Effects of tempo, swing density, and listener's drumming experience, on swing detection thresholds for drum rhythms

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Swing, a popular technique in music performance, has been said to enhance the "groove" of the rhythm. Swing works by delaying the onsets of even-numbered subdivisions of each beat (e.g., 16th-note swing delays the onsets of the second and fourth 16th-note subdivisions of each quarter-note beat). The "swing magnitude" (loosely speaking, the amount of delay) is often quite small. And there has been little investigation, using musical stimuli, into what swing magnitudes listeners can detect. To that end, this study presented continually-looped electronic drum rhythms, with 16th-note swing in the hi-hat on every other bar, to drummers and non-drummers. Swing magnitude was adjusted using a staircase procedure, to determine the magnitude where the difference between swinging and not-swinging bars was just-noticeable. Different tempi (60 to 140 quarter-notes per minute) and swing densities (how often notes occurred at even-numbered subdivisions) were used. Results showed that all subjects could detect smaller swing magnitudes when swing density was higher, thus confirming a previous speculation that the perceptual salience of swing increases with swing density. The just-noticeable magnitudes of swing for drummers differed from those of non-drummers, in terms of both overall magnitude and sensitivity to tempo, thus prompting questions for further exploration.
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I. INTRODUCTION

The *pulse* of a musical rhythm is typically a repeating series of periodic beats (e.g., "1 2 3 4, 1 2 3 4," and so on), either contextually implied or overtly indicated by note onsets. These beats may be considered as having *durations* (the inter-onset intervals from one beat to the next) that define the tempo of the passage. A beat can be divided into smaller intervals called *subdivisions* (or *divisions*). For example, if each beat has quarter-note duration, then it can be divided into two eighth-note subdivisions or four 16th-note subdivisions. Beats are often assumed to be equally divided, so that, for example, both eighth-note subdivisions of a quarter-note beat have the same duration (specifically, half the duration of the beat). But in actual performance, unequal subdivisions are often used (Barton *et al.*, 2017; Friberg and Sundström, 2002).

Swing, a popular technique in music performance, creates unequal subdivisions by systematically delaying the onsets of even-numbered subdivisions. For example, *eighth-note swing* delays the onset of each even-numbered eighth-note subdivision (i.e., the second eighth-note subdivision of each quarter-note beat), and *16th-note swing* delays the onset of each even-numbered 16th-note subdivision (i.e., the second and fourth 16th-note subdivisions of each quarter-note beat).

Figure 1 illustrates how "straight" subdivisions (subdivisions without swing) differ from "swinging" subdivisions. The black and gray rectangles represent odd- and even-numbered subdivisions, respectively. The width of a given rectangle indicates the duration of the corresponding subdivision. Note that the overall tempo of the straight and swinging versions is the same, because the mean duration of subdivisions (represented by the symbol m throughout this paper) is the same. But in the swinging version, because the onsets of the even-numbered subdivision onsets are delayed by amount d (relative to the straight version), unequal subdivisions are created: the odd-numbered subdivisions are lengthened by d, and the even-numbered subdivisions are shortened by d. The quantity represented by d is what the present paper calls *onset displacement*, defined as the absolute time delay of an even-numbered subdivision's onset from when it would have occurred if no swing had been applied. Or equivalently, onset displacement is half the difference in duration between odd- and even-numbered subdivisions.

Swing has been celebrated in the musicological literature for creating a pleasurable, propulsive sense of "groove" that both implies and inspires physical movement (Benadon, 2006; Butterfield, 2011; Frane, 2017). But how swing creates that experience in the listener is not well understood. One explanation is that swing clarifies and reinforces the pulse by helping to distinguish odd-numbered subdivisions from even-numbered subdivisions (Iyer, 2002; Temperley, 2004). For instance, in Fig. 1, consider the black notes as marking the onsets of beats in the pulse. In the swinging version, the pulse is emphasized and easier to locate because the pulse-marking ("on-beat") subdivisions are longer, and thus distinct from the other subdivisions. By contrast, in the straight

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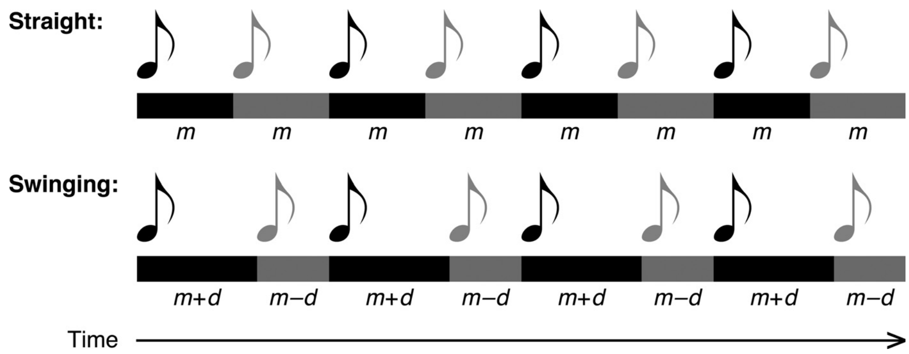

FIG. 1. Straight subdivisions and swinging subdivisions. The black and gray rectangles represent odd- and even-numbered subdivisions, respectively. The black and gray notes are played at the onsets of those respective subdivisions. *m* represents the mean duration of subdivisions (i.e., the mean inter-onset interval). *d* represents the onset displacement (i.e., the delay of an even-numbered subdivision's onset in the swinging version relative to the corresponding onset in the straight version).

version, there are no inherent durational cues to help the listener keep track of where the pulse is in a continuous string of notes (though other cues may be present).

