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Timing deviations in jazz performance: The relationships of selected musical variables on horizontal and vertical timing relations: A case study

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Abstract

The purpose of this study was to examine the effects and relationships of selected musical variables on the horizontal (i.e., successive eighth note timing relationships) and vertical (i.e., the degree of ensemble synchronicity between separate parts) timing properties of jazz rhythm. A total of 949 eighth note samples from five improvised solos by saxophonist Chris Potter were analysed. Musical variables included metrical beat placement, melodic character, intervals, articulation, underlying harmony, and tempo. Results of the simultaneous multiple regression analyses revealed that intervals preceding and intervals succeeding the sample eighth notes had a significant effect on eighth note durations. Articulation had a significant effect on upbeat beat ratio. The relationships between the relative onset timing data of the saxophone, bass, and drums yielded significant results. There was a large, negative correlation between the relative timing onsets of saxophone and bass, a large negative correlation between saxophone and drums, and a moderate, negative correlation between bass and drums. Implications for the fields of music education, pedagogy, and cognitive psychology are discussed.

Keywords

expression, jazz, rhythm, structure, synchronization, temporal, timing

Jazz performance is considered to be a "social process of coordinated innovation with a collective outcome" (MacDonald & Wilson, 2005, p. 397). This process of real-time interactive creativity is driven by group members' shared awareness of experience, knowledge, and procedure (Bastien & Hostager, 1988; Berliner, 1994; Monson, 1996; Sawyer, 1992). Music-making in joint

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contexts requires performers' awareness of individual and group communicative processes (Goebl & Palmer, 2009; Keller, 2008; Wilson & MacDonald, 2012). However, in conversations with practicing jazz musicians, performers emphasize the importance of nonverbal, in-group awareness over individualism (MacDonald & Wilson, 2005). Sawyer (1992) indicates that nonverbal group interaction is a balance of conscious and unconscious processes acting together. Conscious processes (i.e., sympathetic attunement) include responses to syntactical elements of musical knowledge. Unconscious processes (i.e., empathetic attunement) include accordance to collaborative aesthetic judgment (Seddon, 2005). Empathetic attunement has also been described as ensemble "groove" or "group flow" (Berliner, 1994, 1997; Csikszentmihalyi, 1990, 1996; Kenny & Gellrich, 2002; Sawyer, 2006; Wesolowski, 2013a). According to MacDonald and Wilson (2006):

> Given participants' (jazz musicians') claims to have difficulty putting into words what takes place when they improvise... what they experience is essentially non-verbal; to reiterate it in the verbal realm inevitably requires reference to a wider field of psychological description. (p. 72)

The analysis of structural and expressive features of music such as temporal synchronization, therefore, has become increasing popular in the fields of psychology and music performance science, as these features serve as musical markers of empathetic attunement and can be seen as evidence of this social construct.

Music performance is a complex communicative system where performers convey a conceptual interpretation of a musical composition. Eliciting meaning and expressivity in music performance is a contextually driven, top-down sensory process that requires the integration of a system of complex auditory abilities needed to extract, organize, and interpret acoustic information (Baldwin, 2012). Aesthetic musical qualities can be communicated structurally (Clarke, 1998) and expressively (Kendall & Carterette, 1990). Structural information includes (a) formal units such as motives and phrases; (b) temporal units of hierarchically nested intervallic timing systems (i.e., beats and subdivisions); and (c) surface features such as harmonic and melodic tension (Friberg & Battel, 2002; Keller, 2014). Expressive information can be empirically extracted from performers' modulations of various dimensions of sound (i.e., auditory behavioral cues), including timing deviations, intensity, intonation, articulation, and timbre (Keller, 2014).

Expressive timing has been studied extensively in areas of music psychology and performance science (for reviews of literature, see Palmer, 1997; Honing, 2013). Several cognitive and computational models of expressive timing have been offered, each proposing single-factor conceptions of expression indicated by marked deviations from a notated score (Clarke, 1989; Clynes, 1987; Feldman, Epstein, & Richards, 1992; Gabrielsson, 1999; Sundberg & Verillo, 1980; Todd, 1985, 1992). However, these models are problematic for the study of jazz rhythm (and other groove-based music) for several reasons: (a) jazz performance often works in an improvisatory manner without reference to a score; (b) in groove-based contexts (i.e., jazz performance), rhythmic expression occurs on a microstructural (i.e., subtactus) timescale, moving too rapidly for reliance on auditory feedback mechanisms (Fraisse, 1982; Iyer, 2002; Lashley, 1951); (c) discussions of metric organization imply a system of strong and weak beats that do not support the structure of jazz rhythm (Iyer, 2002); (d) little research has included musicians' fine-scaled (i.e., subtactus) rhythmic delivery with an underscoring isochronous pulse; (e) the reliance on tempo curves to extract expressive timing data is not appropriate for music with a continuous, isochronous pulse (Desain & Honing, 1993, 1994); and (f) it is unclear what specific modes of processing (i.e., temporal, rhythmic, grouping) are engaged (if any) at a subtactus timescale in an isochronous context without research accounting for a "perceptual boundary" of analytical counting processes (Iyer, 2002). Therefore, investigation into expressive elements, psychological mechanisms, and cognitive-motor skills related to musical expression in jazz performance is warranted.

