Systematic Variation in Rhythm Production as Tempo Changes

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We investigated the effect of tempo on the production of the syncopated 3-2 *son* clave rhythm. We recorded eleven experienced percussionists performing the clave pattern at tempi ranging from 70 bpm to 210 bpm. As tempo increased, percussionists shortened the longest intervals and lengthened the shortest interval towards an intermediate interval that is located in the first and second positions in the pattern. This intermediate interval was stable across tempi. Contrary to prior studies, we found that the complexity of interval ratios had little effect on production accuracy or stability and the "short" interval in the pattern was not particularly stable. These results suggest that as tempo is varied, (1) experienced musicians systematically distort rhythmic intervals, (2) rhythmic configuration, and not just the complexity of interval ratios, affects the production of rhythmic intervals, and (3) the distinction between long and short intervals is context-dependent.

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The idea that rhythm is invariant across changes in tempo is both intuitively plausible and supported by research (Hulse, Takeuchi, & Braaten, 1992; Marshburn & Jones, 1985; Repp, Windsor, & Desain, 2002). If it were not invariant, altering the tempo of a rhythm would impair a listener's ability to perceive rhythmic similarity. Composers indicate tempo with words such as *allegro*, which allow rhythms to be played at a variety of speeds. This suggests that some variation in tempo is permissible without affecting musical ideas. Further, in Western musical notation, the representation of a rhythm is unaltered if presented at different tempi (e.g., the rhythmic pattern quarter note - eighth note - eighth note is written the same at 70 bpm and 170 bpm).

In contrast to these notational conventions, research has shown that performers vary the proportions of rhythmic intervals, often towards small integer ratios, in different temporal contexts (Collier & Wright, 1995; Handel, 1992, 1993; Monahan & Hirsh, 1990; Palmer, 1997). Thus, we have a scenario where, as tempo changes, performers produce interval proportions that are close enough to notational ideals to preserve a notion of identity, but whose absolute timings can vary from those ideals in significant ways. The nature of this variation, particularly in the case of musically relevant rhythms, is unclear. Here we address several questions: Is this variation lawful? Is it the case that interval proportions tend towards simple integer ratios? Is the production of an interval affected by its position within a rhythmic configuration?

Interval Ratios

A rhythm is defined by the interonset intervals (IOIs) of its notes (from this point on we will say "interval" to stand for "interonset interval"). In contrast, tone durations, i.e., the duration from the onset to the offset of a tone, have little effect on rhythmic organization (Handel, 1993). In Western rhythmic notation, intervals are represented in proportion to other intervals. For example, in the rhythm notated in Figure 1 the ideal interval between note 1 and note 2 is I_1, the interval between note 2 and note 3 is I_2, and so on. These intervals are used to calculate the ideal ratios between adjacent intervals of the pattern, as shown in the bottom line of Figure 1.

In common practice period European art music and contemporary Western popular music, rhythmic proportions are typically small integers (1:1, 2:1, 4:1, 3:2). Some research has shown that performers assimilate complex interval ratios towards simpler integer ratios. This phenomenon has been called *ratio simplification* (Fraisse, 1956; Franěk, Radil & Indra, 1988; Repp et al., 2002; Repp, London, & Keller, 2005, 2013; see Clarke, 2000, for a review). Furthermore, performers produce simple ratios more accurately than complex ones (such as 2.72:1, 3.33:1, 1.82:1, 1:0.7, 1:0.8, 1:1.1, 1:1.4) (Collier & Wright, 1995; Franěk et al., 1988). This has led some researchers to believe that we perceive rhythmic intervals categorically (Clarke, 1987). This would explain how a small group of rhythmic values can be perceived and produced despite minute temporal variation in the

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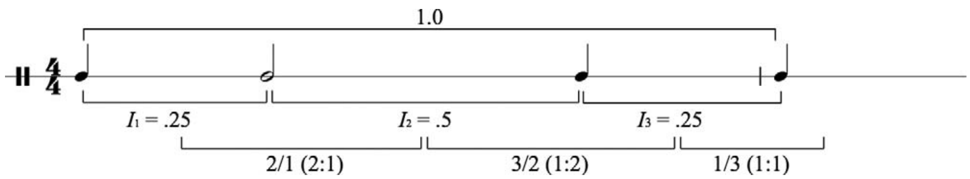

FIGURE 1. A rhythm with proportional durations and adjacent interval ratios. I_i refers to the proportion of time between successive notes relative to the whole pattern in an ideal cyclical performance of the rhythm. n/n-1 refers to the ratio of I_i compared to I_{i-1} with the ratio of the intervals in parentheses.

intervals associated with them. These categorical boundaries tend to be aligned with the prevailing meter of a pattern.