In regard to jazz, some authors and musicians have used the word *swing* in a looser sense, to refer to a general aesthetic (i.e., a "feel") that may involve additional features besides unequal subdivisions (Prögler, 1995). However, the present paper uses the term *swing* only in the stricter sense. It is also important to note that although the word *swing* is often associated specifically with jazz, swing as a feature of rhythm is prevalent in many genres of music (Câmara, 2016; Frane, 2017; Friberg and Sundström, 2002; Houle, 1987, p. 86).

A. Quantifying swing magnitude

Swing magnitude can be quantified by two principal metrics. One metric is onset displacement, i.e., the absolute time delay of an even-numbered subdivision onset (as defined in Sec. I). The other is *swing ratio*, defined as the ratio of an odd-numbered subdivision's duration to an even-numbered subdivision's duration (Friberg and Sundström, 2002). The two metrics are related by the following formula:

$$\text{swing ratio} = \frac{\text{odd subdivision duration}}{\text{even subdivision duration}} = \frac{m+d}{m-d}, \quad (1)$$

where m is the mean duration of subdivisions and d is the onset displacement.

Figure 2 illustrates the relationship between swing ratio and onset displacement at different tempi. For any given tempo, there is a one-to-one correspondence between the two metrics. And when onset displacement is 0, the swing ratio is always 1. But for any positive onset displacement, the corresponding swing ratio increases as tempo increases (i.e., as m decreases).

Thus, swing ratio and onset displacement represent swing magnitude in fundamentally different ways: swing ratio describes a temporal discrepancy in *relative time* (and thus, scales to beat-duration and to tempo), whereas onset displacement describes a temporal discrepancy in *absolute time*. For instance, playing an audio recording of a swinging rhythm at half-speed would double the onset displacement (and all other absolute time intervals), but would not affect the swing ratio (or any other relative timing). Because rhythm perception appears to involve both relative ("beat-based") and absolute timing mechanisms (Grahn, 2012; Teki *et al.*, 2011), it is arguable that when swing is present, neither swing ratio nor onset displacement alone adequately describes swing magnitude (at least when tempo is unspecified).

B. Swing ratios used by drummers

Several studies have analyzed the swing ratios used by musicians in recorded music. For the purposes of the present paper, results regarding drumming are the most relevant. Friberg and Sundström (2002) analyzed multiple excerpts from each of six classic jazz albums, and found that eighth-note swing ratios in the ride cymbal increased from roughly 1 to 3 on average, as tempo decreased from roughly 300 to 120 quarter-note beats per minute (BPM). Dittmar *et al.* (2015) obtained similar results from an automated analysis of

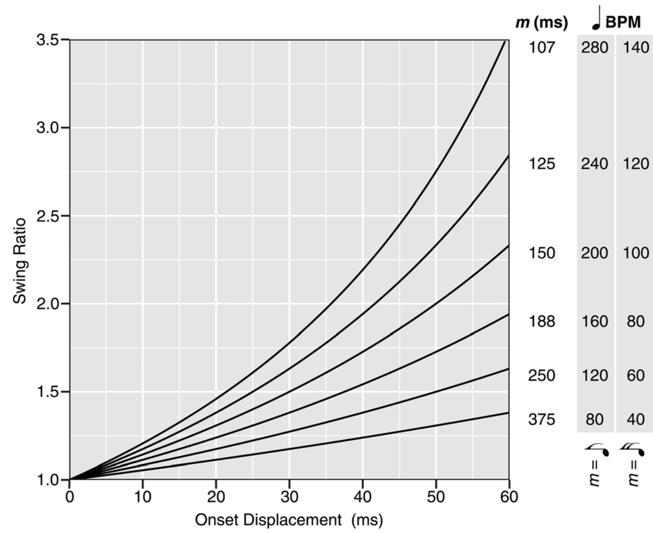

FIG. 2. Swing ratio as a function of onset displacement at different tempi. To the right of each curve is the value of *m* (mean duration of subdivisions) corresponding to the given curve. To the right of each value of *m* is the tempo (in quarter-note BPM) corresponding to the given value of *m* when swing is at the eighth-note level (i.e., when *m* represents the mean duration of eighth-note subdivisions). To the right of that value is the tempo corresponding to the given value of *m* when swing is at the 16th-note level (i.e., when *m* represents the mean duration of a 16th-note subdivision).

hundreds of jazz recordings. For analyses of live jazz drumming in the laboratory, see Collier and Collier (1996) and Honing and Haas (2008).

