across tempos by dividing the observed
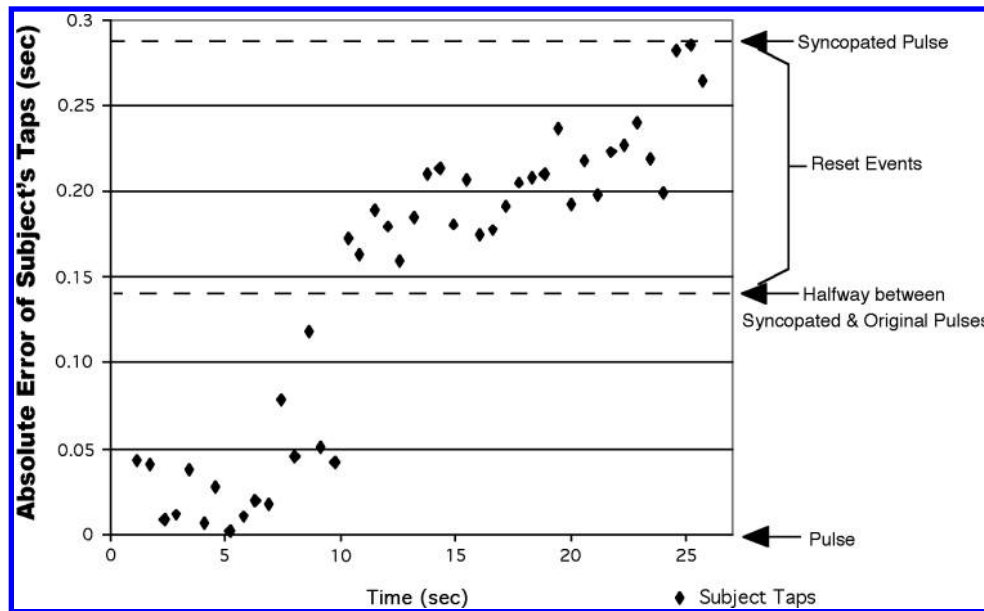
FIGURE 4. The absolute error (in s) of one subject's taps over a single trial; resetting occurs after 10 seconds.

interpulse interval by the correct interval between pulses, generating an error proportional to the correct local interpulse interval. The errors were then subtracted from 1 to convert to normalized accuracy per tap (with 1.0 signifying perfect accuracy). The accuracy per tap was then averaged over the entire trial to generate a mean accuracy per trial for the pulse-tracking task, that was independent across tempos.

The number of "reset" events in each trial was also tallied as a measure of accuracy. A reset event was scored when a subject's tap occurred closer in time to the syncopated pulse (the "offbeat") than to the correct, unsyncopated pulse (the "onbeat"), where the syncopated pulse falls exactly midway between unsyncopated pulses (Figure 5). After the data had been optimally aligned, the number of reset events as so defined was summed for each trial.

RHYTHM REPRODUCTION TASK

In this task, participants heard the pulse and began tapping out the rhythm at an arbitrary starting point determined by the subject. The intervals between consecutive taps of participants' reproductions of the target rhythms were aligned nearly as possible with the correct target rhythm intervals by uniformly shifting the reproduced rhythms by a specified amount. The shift creating the best match between the reproduced rhythm and the target rhythm was calculated via a cross-correlation of the two sets of intervals. The reproduced rhythm was automatically shifted by the computer's "best guess" optimal lag, giving the maximum peak in the waveform of the cross-correlation of the two sets of intervals in most cases. A graphic display allowed the experimenter to verify visually that this shifted rhythm was a reasonable match to the target rhythm. In about one-third of cases this computer estimated match was suboptimal (on average, 11 of each subject's 30 trials), and a smaller cross-correlation maximum yielding a better fit was found instead, by trial and error.