The purpose of this study was to examine the effects of selected musical variables on the horizontal (i.e., successive eighth note timing relationships) and vertical (i.e., the degree of ensemble synchronicity between separate parts) timing properties of jazz rhythm. The design of this investigation is a case study of American saxophonist Chris Potter in a naturalistic, performance-based environment using an analysis-by-synthesis approach. The research questions that guided this study include:

1. What correlations do articulation, interval size, intervallic direction, metrical placement, tempo, and underlying harmony have with horizontal timing relations (i.e., successive eighth note timing relationships)?
2. What correlations do articulation, interval size, intervallic direction, metrical placement, tempo, and underlying harmony have with vertical timing relations (i.e., the degree of ensemble synchronicity between saxophone, bass, and drums)? and
3. What are the vertical timing correlations between soloist, bass, and drums in a jazz performance?

Timing deviations in jazz rhythm

Qualitative descriptions of vertical and horizontal timing deviations in jazz performance have underscored critics' descriptions of jazz rhythm since the music's origin:

> ... progressive retarding and acceleration (Patterson, 1917/2002, pp. 28–29);
>
> Jazzing up a piece is to start (a note) a little ahead of the beat (Thomson, 1925, p. 54);
>
> ... playing rhythms variously suspended around the beat (Hobson, 1935, p. 30);
>
> ... the gifted player tends to place his notes a little away from the beat; he anticipates or lags behind while the real beat tries, like a magnet, to draw the brass note (of melody instruments back) to its own center of force (Blesh, 1946/1958, p. 164);
>
> ... the rhythmic valuations of notes may be lengthened or shortened according to a regular scheme ... as long as a steady beat remains implicit or explicit (Ulanov, 1952, p. 7);
>
> ... the accurate timing of a note in its proper place (Schuller, 1968, p. 7);
>
> ... breaking away from the time framework of the ground beat to produce lines that are essentially rhythmically free (Collier, 1978, p. 24);
>
> ... the melody remains in the vicinity of the beat but floats on either side, without restriction (Kernfeld, 1995, pp. 24–25);
>
> ... a very subtle aspect of jazz phrasing which specifically involves the length of space between the downbeat and upbeat of two eighth notes. The length of ... the triplet ... depending upon how one conceptualizes it, can be varied mathematically and microscopically to reflect a whole palette of proportions between the two divisions of the beat (Liebman, 2003, p. 23).

Liebman (1997) indicates the eighth note (i.e., subtactus metrical level) as the most prominent level of jazz expression and structure. According to Liebman:

> The eighth note is the substructure of jazz rhythm. It is the equivalent of the penny to the dollar… Of course there are permutations … there are longer rhythms and shorter rhythms, but it is essentially the eighth note that is the currency … and to understand how to phrase the eighth notes is crucial to having a good sense of swing. (DVD interview, 1997)

Expressive devices in jazz rhythm, such as the subtle horizontal (i.e., successive eighth note timing relationships) and vertical (i.e., the degree of ensemble synchronicity between separate parts) timing relations can account for the rich variety of nuance found in jazz performance. According to Rasch, "The asynchronization of simultaneous tones should be regarded as the vital deviations in the performance of music" (1988, p. 81). Keil (1966, 1987) considers these "participatory discrepancies" in jazz rhythm as the impetus for its forward-moving propulsion. In spontaneous jazz improvisation, greater rhythmic timing deviations are to be expected compared to non-improvised performances (Keller, Weber, & Engel, 2011). More importantly, listener sensitivity to these timing deviations affects the perception and general responsiveness to its spontaneous nature (Engel & Keller, 2011).