However, some researchers have found that not all interval perception and production aligns with simple ratios. For example, two- and three-note rhythms involving ratios constructed from the integers 1, 2, and 3 are rarely performed according to ideal proportions (Repp et al., 2002). Even trained musicians produce constant errors when asked to perform simple ratios such as 2:1, 3:1, and 4:1 (Collier & Wright, 1995). Musicians systematically distort two-interval rhythms towards a 1:2 ratio (AR: attractor ratio), but the precise value of that AR can be larger than .5 (thus referred to as *upward shift of the attractor ratio,* USAR) (Repp, London, & Keller, 2012). For three-interval rhythms, attractor ratios are close to, but not identical to, the ideal ratios of 1:2:3 and 1:3:2 (Repp et al., 2013). When musicians are asked to notate complex rhythms, they simplify proportional relationships according to rhythmic categories, but the centroids of those produced categories differ from notational ideals (Desain & Honing, 2003). The preference for simple ratios is also not guaranteed: most participants listening to variations of the 2:1 ratio in folk tunes prefer a ratio of ~1.70:1 (Gabrielsson, 1985).

Our problem is challenging because, as Gabrielsson says, the divergences of performers from simple ratios are "neither random nor are they always the same" (1985, p. 70). These divergences may be due to expressive timing and/or stylistic convention. In addition, performers and listeners may not time sub-beat ratios or measure interval proportions precisely. Instead, they measure beat divisions within which they organize sets of "equalities" and "inequalities" according to specific metric contexts, which creates them to diverge from simple ratios (Clarke, 1985). How they do this depends on the notated rhythm, the degree to which the performer is trying to convey "evenness," and the amount of temporal fluctuation that is allowed by the style of the music. Context cannot be ignored.

In summary, the picture of how interval ratios reflect and guide perceptual and production tendencies is not clear. Although performers and listeners transform complex ratios in the direction of simpler ones, they diverge from them in production, identification, and preference tasks.

INTERVAL POSITION

The duration of a produced/perceived interval is affected by the durations of other intervals in a rhythmic sequence. Adjacent intervals affect categorization (Desain & Honing, 1991). For example, given two intervals (t1 and t2) demarcated by three short sounds, the duration of one interval (t2) can be significantly underestimated, a phenomenon called "time shrinking" (Nakajima, ten Hoopen, & van der Wilk, 1991). Furthermore, the order of intervals affects assimilation and contrast in the production of three-interval rhythms (Repp et al., 2013). Even nonadjacent intervals contribute to periodic grouping (Martin, 1972) and may play a role in rhythmic perception and production (Palmer & van de Sande, 1995). With that said, given that experiments typically use either isochronous sequences or relatively short rhythmic patterns consisting of two or three notes, the extent to which nonadjacent intervals affect the production of longer, heterogeneous rhythmic sequences as found in real music has been relatively less explored.

TEMPO

On top of all this, we must consider the possibility that interval proportions are perceived and produced differently at different tempi. Western musical notation does not distinguish between versions of a rhythm played at different tempi. For example, the rhythm in Figure 2 is a 3-2 *son* clave pattern whether it is played at 100 beats per minute (bpm) or 210 bpm. This invariance is analogous to that of melody with respect to key: it is *Frère Jacques* whether it is played in G Major, A Major, or E Major (Dowling & Harwood, 1986; von Ehrenfels, 1890/1988; Wagemans et al., 2012).

Some researchers have found that in adults, rhythmic structure is perceptually invariant across changes in tempo within certain limits (Hulse et al., 1992). For example, in one study participants were able to identify

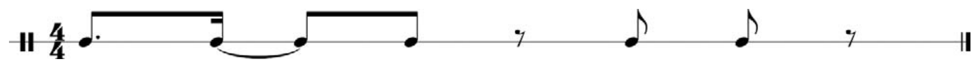

FIGURE 2. The 3-2 *son* clave notated in one measure of 4/4.

four different rhythmic patterns over a range of tempi (Marshburn & Jones, 1985). This extends to production as well: divergence of two-note rhythms involving ratios constructed from the integers 1, 2, and 3 from notational ideals was largely unaffected by changes in tempo (Repp et al., 2002).

And yet it would appear that rhythm perception and production are not always invariant across tempi. The just-noticeable difference for note displacement in a rhythm depends on tempo (in addition to other factors, Monahan & Hirsh, 1990). Similarly, discrimination accuracy (Handel, 1992) and the perception of constancy (Handel, 1993) between nonmetric patterns vary with presentation rate (also see Palmer, 1997, for a review). For simple ratios, performed intervals tend to be smaller than ideals at fast tempi and larger than ideals at slow tempi (Collier & Wright, 1995). The aforementioned produced USAR is more pronounced and consistent at fast tempi (Repp et al., 2012).

Other studies provide conflicting evidence in regard to how performers diverge from the ideal ratios of notated rhythms across tempi. For three-note rhythms constructed from simple ratios, the short interval was produced rather accurately and was stable across tempi while the long intervals showed assimilation that increased as tempo increased (Repp et al., 2002). Performers tend to reduce the "swing ratio" (the 2:1 ratio) of the 3:2:1 rhythm characteristic in jazz drumming at faster tempi (towards 1:1) and increase the ratio at slower tempi (to as much as 3.5:1). At the same time, the short note in this long-short pattern is approximately constant (100 ms) at medium to fast tempi (Friberg & Sundström, 1997). Studies of expressive timing's invariance across tempi, which are beyond the scope of this paper, have produced similarly conflicting results (see Honing, 2007, for a review).