Once the reproduced rhythm was optimally aligned with the target rhythm, the absolute value of the differences between the intervals in the target rhythm and the intervals in the reproduced rhythm was calculated. As before, these interval errors were divided by the correct intertap and interpulse intervals to normalize across different tempos and interval lengths. The reproduction errors were then subtracted from 1 to convert them into accuracy per interval. The reproduction accuracy per interval was then averaged over each trial to generate a mean accuracy per trial for the reproduction task (with 1.0 signifying perfect accuracy).

IMMEDIATE AND DELAYED RECOGNITION TASKS

For both recognition tasks, the number of correct identifications of target rhythms and correct rejections of foil rhythms were summed to give a total percent correct. We also computed a bias free measure of response accuracy (d') following Macmillan & Creelman (2005).
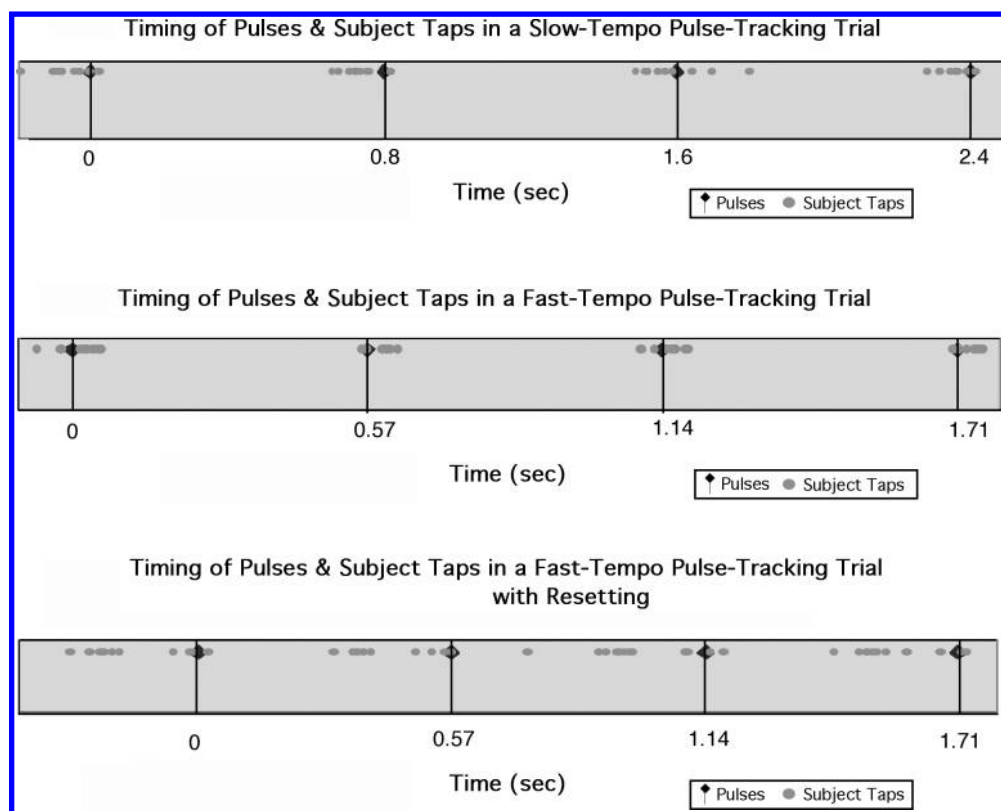
FIGURE 5. Each plot shows a subject's taps (circles) from all 4-pulse periods of a pulse-tracking trial in relation to the correct pulses (vertical lines w/diamond heads). An accurate trial at the slowest tempo (top) using a rhythm with a syncopation index of 3 shows more spread of the subject's taps around the correct pulses than the same rhythm in an accurate fast-tempo trial (middle). A trial with resetting (bottom) shows many taps centered midway between pulses; this trial's rhythm had a syncopation index of 4.

AMMA RHYTHM SUBTEST

Participants' raw scores on the rhythm subtest of the AMMA were converted to percentiles based on the scale calibrated by Gordon (1989) for college students who are not music majors. None of the participants in this experiment were music majors.