Horizontal timing deviations between successive eighth notes can serve to facilitate a hierarchical rhythmic structure and provide a greater aural perception of the isochronous pulse:

> In conventional terms, the swing eighth note pairs are perceptually grouped into the larger regular (isochronous) interval, that is, the quarter note. If all subdivisions were performed with the same duration, it would be more difficult to perceive the main beat. The lengthening of the first of the two swung notes in a pair amounts to a durational accentuation of the beat. Hence, swing enhances the perception of the main pulse. (Iyer, 2002, p. 404)

Quantitative investigations into horizontal timing deviations in jazz improvisation has included the analysis of individual eighth note durations (Busse, 2002; Cholakis & Parsons, 1995; Rose, 1989) as well as the relationships of adjacent eighth note durations (Benadon, 2006; Butterfield, 2011; Collier & Collier, 2002; Friberg & Sundström, 2002; Honing & deHaas, 2008). The relationships of adjacent eighth note durations are traditionally analysed by calculating the "swing ratio" between an eighth note starting on the downbeat (measured in milliseconds) and its consecutive eighth note performed on the upbeat (measured in milliseconds) (Collier & Collier, 2002; Friberg & Sundström, 2002). Benadon (2006) was the first to calculate the quotients of these ratios and discuss these relationships using one continuous value, termed "beat upbeat ratio" (BUR). Furthermore, Butterfield (2011) has elaborated on the significance of BURs as well as introduced the notion of an "upbeat beat ratio" (UBR) in the perception of energy, groove, and expressiveness in jazz rhythm. The literature suggests several common generalizations: (a) notes of the downbeats tend to be performed with longer duration than notes on the upbeat (Busse, 2002; Collier & Collier, 2002); (b) the relationship between tempo and eighth note length is indirectly proportional (i.e., as tempo increases, performers elongate note durations causing swing ratio to decrease and become closer to straight eighth notes) (Busse, 2002; Cholakis & Parsons, 1995; Ellis, 1991; Friberg & Sundström, 2002); and (c) swing ratios oscillate considerably from beat to beat and are sometimes affected by changes in underlying harmony, melodic character, and metrical placement (Benadon, 2006).

Vertical timing deviations (i.e., asynchronous timing relationships) between jazz ensemble members are measured relative to the underlying perceptual pulse of the music (i.e, deviations from the mean between ensemble members), traditionally by analysing the marked deviations of quarter note placements of soloists, bassists, and drummers (Ashley, 2002; Busse, 2002; Prögler, 1995; Reinholdsson, 1987; Rose, 1989). According to Keil (1966, 1987) and Butterfield (2010), the tension resulting from these asynchronous timings results in the perceptual "groove," "energy," and "drive" unique to jazz performance. Non-jazz related studies have demonstrated clear leader–follower relationships in ensemble timing (Goebl & Palmer, 2009; Keller & Appel, 2010). Similarly, studies of soloist, bass, and drummer timing relationships suggest a clear temporal relationship; specifically, in the order of drums, bass, then soloist (Prögler, 1995; Rose, 1989).

Research literature pertaining to timing deviations in jazz performance has unveiled numerous variables that arguably affect horizontal and vertical timing relations. These factors include metrical placement of the beat (Benadon, 2006; Busse, 2002; Collier & Collier, 2002; Rose, 1989), tempo (Cholakis & Parsons, 1995; Collier & Collier, 1994; Ellis, 1991; Friedberg & Sundström, 2002), harmonic character (i.e., the underlying harmonic structure: Benadon, 2006; Butterfield, 2011), and melodic character (i.e., the intervallic approach to and resolution from the eighth note being analysed: Benadon, 2006).

Reviews of research synthesizing timing deviations in jazz performance have indicated disagreement between empirical results (see Benadon, 2006; Butterfield, 2011; Wesolowski, 2013b). For example, disagreement often occurs on the relationship between swing ratio and tempo. Ellis (1991), Cholakis and Parsons (1995), and Friberg and Sundström (2002) indicate that the relationship between horizontal eighth note timing and tempo is indirectly proportional while Collier and Collier (1996), Benadon (2006), and Honing and de Haas (2008) indicate no significant relationship. Additionally, Busse (2002) indicates no statistically significant relationship between vertical timing and tempo whereas Ellis (1991) indicates that as tempo increases, beat placement tends to fall behind the beat.

The framework for which these timing deviations are analysed is of concern. Danielsson (2006, 2010) argues that the mechanical norm and deviations from the mechanical norm in groove-based music are in fact two separate, distinct, but mutually dependent models of representation. According to Danielson, actual sounding events transcend any "virtual reference structures" (i.e., mechanical norm):

> ... what constitutes a relevant representation of rhythmic structure varies ... and it varies not only with the sound in question but also with the position and priorities of the listener ... Rather than asking what the rhythmic structure is, one should perhaps ask how to best represent the reference structures at work..." (2010, p. 7).

The difficulty in analysing microstructural timing data in jazz performance is determining whether fluctuations in timing are random or chaotic, intended or unintended. Additionally, developing an understanding of the value of such deviations themselves is also of consequence. Inconsistency and variability is inevitably found from beat to beat; however, averaged responses are closely synchronized with the rhythmic stimulus (for literature reviews, see Repp, 2005; Repp & Su, 2013). Thaut (2005) argues that timing deviations in rhythm are a stochastic process: "... precise timing of rhythm is achieved in a system state of the human brain that resembles directed Brownian motion—which is random rather than chaotic, but which also contains *correlations*" (p. 44). Therefore, correlations of musical variables may be of interest in the study of jazz rhythm.