Câmara (2016) examined excerpts from 13 funk and jazz-funk recordings (roughly 90–130 BPM), and found that drummers primarily used 16th-note swing ratios between 1.0 and 1.3. Similarly, Frane (2017) found that 16th-note swing ratios between 1.0 and 1.3 predominated among 30 classic "drum breaks" (mostly 80–100 BPM) that have frequently been sampled in hip-hop recordings. Neither Câmara nor Frane found a notable correlation between tempo and swing ratio. One thing revealed by all the studies mentioned in this section is that drummers often use swing magnitudes that are quite small (i.e., swing ratios near 1 and onset displacements near 0).

C. Swing detection thresholds

Although several studies have examined the swing magnitudes used in music performance, there appears to be little empirical literature, using musical stimuli, on *swing detection thresholds*, i.e., the magnitudes at which swing becomes noticeable to the listener. Nonetheless, a few studies have explored listeners' detection thresholds for swing-like patterns, using conventional psychoacoustic stimuli (for a review, see discussion of "cyclic displacement" by Friberg and Sundberg, 1995, p. 2526).

The most thorough study of that type (ten Hoopen *et al.*, 1994) measured detection thresholds for "anisochronous duple rhythm" (which is analogous to swing), using monaural and interaural presentation of white noise bursts. It is interesting that interaural presentation resulted in much higher thresholds (i.e., much lower sensitivity to anisochrony), but for present purposes it is sufficient to describe only the monaural results. Using the *method of limits*, the researchers tested four subjects (all of whom were authors on previous studies by the lab) and found that for monaural presentation, mean onset-displacement thresholds were roughly 19 ms for values of m between 100 and 300 ms. The researchers then conducted a series of additional small-sample experiments, using either the *method of constant stimuli* or the *method of single stimuli*, with students (or a combination of students and authors) as participants. Results varied across experiments, and even within experiments standard deviations were high (higher than the corresponding means in some cases). But generally speaking, for monaural presentation, mean onset-displacement thresholds were 7–13 ms when m was 60–300 ms, and increased with m when m exceeded 300 ms.

Based on those and other results, Friberg and Sundström (2002) proposed two rough heuristics: one based on onset displacement (for smaller values of m), and the other based on swing ratio (for larger values of m). Specifically, for $m < 250$ ms, the *just noticeable difference* (JND) in onset displacement was estimated to be 10 ms, implying that the onset-displacement detection threshold (the JND from an onset displacement of 0) is also 10 ms. And for $m > 250$ ms, the JND in swing ratio was estimated to be 10%, implying that the swing ratio detection threshold (the JND from a swing ratio of 1) is 1.1. However, it is plausible that thresholds would be higher for more authentic musical stimuli (Butterfield, 2011), which are typically more varied and more complex. Indeed, numerous studies suggest that in general, the more varied the acoustic features (e.g., intensity, spectra) of the events within a pattern, the poorer temporal discrimination becomes (David *et al.*, 2014; Divenyi and Danner, 1977; Grose *et al.*, 2001; Penner, 1976; Phillips *et al.*, 1997; Woods *et al.*, 1979).

One study (Friberg and Sundberg, 1994) measured swing detection thresholds using an overtly musical stimulus (specifically, a synthesizer melody) though only at a single tempo (170 BPM, which for eighth-note swing corresponds to $m = 176$ ms). The mean threshold was a roughly 1.2 swing ratio, but measurements varied widely. Altogether, there has been very little research on swing detection thresholds for musical stimuli, let alone for drum rhythms specifically.

D. Swing density

A subdivision, as the term is used in this paper, is not a note. Rather, it is a temporal interval occupying a particular location within the pulse, i.e., a particular position on a theoretical time-grid. Thus, for example, each quarter-note beat theoretically contains four 16th-note subdivisions, even if notes are not played at all of those subdivisions. Often only some subdivision onsets are overtly indicated ("marked") by note onsets.

Swing density is the proportion of even-numbered subdivision onsets that are overtly indicated by note onsets in a given passage (Frane, 2017). For example, in the swinging pattern shown in Fig. 1, notes are played at all four even-numbered subdivisions, so the swing density is 100%. However, if the first and third gray notes were omitted, then notes would be played at only two of the four even-numbered (gray) subdivisions in the sequence, so the swing density would be 50%.

Because lowering the swing density lowers the proportion of overtly unequal subdivisions in a swinging sequence, Frane (2017) speculated that a swing's perceptual salience may decrease as the swing density decreases (see also Ikegami and Shigeno, 2016). If lowering swing density does in fact reduce swing's perceptual salience, then one might expect listeners' swing detection thresholds to be higher when swing density is low.

Some types of temporal discrimination have indeed been found to improve when more intervals are available for the listener to compare—a phenomenon that has been called the *multiple-look effect* (Drake and Botte, 1993; ten Hoopen *et al.*, 2004). Although ten Hoopen *et al.* found no multiple-look effect on anisochrony detection thresholds, they had manipulated the number of comparison-intervals by simply extending or truncating the presented sequence, not by adding or removing sounds within the sequence (which would be analogous to a manipulation of swing density).