Results

Participants readily understood the instructions for the task regardless of their level of musical training. However, even musically trained participants reported that the most highly syncopated rhythms were difficult to reproduce and remember. These subjective impressions were confirmed by the data.

Statistical analyses were performed in Statview 5.0 and JMP 6.0, mainly using parametric statistics. However, due to some deviation from normality in histograms of subject error on each task, all statistics were verified using the equivalent nonparametric statistics,

which gave equivalent outcomes to the parametric tests unless otherwise noted.

Pulse-Tracking Task

This task demanded that participants "tap to the beat," keeping the pulse for each of the 30 rhythms. To analyze the effect of syncopation on accuracy, accuracy in the pulse-tracking task was first averaged across participants for each of the 30 rhythms used. Beat-tapping error on this task was strongly correlated with the rhythms' syncopation indices, $r(29) = .82$, $p < .0001$. Syncopation also led to resettings. The number of reset events per trial was averaged for each rhythm, across participants. The number of reset events per rhythm was strongly correlated with the rhythms' syncopation indices, $r(29) = .78$, $p < .0001$.

Because tempo was randomly assigned to each rhythm, each of our 30 main rhythms was presented at each of the 3 tempi to many participants. We therefore

performed one-way factorial ANOVAs with tempo as the independent variable and beat-tapping error as the dependent variable, and found unsurprisingly that tempo influenced absolute accuracy, $F(2, 477) = 8.37$, $p < .001$, with fast tempi showing lower absolute errors. However, we found no significant effect of tempo on accuracy in this task once accuracy was normalized across tempos, $F(2, 477) = 0.15$, $p = .86$. A two-way ANOVA on tempo-normalized error with syncopation level and tempo as independent variables revealed no main effect of tempo, $F(2,432) = 0.66$, $p = .52$, a strong main effect of syncopation level, $F(15, 432) = 4.76$, $p < .0001$, and no significant interaction, $F(30, 432) = 1.20$, $p = .22$. Thus, it was significantly harder for participants to tap the pulse with syncopated rhythms, regardless of the tempo at which they were presented.

Rhythm Reproduction Task

Accuracy on trials of the reproduction task, where participants tapped out the target rhythm to a computer generated pulse, was averaged across participants for each rhythm. Again, playback error on this task was significantly correlated with the rhythms' syncopation indices, $r(29)= .51$, $p < .005$. Increasingly syncopated rhythms are thus reproduced less accurately. Accuracy on the reproduction task for each rhythm was also significantly correlated with accuracy for the same rhythm on the pulse-tracking task, $r(14) = .65$, $p < .01$. ANOVA results suggested that, in this task, tempo did have a minor effect on participants' normalized error, with accuracy being lower at slow tempi, $F(2, 447) = 3.33$, $p < .05$; however, this was not significant by the Kruskal-Wallis nonparametric test, $H(2) = 5.95$, $p > .05$.

Recognition Tasks

The mean percent correct on the immediate recognition task (53%) was not significantly better than chance (50%) by a one sample t-test, $t(15) = 1.15$, $p =.27$. In contrast, participants' percent correct on the delayed recognition task 24 hours later (63%) was significantly better than chance, $t(15) = 4.89$, $p < .001$,[3] and significantly better than participants' percent accuracy on the immediate recognition task, $t(15) = 3.47$, $p < .01$. This result was not due to a change in response bias: when we computed a bias free measure of response accuracy (d') following Macmillan & Creelman (2005, p. 21), we still

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[3]Due to experimental error, only 14 of the 15 distractor rhythms in the delayed recognition task could be included in the analysis.

found a significant difference in accuracy as measured by d' [paired t-test, $t(15) = 2.614$, $p < .05$], and no significant difference in calculated bias [beta; paired t-test), $t(15) = 0.48$, $p =.64$]. Thus, surprisingly, participants were better able to recognize the target rhythms after a 24-hour delay than immediately after the experiment.