CURRENT STUDY

Most previous research has focused on two or three-note rhythms. Here we study longer rhythms with heterogeneous intervals, which are common in music but rare in experimental settings. Our study focuses on the 3-2 *son* clave pattern, which contains five notes with both simple (such as 1:1 and 1:2) and more complex (such as 3:4 and 4:3) adjacent (Figure 3) and nonadjacent (Figure 4)

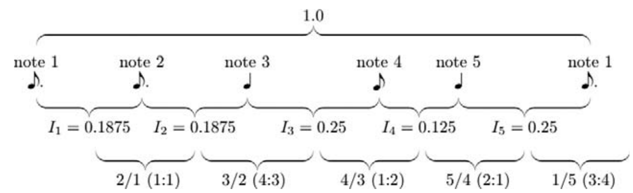

FIGURE 3. The *son* clave with proportional durations and adjacent interval ratios.

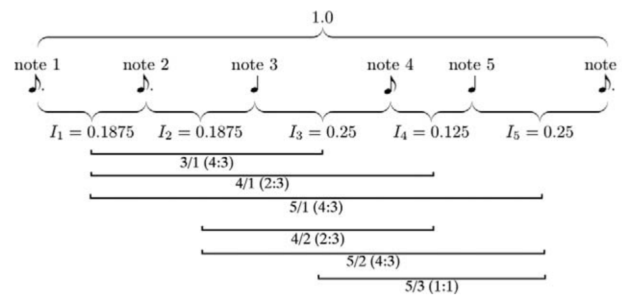

FIGURE 4. The *son* clave with proportional durations and nonadjacent interval ratios. Interval comparisons are indicated under each bracket, e.g. 3/1 (4:3) refers to I_3 in comparison with I_1; (4:3) is the ratio between the two intervals.

interval ratios. Using this pattern we seek to answer two series of questions:

1. What is the effect of tempo on production accuracy and variability of the *son* clave by experienced percussionists? Is this effect consistent among performers? How do the *position* and *duration* of intervals affect performance across tempi?
2. Is performance affected by the *simplicity/complexity* of an interval ratio? Is the effect similar for *adjacent* and *nonadjacent* intervals?

Method

PARTICIPANTS

Twelve experienced percussionists volunteered to participate. We offered them no compensation. We excluded the data of one performer who exhibited a lack of proficiency in performing the 3-2 *son* clave rhythm. Of the remaining 11, two were professional percussionists and nine were undergraduates at Worcester Polytechnic Institute or the University of Virginia.

DESIGN AND PROCEDURE

Before the experiment, the participants confirmed that they were familiar with the 3-2 *son* clave as notated in 4/4 meter (Figure 2). We asked them to perform the clave pattern at 15 tempi, which ranged from 70 bpm to 210 bpm in increments of 10 bpm (which is both a wider range and a greater number of tempi than hitherto used: Handel, 1993; Fitch & Rosenfeld, 2007; Ladinig & Honing, 2011; Longuet-Higgins & Lee, 1984). They played the rhythm in ascending order of tempo. Because of time constraints, four of the participants only finished 11 of 15 tempi (i.e., they did not perform the 80, 90, 110, and 130 bpm tempi).

At the beginning of each performance, the performer listened to a click track at the desired tempo. Each click was a 300 Hz sine wave (attack =1 ms, sustain = 10 ms, release = 10 ms). After hearing eight (two measures) clicks, the clicks were silenced and the participants played the 3-2 *son* clave at the tempo of the clicks. They played the pattern four times (4 measures of 4/4), plus the first beat of measure five (in order to measure the duration of the fourth repetition).

The performers played the rhythms with a drumstick using one hand on either the foam pad of a malletKat MIDI controller (http://www.alternatemode.com/malletkat.shtml) or a hard table (the drumming surface chosen was a function of experiment logistics). We recorded audio and MIDI information and measured the time intervals between drum hits in a program written in Max 5 (http://cycling74.com/products/max/) by one of the authors.

ANALYSIS

All the analyses for this paper were performed with R (R Development Core Team, 2015) using linear mixed models (LMMs), computed using the package lme4 (Bates, Maechler, Bolker, & Walker, 2015). LMMs, which use maximum-likelihood estimation, have many advantages over traditional repeated-measures analysis of variance (ANOVA), which use ordinary least-squares. In addition to providing estimates of fixed effects, they allow us to predict subject-by-subject variations in model parameters (called random effects). Because we are interested not in effects present only at an individual level but rather in generalizable effects, LMMs allow us to partition out differences between individuals and model them jointly as random effects, thus leaving the variance we care about (the generalizable effect) to be explained by the fixed effects. This provides a clear advantage over traditional ANOVA approaches that require prior averaging across subjects and/or items (Baayen, Davidson, & Bates, 2008).

To give us an idea of the absolute fit of our models, we computed two types of R^2 for LMMs using the MuMIn package (Bartoń, 2014). The first, called the marginal R^2 ($R^2_{marg.}$), estimates the proportion of variance accounted for by the fixed effects only, whereas the second, called the conditional R^2 ($R^2_{cond.}$), estimates the proportion of variance accounted for by the fixed and random effects taken together (Johnson, 2014; Nakagawa & Schielzeth, 2013).