E. The present study

This study examined the ability of drummers and non-drummers to detect a difference between swinging and straight drum rhythms. Drums were used for the following reasons: (a) drums are presumably more ecologically valid than conventional psychoacoustic stimuli, (b) drums are often the primary timekeeping instrument in modern music, and (c) when sufficiently basic, isolated drum patterns can be relatively genre-nonspecific. The dependent variable was swing detection threshold, estimated as follows: a one-bar (four-beat) drum rhythm was presented in a continual loop, with 16th-note swing in the hi-hat on every other bar, and the swing magnitude was adjusted using a *staircase procedure* until the threshold (the JND between swinging and straight bars) was obtained.

Two independent variables were manipulated: tempo and 16th-note swing density (the proportion of even-numbered 16th-note subdivision onsets overtly indicated by note onsets). Tempo effects were examined largely to establish which metric of swing magnitude (onset displacement or swing ratio) was more stable across tempi; it was expected that onset-displacement JND would be more tempo-invariant, based on the aforementioned heuristics of Friberg and Sundström (2002), which suggest that onset-displacement JND is constant at roughly 10 ms across the values of m used in this study. Swing density was the principal independent variable of interest; it was expected that thresholds would be lower when swing density was higher, due to enhanced perceptual salience.

The grouping variable (drumming experience) was of somewhat lesser *a priori* interest than the independent variables, but was considered important because it seemed intuitive that drummers would be inherently superior at discriminating drum rhythms. Moreover, Ehrlé and Samson (2005) found that in a related task—detecting a single displaced tone in an otherwise isochronous series of tones—percussionists, but not musicians in general, exhibited particularly low thresholds.

II. METHODS

A. Participants

Two groups of participants were recruited: drummers and non-drummers. The drummers were eight males (mean age = 33 yrs) known to the authors, each with at least six years of experience playing drums. The non-drummers were 14 college undergraduates (10 female, 4 male, mean age = 21 yrs) who earned course credit for their participation. The non-drummers reported no experience playing a percussion instrument; five had no experience playing any musical instrument, and the other nine had a mean of 6 yrs experience playing a non-percussive instrument.

B. Stimuli

Rhythms were assembled from individual drum samples, using a MATLAB program. Each rhythm was in 4/4 time, with bass drum on odd beats and snare drum on even beats (a standard pattern in many genres of music). In the high swing-density rhythm [Fig. 3(a)], a closed hi-hat (as struck by a stick) appeared on every 16th-note subdivision except subdivision 16. In the low swing-density rhythm [Fig. 3(b)], a closed hi-hat appeared on every 16th-note subdivision

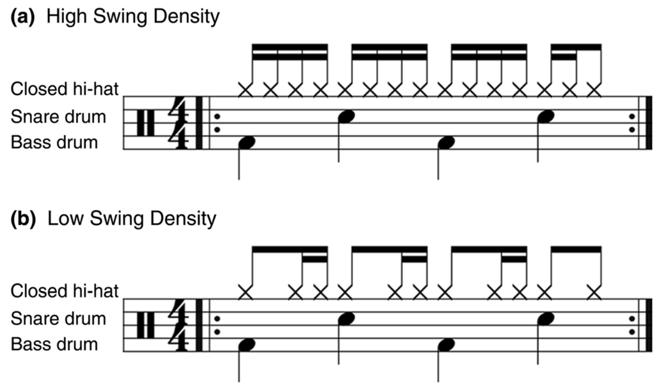

FIG. 3. Rhythms used in the experiment.

except subdivisions 2, 6, 10, 14, and 16. For both rhythms, hi-hat gain was lowered by 6 dB at even-numbered 16th-note subdivisions, producing what the authors judged to be reasonably natural-sounding dynamics. Tempo had five levels: 60, 80, 100, 120, and 140 BPM, which correspond to mean 16th-note inter-onset intervals of $m = 250$, 188, 150, 125, and 107 ms, respectively. Sixteenth-note swing density had two levels: 87.5% ("high") and 37.5% ("low").

To avoid problematic timing inaccuracies during stimulus presentation (Madison and Wallace, 2012), drum patterns were not generated in real time. Instead, prior to each trial, audio data were rendered for all possible versions of the given drum pattern (i.e., for all onset displacements from 0 to nearly m, in 0.5 ms increments), using a 44.1 kHz sample rate. Thus, each bar was presented as a single, premade vector of audio, thereby preventing timing inaccuracies within the bar. The start-time for each bar was controlled in MATLAB, using Psychophysics Toolbox Version 3, which enforced sample-level accuracy (as verified by waveform analysis of test runs).

C. Procedure

The experiment was automated by a MATLAB program and lasted roughly 1 h. There were 20 experimental trials (two for each combination of tempo and swing density), presented in a unique randomized order for each participant, with 1-min breaks every five trials. Afterwards, participants completed a short survey on their musical training and preferences.

Participants were seated in front of a desktop computer in a sound-treated room. In each trial, a rhythm was presented diotically through Sony (Tokyo, Japan) MDR-7506 headphones, in a continuous loop, at roughly 70 dB sound pressure level. The rhythm was straight on odd-numbered bars, and swinging (at the 16th-note level) on even-numbered bars. Because no notes occurred at the last 16th-note subdivision of any bar, the change in swing was not unduly enhanced at transitions between bars.