The percent accuracy for each rhythm on the delayed recognition task was negatively correlated with its syncopation index, $r(14) = .58$, $p < .02$. Increasing syncopation thus decreased recognition performance.

The percent accuracy for each rhythm on the delayed recognition task showed a significant correlation with average accuracy per rhythm on the pulse-tracking task, $r(14) = .61$, $p = .016$. It also showed a borderline negative correlation with the number of resets per rhythm in the pulse-tracking task, $r(14) = .72$, $p = .05$, though this correlation was nonsignificant using a nonparametric Spearman correlation, rho $= −.41$, $p = .12$.

Musical Aptitude and Activity

Participants' performance on the rhythm subtest of the AMMA was strongly correlated with accuracy on the reproduction task, $r(14) = .77$, $p <.001$. There was a trend toward a negative relationship between participants' performance on the rhythm subtest and their number of reset events in the pulse-tracking task, $r(14) = .47$, $p =.07$. Musical activity had surprisingly little effect on experimental performance. Participants were divided into two groups based on whether they currently participated in any sort of regular musical activity, such as singing, instrumental music, or dancing ($N = 10$ musically inactive; $N = 6$ musically active participants). The only statistically significant finding was that musically active participants had significantly less error on the reproduction task than musically inactive participants [t-test assuming unequal variances, $t(9.47) = 2.27$, $p = .048$]. However, this result was not significant with a nonparametric Mann-Whitney U test, ($U = 12.00$, $p = .08$).

Discussion

This experiment was designed to determine how syncopation affects listeners' perception and production of rhythmic stimuli, and how well rhythms with varying levels of syncopation are encoded in listeners' memories. Participants' accuracy in tapping the beat along with the target rhythms decreased as the rhythms' syncopation indices increased. This finding supports the hypothesis that, because syncopated rhythms have an accent structure in opposition to the pulse, listeners

have more difficulty in maintaining an internal representation of the pulse in the presence of even moderately syncopated rhythms. Participants were significantly more likely to switch from tapping the pulse to tapping closer to the syncopated, offbeat pulse (termed "resetting") for more syncopated target rhythms, suggesting that participants shift their inferred pulse to match the implied syncopated pulse with moderately or highly syncopated rhythms. In reproducing the target rhythms immediately after tapping along with them, participants were again less accurate at higher levels of syncopation. This indicates that these rhythms were either more difficult to encode in participants' memories, harder to retrieve from memory for reproduction, or just more difficult to perform. In general then, participants' accuracy decreased for more syncopated target rhythms.

Participants performed significantly better than chance on the delayed recognition task, the day after their initial exposure, but not on the immediate recognition task. Less syncopated rhythms proved significantly easier for participants to recognize in the delayed recognition task. Also, the more participants tended to reset the pulse when tapping with a rhythm, the less likely they were to correctly recall that rhythm in the delayed recognition task. This suggests that rhythms that encourage pulse resetting are more difficult to encode and/or recall after a 24-hour period. Furthermore, rhythms that were played more accurately on the reproduction task also tended to be identified more accurately on the delayed recognition task. This indicates that rhythms that are easier to reproduce motorically may be easier to encode perceptually and/or recall. Finally, our results also showed a relationship between rhythmic aptitude, as measured by the rhythm subtest of Gordon's (1989) *Advanced Measures of Music Audiation* and performance on our experimental rhythmic tasks.

Longuet-Higgins & Lee's Syncopation Metric

The results of this study indicate the general psychological relevance of Longuet-Higgins and Lee's (1984) theoretical model of syncopated rhythms. In the pulse-tracking, rhythm reproduction, and delayed recognition tasks the index of syncopation of each rhythm according to the LHL metric was a strong predictor of participants' performance. As syncopation index increased, participants' average performance decreased in accuracy. In general, more syncopated rhythms were judged to be more difficult to perceive and produce by musicians, and different measures of complexity agreed in assigning increasing complexity to increasingly syncopated rhythmic figures. Thus, at least

for the stimuli used in our study, the LHL metric seemed to accurately rank the relative levels of syncopation in accord with both musical intuition (upon which their original discussion was based) and experimental results.