Results

We performed the analyses two ways: in the first, we excluded the data of the four participants who did not complete trials at all 15 tempos, and in the second, we included all participants but excluded trials from the four tempos with missing data. As the results were similar for these two data sets, we report the analysis of all participants without the trials for 80, 90, 110, and 130 bpm. This left us with data from 11 participants performing four repetitions of the clave pattern at 11 tempos.

EFFECT OF TEMPO ON PERFORMANCE DEVIATION

Our primary question was whether tempo had systematic effects on the performance of the *son* clave pattern. To answer this question, we fitted a non-additive LMM to predict *performance deviations* (PDs). PDs were defined as the difference (in proportion change) between the *performed intervals* we recorded and the *ideal intervals* of the clave (shown in Figure 2). Our model included tempo (quadratic[1]), interval (categorical), and their interaction as fixed effects, and the subject-by-subject variation of the intercept and the slope of interval as random effects. The model shows a moderate amount of variance explained by the fixed effects ($R^2_{marg.} = .38$). When adding in the variance of the random effects, approximately an additional 15% of variance is explained ($R^2_{cond.} = .55$).

Figure 5 shows the predictions of the model as well as the mean PD at each tempo as estimated by a model that does not constrain the predictions to fall on a quadratic regression line (including a 95% confidence interval). The effect of tempo on PD is clear for all intervals; the effect is predominantly negative for I_3 and I_5, predominantly positive for I_4, and fairly close to 0 for intervals I_1 and I_2. This means that performers lengthened I_4 and shrunk I_3 and I_5 as tempo increased. Therefore, it is the

[1] The quadratic effect allows us to detect any non-linearity in the relation between tempo and PD.

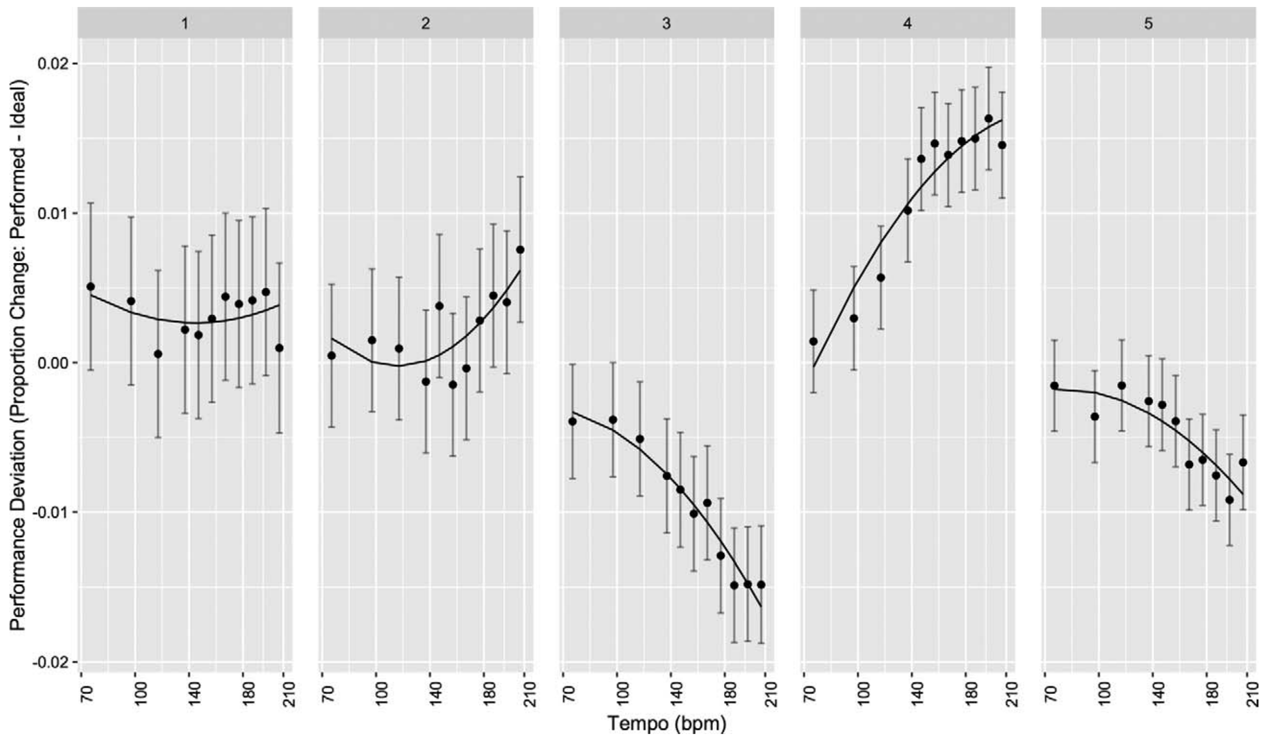

FIGURE 5. Effect plot showing the performance deviation for each of the five intervals of the 3-2 *son* clave pattern (panels) by tempo (*x*-axis). Points and confidence intervals were computed with a categorical model of tempo, whereas model curves were computed with tempo constrained to be a continuous, quadratic predictor. Although I1 and I2 were stable across tempi, performers lengthened I4 and shrunk I3 and I5 as tempo increased.

first two intervals of the pattern (I_1 and I_2) that are the most stable, whereas the intervals later in the pattern deviate from the ideal interval as tempo increases. We also see that the shortest interval (I_4) is not performed more accurately than other intervals. The effect of position seems to outweigh the effect of duration for performance of this particular pattern. Additionally, the small 95% confidence intervals show that the effect was systematic across participants.