The computer screen displayed a 1.5×1.5 in. square that was blue during odd-numbered bars (the straight version) and red during even-numbered bars (the swinging version). Participants were instructed to press the left arrow key to decrease the swing in the red-labeled version if they could hear a difference between versions, and to press the right arrow key to increase the swing in the red-labeled version if they could not hear a difference, and to continue this process until the rhythm stopped. In accordance with these instructions, each registered key-press produced a corresponding change in onset displacement in the swinging (red-labeled) version of the rhythm. The straight (blue-labeled) version did not change. Because a given adjustment did not take effect until the following iteration of the swinging version, only one key-press (the last one, in the case of multiple key-presses) was registered per bar. If no key was pressed during a given two-bar cycle, the cycle simply continued, so there was no pressure on participants to make hasty judgments.

Before the experimental trials began, participants completed two practice trials in the presence of the experimenter, who verified participants' understanding of the task. Participants were also told that it was not necessary to fixate on the colored square, and that they should close their eyes if that made the task easier. This instruction was to encourage participants to base their judgments on listening, and not be distracted or biased by the visual cues. In post-experiment interviews, nearly all participants reported that they indeed found the task easier with eyes closed, and that the visual cues rapidly became unnecessary as alternation between versions of the rhythm became established.

In each trial, onset displacement in the swinging version was initialized at $0.44 \times m$, which corresponds to a swing ratio of approximately 2.6 (irrespective of tempo), and which pilot testing had determined was easily distinguishable from a swing ratio of 1 at all the examined tempi. In each trial, the *step size* (i.e., the increment of change in onset displacement invoked by each key-press) was initialized at $0.11 \times m$, which was one-fourth the initial onset displacement and thus sufficiently large to reach near-threshold levels within a few steps (in accordance with recommendations; Cornsweet, 1962; Kingdom and Prins, 2016, p. 130). The step size was halved every time the participant reversed the direction of adjustment, so that the swing magnitude would converge on the JND as the step size decreased (Taylor and Creelman, 1967). Once the step size diminished to <0.5 ms, which occurred after six or seven reversals depending on tempo, the onset displacement was recorded and the trial ended.

This staircase method was chosen over alternative approaches for the following reasons: (a) estimates could be efficiently obtained from a relatively small number of trials, (b) measurement precision was controlled by the designated minimum step size (0.5 ms), rather than left to the participant as in the method of adjustment, (c) participants did not need to explicitly categorize rhythms as straight or swinging, which could be a problematic task—especially for the participants with little or no musical training, and (d) it was clear even to musically inexperienced participants what they were supposed to "listen for," because the difference between swinging and straight versions always started at an easily detectable level and changed incrementally (unlike in the method of constant stimuli).

III. RESULTS

A. Effect of tempo

For each subject, JND for a given combination of tempo and swing density was computed as the mean of the two measurements obtained for that combination. The graphs in Fig. 4 plot that JND as a function of tempo, with black representing high swing density and gray representing low swing density. For each swing density, the mean onset-displacement JND across non-drummers [Fig. 4(a)] was fairly insensitive to tempo, and the corresponding swing-ratio JND [Fig. 4(b)] monotonically increased with tempo. Note that the first statement implies the second. That is, for any positive, constant onset displacement, the corresponding swing ratio monotonically increases with tempo (as evident from Fig. 2). The mean onset-displacement JNDs across drummers [Fig. 4(c)] appeared somewhat sensitive to tempo, though not hugely so. Most notably, JNDs increased slightly as tempo decreased from 100 to 60 BPM, and correspondingly, drummers' swing-ratio JNDs [Fig. 4(d)] appeared nearly flat in that tempo range.

In order to statistically confirm the trends implied by Fig. 4, two repeated-measures analyses of variance (ANOVAs) (one using swing-ratio JND as the dependent variable, and the other using onset-displacement JND as the dependent variable) were conducted for each group, using swing density and tempo (and the interaction of the two) as predictors. For non-drummers (see Table I), the ANOVA results were unequivocal: swing-ratio JND was highly sensitive to tempo and to the interaction, whereas onset-displacement JND was highly insensitive to tempo and to the interaction. For drummers (see Table II), swing-ratio JND was highly sensitive to tempo and to the interaction, and onset-displacement JND was highly insensitive to the interaction—but unlike for non-drummers, onset-displacement JND was sensitive to tempo. Nonetheless, because onset-displacement JND was highly insensitive to tempo for non-drummers, was not hugely sensitive to tempo for drummers, and was not sensitive to the interaction for either group, all remaining statistical comparisons in this paper use onset displacement as the metric of JND, so that effects can be described more simply.

Note that the main effect of tempo on drummers' onset-displacement JNDs does not indicate which specific tempi differed with respect to JND. Therefore, in order to examine the tempo effect in more detail, drummers' onset-displacement JNDs were compared from tempo to tempo, using paired-samples *t*-tests (see Table III). Results suggested that the tempo effect on drummers' onset-displacement JNDs manifests, at least in part, in the 60–100 BPM range (i.e., $m > 150$ ms), where JND increased to a statistically significant extent as the tempo decreased. The *p*-value comparing 100 to 140 BPM was fairly low (0.025) and may reflect a genuine effect, but was not statistically significant after adjustment for multiple comparisons.