The occurrence of resetting for more syncopated rhythms supports Longuet-Higgins and Lee's (1984) hypothesis that in choosing a rhythmic interpretation for a given note sequence, listeners will construe the sequence as unsyncopated if possible. By reference to this aspect of LHL's cognitive model, participants' resettings in the pulse-tracking task can be seen as attempts to reinterpret syncopated rhythm patterns as less syncopated, by inferring a new, phase shifted pulse. The impetus for this predilection for unsyncopated rhythms may be a preference for less complex environmental stimuli in order to simplify perceptual processing. However, this hypothetical predilection for simplicity leaves open the question of why syncopated rhythms are pervasive in many musical genres (see below).

Complexity of Syncopated Rhythms

Our findings indicate that syncopated rhythms are more difficult to play back and remember than unsyncopated rhythms. However, a plausible alternative perspective is that the rhythms used in our study increased in some more general aspect of complexity, not just syncopation. For example, Shumulevich and Povel (2000a, 2000b) discuss several distinct complexity metrics and their relation to subjective judgments of rhythmic complexity. The LHL syncopation index utilized in our experiment appears to correspond to their categories of hierarchical, dynamic, and generative complexity. An evaluation of our rhythms under other complexity measures would clarify the extent to which variation in complexity explains the syncopation levels of our rhythms, but would require an experimental design expressly designed for this purpose, using stimuli in which syncopation and alternative measures of complexity vary independently. Lacking this data, we can conservatively term the rhythms utilized in this study as more or less rhythmically complex, where "complexity" encompasses both regularly increasing syncopation strength (which we quantified) and other potential factors that remain a topic for future study.

Coexistence, Assimilation and Resetting:
Processing Strategies for Complex Rhythms

The cognitive strategy of "resetting," proposed above, entails shifting one's cognitive representation of the pulse from agreement with the original intended pulse,

or beat, to agreement with the syncopated pulse, or off-beat (Warren & Gregory, 1958). We found a significant positive relationship between the syncopation index of a rhythm pattern and the occurrence of resettings.

According to Bregman and Campbell (1971) and Bregman (1990), regularly recurring auditory stimuli may be grouped together into a perceptual "stream" based on the similarity of their onset intervals. Such a stream often implies a single source for the associated elements (Bregman, 1978). In accordance with Bregman and Campbell's "primary auditory stream segregation" hypothesis, when stimuli with a different temporal structure are introduced, the novel rhythms will be separated into their own perceptual streams, and attributed to distinct sources. Greater differences in perceived stimulus qualities (e.g., temporal variation, frequency, intensity, duration) increase the probability of stream segregation (Bregman, 1978; Jones, Kidd, & Wetzel 1981).

In our study, the pulse presented to participants at the beginning of every pulse-tracking trial consisted of acoustically uniform, evenly spaced acoustic events, presumably perceived as a single auditory stream. Bregman and Campbell's (1971) model predicts that rhythmic patterns whose strong and weak events generally maintain the accent structure of this pulse stream (i.e., rhythms with low syncopation indices) may be integrated with this pulse stream relatively easily. We call this cognitive strategy "assimilation." In contrast, rhythm patterns whose strong and weak events do not preserve the inferred accent structure of the pulse stream (i.e., patterns with moderate or high syncopation indices) may be segregated into a different stream and thus attributed to a second independent source. In these terms, one of the hypothesized strategies for perceiving rhythmically complex patterns, "coexistence," can be defined as the simultaneous perception of two distinct auditory streams, with independent, out-of-phase metrical structures. Gestalt psychology generally holds that only a single stream of perceptual information can be attended to at any given time (Koehler, 1947; Moore, 1989). However, recent research on "integrative attending" supports the idea that at least for some listeners, such as trained musicians and conductors, multiple streams may be simultaneously processed, even if a single stream is perceptually dominant (Keller, 1999). The coexistence strategy, involving such multiple stream parallel processing, would allow listeners to maintain awareness of both the original pulse and the novel complex rhythm as two separate streams.