Tempo drift. Because the participants performed the four repetition cycles of the clave pattern without a concurrent metronome, we were also interested in overall changes in performance tempo across the four cycles. Figure 6 shows the predictions of the model as well as the mean drift for each cycle and tempo as estimated by a model that does not constrain the predictions to fall on a linear regression line (including a 95% confidence interval). At 70 bpm, participants started at approximately the correct tempo and sped up throughout the four pattern cycles. At 100-140 bpm, participants remained at approximately the correct tempo throughout the four pattern cycles. Above 140 bpm, participants started at increasingly slower tempi and slowed down throughout the four pattern cycles. The confidence intervals show that this effect was relatively stable across all performers.

EFFECT OF TEMPO ON RATIO PERFORMANCE DEVIATION

Our second question was whether the simplicity/complexity and adjacency of interval ratios affects performance across tempi. To answer this question, we found the best-fitting LMMs to predict *ratio performance deviations* (ratio PD). Ratio PDs were defined as the difference (in proportion change) between the performed interval ratios *(performed ratios)* based on what we recorded and the ideal adjacent and nonadjacent interval ratios (*ideal ratios)* of the clave (shown in Figure 3 and Figure 4).

Adjacent ratios. Our model included tempo (quadratic), ratio (categorical), and their interaction as fixed effects, with the same random effects as before. The fixed effects of the model account for a large proportion of the ($R^2_{\text{marg.}}$ = .53). The variance of the random effects accounted for an additional 13% of variance ($R^2_{\text{cond.}}$= .65). The predictions of the model and the mean ratio PD at each tempo (including a 95% confidence interval) are shown in Figure 7. The effect of tempo on PD is