B. Effect of swing density

The repeated-measures ANOVAs indicated statistically significant main effects of swing density on onset-displacement

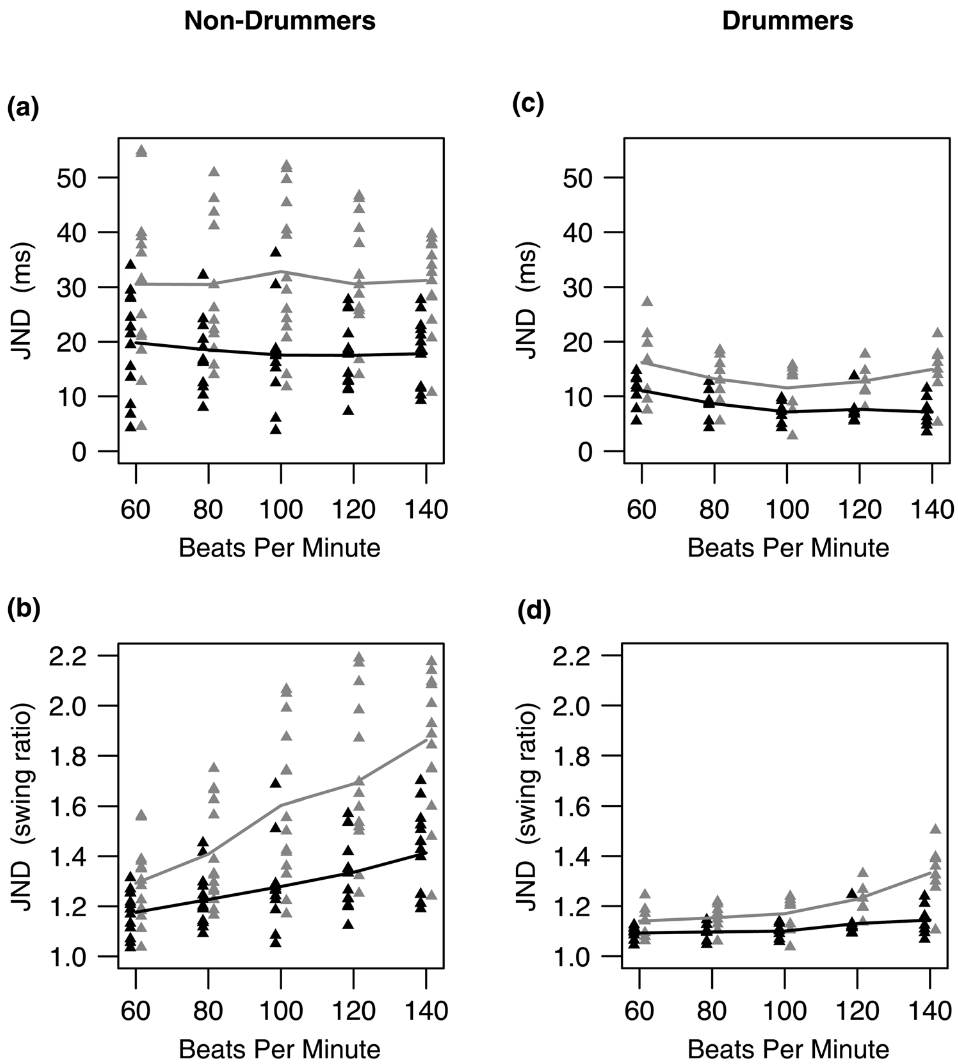

FIG. 4. JND as a function of tempo for high (black) and low (gray) swing density. Triangles represent individual participants' JNDs, and lines indicate mean JNDs across participants. JNDs in the top two graphs represent minimum detectable 16th-note onset displacements. The bottom two graphs show those same JNDs transformed into swing ratios.

JND, both for non-drummers (Table I) and for drummers (Table II). Table IV gives the corresponding descriptive statistics and confidence intervals (CIs), which show that JND was indeed considerably higher for low swing density than for high swing density. In fact, for every participant, the mean JND across tempi was at least nominally higher for low swing density than for high swing density.

C. Drummers versus non-drummers

Drummers' and non-drummers' onset-displacement JNDs were compared using two-sided Welch's *t*-tests. For both low swing density (Table V) and high swing density (Table VI), and at every tempo, JND was higher for non-drummers than for drummers. Variance was also considerably higher among non-drummers, which is to be expected given that drummers' JNDs were lower and thus closer to the floor of possible values (i.e., onset-displacement JND cannot be ≤ 0, so variance around the mean is naturally constrained for means that are only slightly above 0).

Because the groups differed on additional dimensions besides drumming experience, potential confounds should be acknowledged. First of all, drummers were not matched to non-drummers on variables such as age, sex, musical taste, and amount of musical training. Additionally, the drummers may have felt more pressure to perform "well" on

TABLE I. Results from two repeated-measures ANOVAs: one for each metric of non-drummers' JND (the dependent variable).