Our results suggest that, in principle, either coexistence or assimilation strategies can be used by participants to maintain the intended original pulse with less complex rhythms, even in the absence of a sounded pulse. But when highly syncopated stimuli were presented without the pulse, many participants demonstrated "resetting," a third possibility for interpreting a complex rhythmic figure. Streams of auditory information containing inconsistent perceptual information (specifically, conflicting information concerning accent structure) are difficult to assimilate into a single stream. Two such distinct streams are difficult to attend to simultaneously, and one perceptual stream dominates conscious awareness. Resetting allows the subject to "rehear" or re-interpret the syncopated rhythm as less syncopated, assimilating it to the novel inferred "pulse" or hearing the two as coexistent. Subjectively, this strategy converts the pattern from seemingly complex and difficult to seeming simpler and easier to play. Note however that the pattern itself is identical: it is the inferred metrical alignment that changes.

A single integrated stream may be more easily encoded in memory than the two separate streams evoked by rhythms with opposing pulse structures. In addition to reducing listeners' cognitive load, a single integrated stream would also contain more unambiguous information emphasizing the (shared) accent structure. This added information on the accent structure may make it easier for participants to match less complex encoded rhythms with their replayed counterparts in the delayed recognition task.

Clocks, Context, and Cognitive Effort

A complementary perspective on our results stems from work on "beat induction": the formation of a subjective "internal clock," that provides a temporal context when listening to rhythmic stimuli (Povel & Essens, 1985), analogous to our inferred pulse. Povel and Essens found that rhythmic patterns with fewer accents coinciding with the pulse (i.e., syncopated rhythms) induced weaker internal clocks, and that patterns that generate robust internal clocks are reproduced more accurately. Thus, our participants' decreased accuracy in reproducing more complex rhythms may have been due to the poor formation of an internal clock with which to organize complex rhythms. Several previous experimental studies demonstrate that complex rhythms are more difficult to process. For example, studies with synchronization tasks utilizing only a steady pulse indicate that maintaining or transitioning to the offbeat pulse requires increased cognitive effort (Scholz & Kelso, 1990), cortical resources (Mayville et al., 1999), and attention (Temprado et al.,

1999). Our finding of resetting at higher levels of rhythmic complexity implies that listeners have difficulty maintaining the accent structure of the original pulse when the auditory representation of the pulse is absent and a pattern with a conflicting accent structure is present. Similar results were obtained by Mayville et al. (1999) using simple isochronous tapping. Their participants were provided with a regular auditory pulse and were instructed to tap exactly halfway between consecutive pulses (i.e., to produce an offbeat "syncopated" pulse). When the increasing tempo reached a critical point, participants were unable to maintain the internal offbeat pulse, and they reset their tapping to synchronize with the sounded, "unsyncopated" pulse.

Complexity and Rhythmic "Dissonance"

In most musical styles, syncopation is less persistent than in the syncopated stimuli in this study, and the unsyncopated pulse is often either perceptually present or implied, keeping listeners from resetting their internal pulse representation. On the other hand, the conflict between syncopated and unsyncopated accent structures may engender a certain amount of ambiguity and tension in the listener, increasing with the degree and persistence of syncopation and complexity. Thus, particularly in rhythmically complex musical styles (e.g., many African, Afro-Caribbean, and Brazilian styles), syncopation provides an alternative dimension in which tension and resolution can be employed for musical effect. This concept is analogous to the phenomenon of tonal dissonance, in which certain intervals between musical pitches generate a perceptual "roughness" which, if persistent, is often unpleasant to listeners. However, variations in tonal dissonance in music create rich emotional texture and mood, with the resolution of the dissonance releasing the tension created (see, e.g., Jackendoff & Lerdahl, 2006; Lerdahl & Jackendoff, 1983). Analogously, rhythmic dissonance in the form of syncopation and rhythmic complexity may also create tension that is resolved by a return to unsyncopated, simpler rhythms and the original accent structure (Krebs, 1987, Temperley, 2001). Such rhythmic tension and release, implemented at various time scales, offers an independent and complementary dimension for musical innovation and expression.