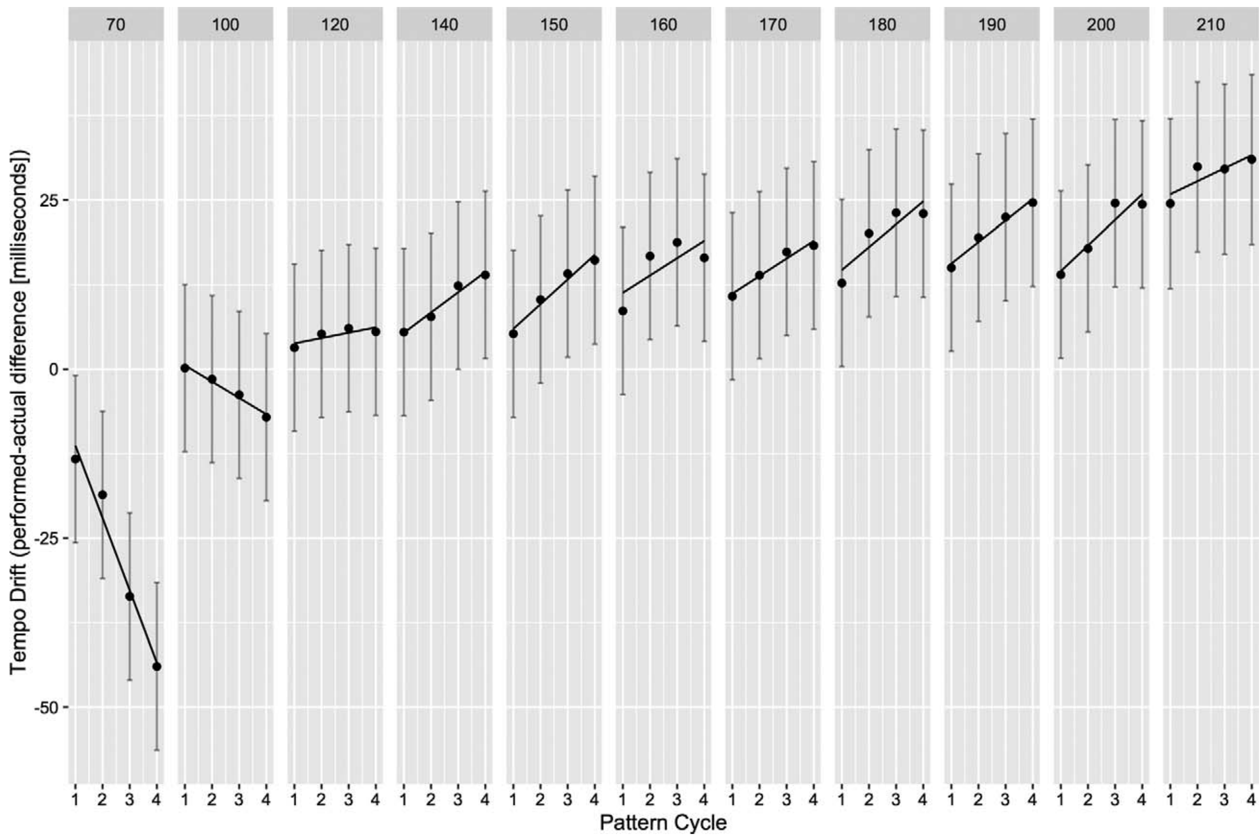

FIGURE 6. Effect plot showing the tempo drift for each performance tempo (panels) by pattern repetition cycle (*x*-axis). Points and confidence intervals were computed with a categorical model of cycle, whereas model curves were computed with cycle constrained to be a continuous linear predictor. Participants generally sped up at 70 bpm, were relatively accurate at 100-120 bpm, and generally slowed down above 140 bpm.

clear for all interval ratios. The effect is predominantly positive for 4/3, predominantly negative for 3/2 and 5/4, and fairly close to 0 for 1/5 and 2/1. This means that performers contract ratios 3/2 (4:3) and 5/4 (2:1) and expand the ratio 4/3 (1:2) as a function of tempo.

Nonadjacent ratios. Because we used the five-note *son* clave pattern, we analyzed performance deviation among nonadjacent intervals as well. As was the case with our analysis of adjacent ratios, our model included tempo (quadratic), ratio (categorical), and their interaction as fixed effects, with the same random effects as before. A fair amount of variance was accounted for by the fixed effects ($R^2_{\text{marg.}} = .22$); an additional 16% of variance was accounted for by the random effects ($R^2_{\text{cond.}} = .38$). We show the predictions of the model and mean PDs (with 95% confidence intervals) in Figure 8. The effect of tempo on PD is clear for all interval ratios. The effect is predominantly negative for 3/1, slightly negative for 5/1 and 5/2 (especially at higher tempi), predominantly positive for 4/1 and 4/2, and slightly positive for 5/3 (especially at higher tempi). This means that performers contract ratios 3/1 (4:3), 5/1 (4:3), and 5/2 (4:3) and expand ratios 4/1 (2:3), 4/2 (2:3), and 5/3 (1:1) as a function of tempo.

Discussion

As tempo increases, experienced percussionists' performance of the 3-2 *son* clave pattern deviates systematically from the expected intervals. This reinforces the view that performers alter temporal intervals as a function of tempo (Collier & Wright, 1995; Friberg & Sundström, 1997; Repp et al., 2002; Repp et al., 2005).

Our percussionists systematically expanded the duration at I_4 and shrunk the durations at I_3 and I_5 as tempo increased. In terms of interval *position*, this means that the first two intervals remained relatively stable at all tempi, whereas the later intervals changed significantly. We believe that the initial interval is stable because of (1) its position in the pattern and (2) that it is immediately repeated. The allows it to act as a reference point or