			Swing-ratio JND		Onset-displacement JND	
Effect	Num. df	Den. df	*F*	*p*	*F*	*p*
Swing density	1	13	47.57	<0.0001[a]	57.53	<0.0001[a]
Tempo	4	52	26.43	<0.0001[a]	0.10	0.983
Swing density × tempo	4	52	6.71	<0.001[a]	0.45	0.774

[a]Statistically significant using a Bonferroni-adjusted alpha level of $0.05/12 = 0.004$, accounting for all 12 tests in the four ANOVA models in this paper (i.e., all tests in Tables I and II).

TABLE II. Results from two repeated-measures ANOVAs: one for each metric of drummers' JND (the dependent variable).

			Swing-ratio JND		Onset-displacement JND	
Effect	Num. df	Den. df	*F*	*p*	*F*	*p*
Swing density	1	7	27.55	0.001[a]	28.28	0.001[a]
Tempo	4	28	27.64	<0.0001[a]	6.24	0.001[a]
Swing density × tempo	4	28	5.30	0.003[a]	0.91	0.473

[a]Statistically significant using a Bonferroni-adjusted alpha level of 0.05/12 = 0.004, accounting for all 12 tests in the four ANOVA models in this paper (i.e., all tests in Tables I and II).

the task, which could have biased their responses or motivated them to try harder, whereas some of the non-drummers may have been less engaged with the task. It is also conceivable that the drummers' talents for temporal discrimination led to their acquisition of drumming experience in the first place, rather than the other way around.

Nevertheless, it is reasonable to assume that drumming experience is at least a key factor explaining the inter-group differences in JND, especially considering that non-percussive musicianship did not appear to strongly influence JNDs. In fact, the Pearson correlations of non-drummers' JNDs with their years playing a musical instrument were negligible, and not even nominally negative on average ($r = 0.16$, $p = 0.594$ for onset-displacement JND, pooling across all tempi and swing densities). That is not surprising, given that Ehrlé and Samson (2005) obtained analogous results for their anisochrony detection task: percussionists had particularly low thresholds and other musicians did not (but see Yee *et al.*, 1994).

IV. DISCUSSION

The present study confirms a previous speculation (Frane, 2017) that the perceptual salience of swing increases with swing density, at least when swing is at near-threshold magnitudes. Indeed, for both drummers and non-drummers, JNDs were considerably higher for low swing density than for high swing density. This may reflect a type of multiple-look effect (Drake and Botte, 1993), in that higher swing density provides the listener a greater number of temporal intervals to compare, and thus a greater number of cues regarding the presence of swing. Another explanation is that low swing density is more complex for listeners to cognitively process. Indeed, psychoacoustic data suggest that temporal discrimination is poorer when the target intervals being compared are adjacent to task-irrelevant intervals (*distractors*) of longer duration (Hirsh *et al.*, 1990), which is similar to what occurred in the low swing-density rhythm, in that eighth-notes (which were not informative regarding the presence of swing) were interspersed among the 16th-notes. A similar effect has been observed when the distractors have a shorter duration than the target intervals (Yee *et al.*, 1994).

The effect of tempo was different for the two groups. For non-drummers, onset-displacement JND was relatively insensitive to tempo, which was predicted given that that m was ≤ 250 ms for all the examined tempi (Friberg and Sundström, 2002). Drummers' onset-displacement JNDs were sensitive to tempo, which was not expected. Most notably, drummers' onset-displacement JNDs increased slightly as tempo decreased from 100 to 60 BPM, and correspondingly, their swing-ratio JNDs were less sensitive to tempo in that range. Perhaps drummers exploited a combination of relative and absolute timing "strategies" (presumably automatic, rather than intentional), making JND slightly more stable as swing ratio across the slower tempi and slightly more stable as onset displacement across the faster tempi—just as is presumed to occur for listeners in general, though the transition is generally thought to occur at slower tempi (specifically, where $m > 250$ ms; Friberg and Sundström, 2002). Future studies using larger sample sizes and additional tempi can evaluate this apparent trend in drummers more conclusively.

As expected, drummers' JNDs were much lower than non-drummers'. Most non-drummers exhibited onset-displacement JNDs (mean = 18 ms for high swing density, 31 ms for low swing density) that were considerably higher

TABLE III. Comparisons of drummers' onset-displacement JNDs (in ms) between tempi, using two-sided paired-samples *t*-tests. JNDs are averaged across swing densities, because the interaction of swing density and tempo was not statistically significant.

Tempi compared (BPM)	Mean difference	95% CI	*p*
60–80	2.7	[0.7, 4.7]	0.017
60–100	4.3	[1.8, 6.8]	0.005[a]
60–120	3.5	[0.3, 6.6]	0.035
60–140	2.6	[−0.2, 5.4]	0.064
80–100	1.6	[0.2, 3.0]	0.034
80–120	0.8	[−1.3, 2.9]	0.392
80–140	−0.1	[−2.4, 2.2]	0.927
100–120	−0.8	[−2.3, 0.7]	0.241
100–140	−1.7	[−3.1, −0.3]	0.025
120–140	−0.9	[−2.4, 0.6]	0.211

[a]Statistically significant using an adjusted alpha level of 0.05/6 = 0.008, which controls the familywise Type I error rate for all ten pairwise comparisons following a statistically significant main effect of tempo.