The validity of this concept of "rhythmic dissonance" could be experimentally examined by tracking physiological responses (e.g., heart rate, galvanic skin response and/or EEG amplitude) during the tasks of the present study. Oléron and Silver (1963) hypothesized that changes in music that disrupt listeners' motor responses lead to a perception of tension with physiological consequences. In accordance with this finding, Sloboda (1991) examined physical reactions to music and found that "racing heart," associated with anxiety and/or tension, was typically linked to syncopation. Syncopated rhythms, by emphasizing a different accent structure, thus appear to elicit tension in listeners. Our hypothesis of rhythmic dissonance predicts that listeners should experience heightened physical arousal when tapping the pulse with more complex rhythms. Most interesting, this arousal would presumably decrease again with resetting, as participants would have resolved the apparent rhythmic dissonance by "re-hearing" the pattern as less complex.

Delayed Recognition & Auditory Memory Consolidation

The improvement on the recognition task from the immediate to the delayed condition was a surprising outcome. Participants failed to identify target rhythms above chance level immediately after they had heard all of the rhythms, yet when participants returned approximately 24 hours later, they were able to recognize some rhythms at a level significantly greater than chance. One reason for this improvement may simply have been that participants were listening to the familiar rhythms for the second time in the immediate recognition task and for the third time in the delayed recognition task, possibly allowing enhanced encoding of these rhythms.

However, part of the next day improvement may be explained by the effects of sleep dependent memory consolidation (Walker & Stickgold, 2004). In various procedural memory tasks, skill improvement relies on sleep processes and is independent of circadian changes, additional practice, or the mere passage of time. Auditory learning has also been connected to sleep dependent changes in memory consolidation (Gaab, Paetzold, Becker, Walker, & Schlaug, 2004; Fenn, Nusbaum, & Margoliash, 2003) and attentional focus (Atienza, Cantero, & Stickgold, 2004). The post-sleep memory enhancement observed in the present study involved declarative recall of discrete auditory episodes (a "familiar" or "unfamiliar" decision), rather than performance on a procedural task (e.g., reproduction accuracy). However, these episodic memories may have been encoded via motor tasks (the pulse-tracking and reproduction tasks), and sleep-dependent processes may have enhanced not only participants' learning of the novel motor tasks performed during the study, but also participants' explicit memories for the stimuli involved. Paradigms similar to those used in the studies cited above (see Stickgold, James, & Hobson, 2000) may

be useful in further exploring the possibility of sleep dependent effects on memory for rhythm patterns. Tasks from the present study might be utilized to first compare performance across a period of wakefulness to performance across an equal period including sleep to ascertain whether sleep-dependent processes are involved in improvement on the pulse-tracking, rhythm reproduction, and/or recognition tasks.

Conclusions

The present study documented several noteworthy phenomena in human perception of complex syncopated rhythms. More complex and syncopated rhythms proved more difficult for participants to reproduce and recall, and resetting was reliably elicited in a behavioral setting by rhythms rated as more syncopated by the metric of Longuet-Higgins and Lee (1984). The findings of the present experiment indicate that the study of syncopation is a fertile area for future exploration, providing an arena for the experimental study of both musical production and perception, where synthetic stimuli can be generated that vary in precisely quantifiable fashion. The current study paves the way for use of additional subject populations and additional experimental techniques (such as EEG, functional neuroimaging, and physiological measures of emotion or attention). More generally, our results suggest that syncopation can provide a powerful conceptual and empirical tool for exploring human rhythm perception and temporal processing.