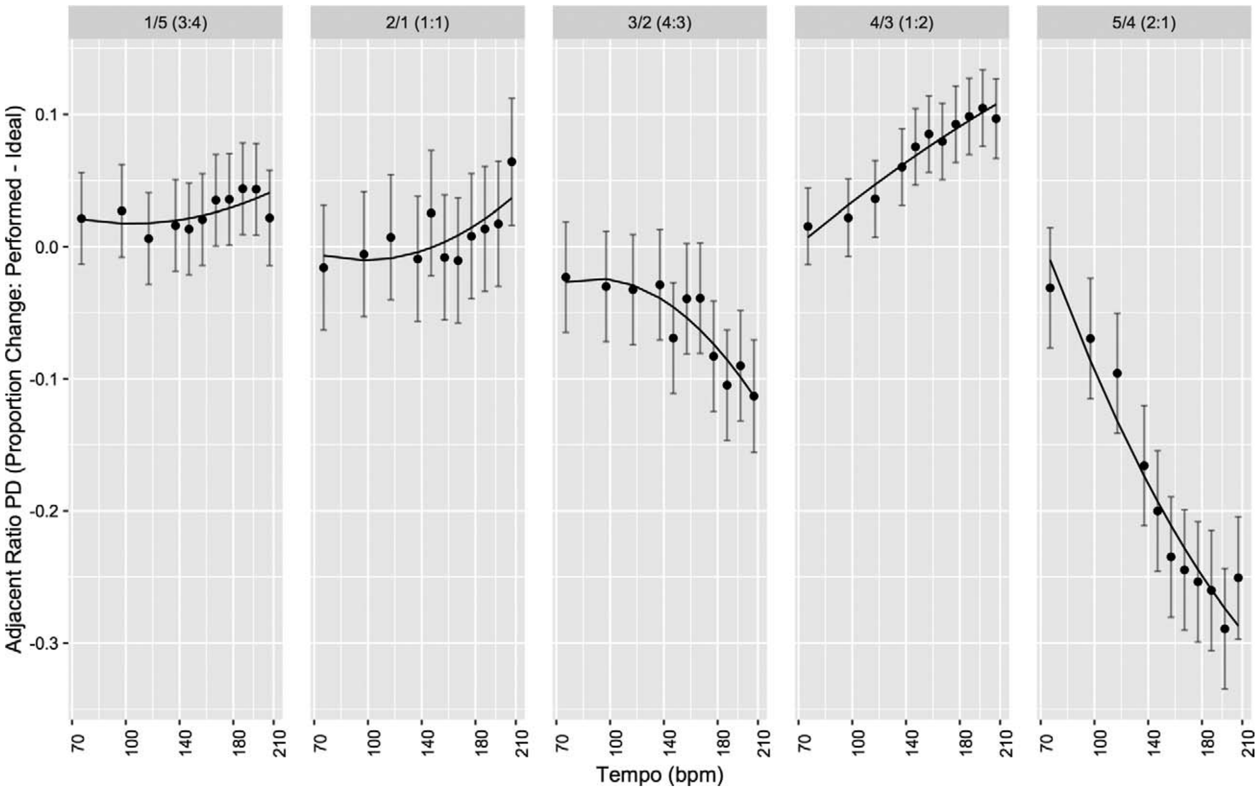

FIGURE 7. Effect plot showing the performance deviation for each of the five adjacent interval ratios (see Figure 3) of the 3-2 son clave pattern (panels) by tempo (x-axis). Points and confidence intervals were computed with a categorical model of tempo, whereas model curves were computed with tempo constrained to be a continuous, quadratic predictor. The effect is predominantly positive for 4/3, predominantly negative for 3/2 and 5/4, and fairly close to 0 for 1/5 and 2/1 as tempo increases.

anchor for the other durations in the pattern.[2] As tempo speeds up, the anchor durations (I_1 and I_2) remain relatively stable while the other intervals (I_3, I_4, and I_5) assimilate towards them.[3]

In terms of interval *duration*, we found that the shortest interval in the pattern, I_4, was expanded significantly, which contrasts with previous research that found the shortest interval in a rhythmic pattern to be stable across tempi (Fraisse, 1956; Friberg & Sundström, 1997; Repp et al., 2002). This lengthening was probably not due to motoric constraints, since the produced intervals at this position were above the 100 ms limit commonly regarded as the floor for metrical intervals (London, 2004). At the same time, the longest intervals contracted as a function of tempo. Thus for the performance of this clave pattern, the extreme intervals tended towards an intermediate proportion featured prominently at the beginning of the pattern.

In regard to interval *simplicity/complexity*, we found that ratio complexity did not affect the accuracy of produced ratios relative to ideal ones for both adjacent and nonadjacent ratios. In fact, some of the simplest adjacent ratios (1:2 and 2:1) were distorted the most as tempo increased. Although it is true that the complex ratios in our pattern (3:4 and 4:3) are less complex than the ones used in previous experiments, our results challenge the notion that the simplest ratios in a pattern are the most stable. The ubiquity of low integer proportions in rhythmic theory may be due to their representational and descriptive convenience, and not their efficacy in characterizing tendencies in rhythm perception or production.

Our results support the notion of assimilation (Fraisse, 1956) as a "central tendency" (Franěk, Mates, Radil, Beck, & Pöppel, 1994, p. 204). However, the assimilation seen here differs from that observed in previous research, which suggests that the short interval of the 3-2 *son clave* (I_4) would be stable whereas the longer

[2] This is distinguished from "a clock with a time unit derived from the sequence" as described by Povel and Essens (1985). Here, 1) the anchor duration is not the shortest unit in the sequence and 2) the anchor duration is one that other intervals gravitate towards, rather than are measured by, across tempi.

[3] Though the actual intervals produced never reach such equilibrium and are thus quite complex (Repp et al., 2002, discuss this tendency similarly).