TABLE IV. Comparisons of onset-displacement JNDs (in ms) between swing densities. JNDs are averaged across tempi, because the interaction of swing density and tempo was not statistically significant.

	Low swing density		High swing density		Difference	
Group	Mean	SD	Mean	SD	Mean	95% CI
Non-drummers	31.1	12.0	18.2	7.3	12.9	[9.2, 16.5]
Drummers	13.7	3.9	8.3	1.6	5.4	[3.0, 7.8]

TABLE V. Comparisons of drummers' to non-drummers' onset-displacement JNDs (in ms) for low swing density, using two-sided Welch's *t*-tests.

	Non-drummers		Drummers		Difference		
Tempo (BPM)	Mean	SD	Mean	SD	Mean	95% CI	*p*
60	30.5	14.6	16.2	6.6	14.3	[4.8, 23.8]	0.005
80	30.5	12.6	13.2	4.4	17.3	[9.5, 25.1]	<0.001[a]
100	32.8	13.7	11.5	4.6	21.2	[12.8, 29.7]	<0.0001[a]
120	30.6	11.3	12.7	3.0	17.9	[11.1, 24.7]	<0.0001[a]
140	31.2	8.3	14.9	4.8	16.3	[10.5, 22.1]	<0.0001[a]

[a]Statistically significant using a Bonferroni-adjusted alpha level of 0.05/10 = 0.005, accounting for all ten between-groups tests (i.e., all tests shown in Tables V and VI).

than the 10 ms heuristic proposed by Friberg and Sundström (2002), and variation across participants was high. By comparison, drummers' onset-displacement JNDs (mean = 8 ms for high swing density, 14 ms for low swing density) were closer to the heuristic on average and were less varied across participants. It is not certain that the observed group differences were due to drumming experience alone, because the groups differed on other dimensions. But even if the differences are better explained by a combination of drumming experience and other factors, the drummers' thresholds can be at least roughly interpreted as thresholds one should expect from a particularly discriminating population of listeners. Note also that although mean JNDs across participants are useful benchmarks for making comparisons, the mean values are not particularly meaningful in themselves, given the considerable variation across participants. Indeed, "typical" JNDs for a population may be more appropriately represented as a range of values than as a mean.

An important limitation of the staircase method used in this study is that it cannot neutralize response bias by adjusting for false detections (*false alarms*, in the parlance of signal detection theory; Tanner and Swets, 1954). False detections (i.e., left arrow key-presses when the onset displacement was zero), occurred only twice in the study and in only one participant (a non-drummer). In those cases, the left arrow key-presses had no effect, but the participant was not alerted that the zero point had been reached.

There are other important limitations of this study that leave questions open for further investigation. For example, very slow tempi, for which swing ratio would likely be a more relevant metric than onset displacement (Friberg and Sundström, 2002), were not examined. Additionally, only hi-hat was directly affected by swing, because other types of events did not occur at even-numbered 16th-note subdivisions. Swing may have different salience when applied to events with longer decay (e.g., ride cymbal) or lower-frequency spectra (e.g., bass drum), or when applied to more than one type of event in a given passage. Other factors are likely to influence swing's salience as well, such as loudness variations between events, variability of the tempo, and variability of the swing magnitude itself (both within and across instruments, when multiple instruments are present).

Last, it should be emphasized that detection of a difference between straight and swinging versions of a rhythm does not imply categorical perception of one version as straight and the other as swinging, and does not imply perception of swing's musical effects (e.g., its propulsive, "groove enhancing" quality). In fact, an onset displacement that is noticeable to someone under laboratory conditions could become perceptually irrelevant—for that same person—under passive listening conditions. Conversely, a person might be capable of "feeling" subtler magnitudes of swing when listening to long passages of music for pleasure than when listening to short passages for an experiment; indeed, to what extent subtle rhythmic features may affect the listener without being consciously recognized remains an intriguing question that is difficult to assess. Altogether, the present study extends some results of previous psychoacoustic studies, empirically confirms the importance of swing density to the perceptual salience of swing, and provokes questions regarding how the mechanisms of rhythm perception may differ for different populations.

TABLE VI. Comparisons of drummers' to non-drummers' onset-displacement JNDs (in ms) for high swing density, using two-sided Welch's *t*-tests.

	Non-drummers		Drummers		Difference		
Tempo (BPM)	Mean	SD	Mean	SD	Mean	95% CI	*p*
60	19.8	9.0	11.0	3.1	8.8	[3.2, 14.4]	0.004[a]
80	18.5	7.4	8.6	2.8	9.9	[5.2, 14.5]	<0.001[a]
100	17.5	8.2	7.1	1.9	10.4	[5.5, 15.3]	<0.001[a]
120	17.5	6.3	7.6	2.6	9.9	[5.9, 13.9]	<0.0001[a]
140	17.8	6.2	7.1	2.7	10.7	[6.7, 14.7]	<0.0001[a]

[a]Statistically significant using a Bonferroni-adjusted alpha level of 0.05/10 = 0.005, accounting for all ten between-groups tests (i.e., all tests shown in Tables V and VI).

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