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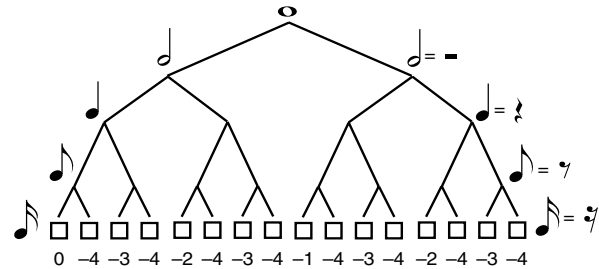
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Appendix
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Calculating the Syncopation Index

Our measure of syncopation is derived from the work of Longuet-Higgins and Lee (1984), whose definition of "syncopation" and calculation of "syncopation strength" we adopt. Our syncopation index is simply the sum of the strengths of all the syncopations in a given rhythmic pattern.

1. **Weight Values:** Each note or rest in the grid is given a weight value of zero or less (there are no positive weights), with each binary division of the metrical tree subtracting one from the weight. Specifically, assuming 4/4 time ("1 ee and a 2 ee and a 3 ee and a 4 ee and a . . .") these are calculated as follows and summarized in the figure:
    a. The largest level notated (the "1," which initiates the whole note representing an entire 4/4 measure) is given weight 0.
    b. The next level (the "3," initiating the half note on beat 3) is given the next smallest weight, −1. Note that one can think of both the 1 and the 3 as having weight −1, but the largest weight always "trumps" any lower weights assigned to that slot by smaller subdivisions.
    c. The next level—the quarter notes on "2" and "4" (the "up beats") receive the next smallest weight, −2.
    d. The next level—the eighth notes on the "and" of each beat—receive weight −3.
    e. The next level—the sixteenth notes on the "ee" and "a" of each quarter, receive weight −4.
    f. And so on ad infinitum (although we never used note values smaller than a sixteenth in our experiments).
2. **Syncopations:** Syncopations occur when a rest (or tied note) is preceded by a sounded note of lesser weight. Given a rest of weight R and a preceding sounded note of weight N, a syncopation occurs when $N < R$, and the **strength** of the syncopation is given by $S = R − N$. Thus, if a rest on the "3" of a 4/4 phrase (weight $R = −1$) is preceded by a note on the "2" (weight $N = −2$), that represents a syncopation value of 1. (Because −1 minus −2 = 1).
3. **Grain of Analysis:** The value of the smallest note or rest value in the pattern determines the "grain" of the analysis. If the smallest weights sounded are −3 (eighth notes), the grain is −2, which means that you only have to consider rests at locations of −2 or greater weight. You don't have to consider rests at the next smallest weight (e.g. −3), because these cannot be preceded by notes of a smaller weight.
4. **Algorithm:** Given these preliminaries, the calculation of LHL index is simple:
    i. Set *Total* to zero
    ii. For each rest (weight R) at the current grain of analysis:
        Find the preceding sounded note (weight N)
        If $N < R$ then:
        Strength = R − N
        Add *Strength* to *Total*

Rhythmic tree showing weight values for each note/rest "slot." Such a tree can be used as a template for calculating a syncopation index by hand, by marking each slot where a note is sounded.

NB:

1. If a rhythmic pattern is repeated, as in our experiments, the rhythm "wraps around." That is, the "preceding notes" defined in the algorithm above could come from later in the rhythm when it is written as a single bar. Put differently, if the first event in a repeated rhythm is a rest, the predecessor notes come from the end of that rhythm.

2. A single sounded note, say on an eighth note, can lead to two (or more) following rests being syncopated. Thus a repeated 4/4 rhythm that had a single sounded note, on the "2" (weight −2) would represent a syncopation for both the following "3" (weight −1, therefore a syncopation of 1) and for the "1" (which is weight 0–2, giving a syncopation value of 2). The total syncopation index then includes both of these, and is 3.