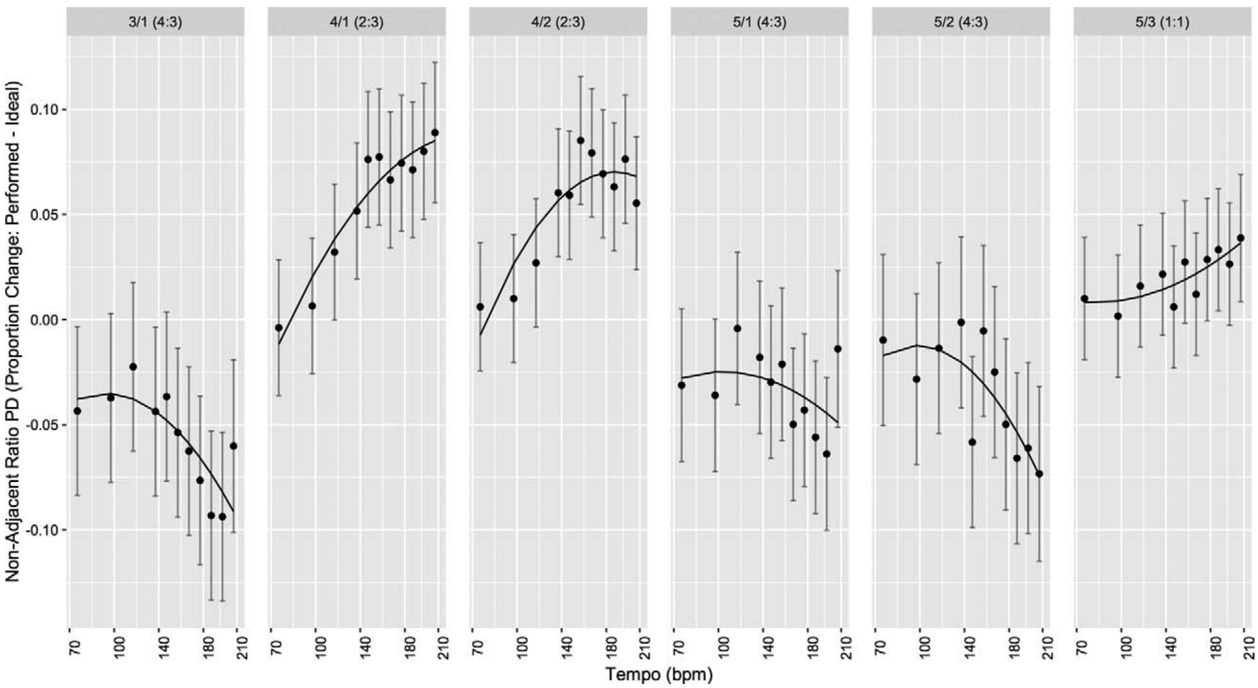

FIGURE 8. Effect plot showing the performance deviation for each of the six nonadjacent interval ratios (see Figure 4) of the 3-2 son clave pattern (panels) by tempo (x-axis). Points and confidence intervals were computed with a categorical model of tempo, whereas model curves were computed with tempo constrained to be a continuous, quadratic predictor. The effect is predominantly negative for 3/1, slightly negative for 5/1 and 5/2 (especially at higher tempi), predominantly positive for 4/1 and 4/2, and slightly positive for 5/3 (especially at higher tempi).

intervals assimilate as tempo increases, maintaining and emphasizing the long/short distinction (Fraisse, 1956; Repp et al., 2002).[4] We do not see this tendency; instead, the long and short intervals converged towards the intermediate interval.

The tempo drift that we observed can also be interpreted as a central tendency towards an intermediate duration (here, the tempo range 100-120 bpm). Below 100 bpm (70 bpm), participants successively sped up. At 100-120 bpm, the tempo was produced most consistently. As tempo increased above 140 bpm, participants both started at increasingly slower tempi and slowed down within trials. This is consistent with previous research that has found 100 bpm / 600 ms IOI to be the rate that is determined to be neither too fast nor too slow and is judged most accurately, thus it is known as the indifference interval (Parncutt, 1994; Wundt, 1911). Thus, both absolute (e.g., the indifference interval) and relative (e.g., other intervals in a pattern) durations influence rhythm production. Separating the contribution of each type of temporal divergence may be a topic for future research.

Our results suggest that the way in which intervals are timed within rhythmic configurations may have less to do with mathematical ideals and more to do with local temporal references. The local position and relative duration of intervals affected how a rhythm was articulated more than the complexity or simplicity of constituent interval ratios as tempo increased. It may be that faster tempi induce beats at higher metrical levels, leaving fewer beats as temporal references, or "metrical attractors," relative to which to orient intervals (Clarke, 1985; Repp et al., 2002; Repp et al., 2013). Performers are then faced with the task of configuring more uneven intervals within a beat period, and thus look for nonmetrical temporal references. Likely references are intervals that are most prominent (because of their position within the sequence

[4] Alternatively, one could argue that as tempo increases, the absolute durations are either generally contained by or gravitate towards Fraisse's (1956) *short* category (200-300 ms). As tempo increases, there are more "short" durations and fewer "long" durations, thus we see assimilation towards a single representative "short" value. This explanation is not totally satisfying as 1) many of the actual produced durations were either < 200 ms or > 300 ms, and thus outside the proposed "short" category boundaries; and more importantly 2) we must be careful to not confuse the idea of a "short" category with the idea that all durations within that category are normalized to a particular value. That is, even if all the intervals produced at the fastest tempi were within the boundaries of the "short" category, this doesn't mean that performers stopped trying to make distinctions between intervals in order to convey the identity of the rhythm.

or the number of times they are repeated, for example), which subsequently influence how other intervals are produced.

Although the findings showed systematic deviations across participants, the generalizability is limited by several factors. First, we only investigated one rhythm pattern; thus, future experiments should vary the meter, the number of notes, the proportion of interval ratios, and the length of patterns. Second, the 3-2 *son* clave contains syncopation, which may have affected how the rhythm was perceived and produced as tempo changed. Third, because there is a relationship between faster tempi and heightened sense of "the groove" (Janata, Tomic, & Haberman, 2012), it is possible that performers' sense of groove changed as tempo increased in this experiment, leading to alterations of produced interval ratios. Fourth, the ways in which rhythms are produced and perceived depends on context. It is an open question how sensitivity to stylistic conventions, performance strategies, expertise, setting (recording studio, concert hall, laboratory, etc.) and materials (full piece, musical excerpt, pseudo-musical temporal configuration, etc.) affect rhythmic production and perception tendencies. Finally, the study reported here focused solely on rhythm performance. It is an open question how performers *perceive* rhythms at different tempi.

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