The ability to draw such conclusions regarding timing deviations in jazz rhythm (specifically, analysing data derived from musical performances without consideration to other cognitive or perceptive processes), however, is hindered by several data analysis problems with the existing literature: (a) conclusions are often drawn from a "snapshot" analysis without an attempt to use statistical means to generalize the population; (b) contradicting inferences occurring in the literature may be due to a lack of statistically-reliable data and too small sample sizes; and (c) the absence of statistically reliable data prohibits the application of a meta-analysis to holistically approach multiple data sets and performances (Wesolowski, 2013b).

The purpose of this study was to empirically examine the effects and correlations of selected musical variables with the constructs of horizontal and vertical timing deviations in jazz performance. Specifically, this study investigated the effects and correlations of selected musical variables with: (a) individual eighth note length; (b) beat upbeat ratio (i.e., BUR); (c) upbeat beat ratio (i.e., UBR); and (d) asynchronous relationships of jazz ensemble members. It should be noted that this study had two limitations: (a) the use of one subject as an exemplar in a case-study research design restricts the generalizability outside of the specific performer studied; and (b) the analysis-by-synthesis approach that examines performance data constrains any analysis of psychologically distinct, expressive actions (e.g. performer intent, motor response, adaptive timing; Thompson, Sundberg, Friberg, & Frydén, 1989).

Method

Gathering and coding of musical variables

Musical factors included in this study were limited to (a) articulation of the sample eighth note; (b) interval size preceding the sample eighth note; (c) interval size succeeding the sample eighth note; (d) interval direction preceding the sample eighth note; (e) interval direction succeeding the sample eighth note; (f) metrical placement of the sample eighth note; (g) tempo of the sample eighth note; and (i) underlying harmony of the sample eighth note. Articulation was coded dichotomously as tongued or slurred. Interval sizes preceding and succeeding the sample eighth note were coded ranging from zero semitones (i.e., perfect unison) to twelve semitones (i.e., perfect octave). Interval directions preceding and succeeding the sample eighth note were coded as either ascending or descending. Metrical placements of the sample eighth note were coded for each downbeat and upbeat of a measure containing four beats. Tempo was calculated for each sample eighth note utilizing the MIR*toolbox* 1.3.3 autocorrelation function using MATLAB algorithmic computing environment software (Lartillot, Toiviainen, & Eerola, 2008). The data was continuous (interval). The underlying harmony of the sample eighth note was coded as tonic, dominant, subdominant, submediant, or mediant.

Gathering of recorded material. Specific musical criteria were set when selecting the material to be analysed: the quality of the recording had to be clear enough in order to measure onset and offset discrimination accurately; the tempo was to be slower than 250 beats per minute (bpm) (Benadon, 2006, pp. 95–96); the overall style was to be performed with a swing eighth-note subdivision (solos performed with a "Latin" or "funk" feel were avoided); the underlying harmony of the vehicle for improvisation was based on functional harmony; modal and altered harmony were avoided; and the meter of the vehicle for improvisation was in 4/4 time.

The recorded material was based upon the solos of saxophonist Chris Potter. Chris Potter was selected as a focal point for this case study for the following reasons: (a) his performance of eighth note lines was performed in a clear manner in all registers of the saxophone (Saltzman, 2002, p. 74); (b) his performances were based upon a strong rhythmical foundation rooted in the jazz tradition (Saltzman, 2002, p. 74); (c) his performances contained a wide variety of applied articulations (Kluth, 2006, p. 180); (d) the accessibility of performed solo interpretations meet the sample size and criteria needed for this research study; (e) the accessibility of performed solos with rhythm section accompaniment based upon the outlined criteria; and (f) cooperation to participate in this research study.

In order to avoid difficulties due to nesting, the analyses were drawn from five distinct performances. These performances included four commercially unavailable solo performances:

(a) *Confirmation*; (b) *26–2*; (c) *It Could Happen to You*; (d) *Rhythm Changes*; and one ensemble recording: (e) *Anthropology* (Cohen, Potter, Herbert, & Madsen, 1999).

The musical examples were transcribed by the author with the aid of Seventh String's Transcribe!™ version 8.10 software. The transcription was scored using MakeMusic's Finale™ 2007 music notation software. An outside auditor verified the accuracy of the transcriptions.

Power analysis and determination of minimal sample size. A power analysis was run and sample size was calculated based upon the Root Mean Square Error of Approximation (RMSEA) model of fit (Kim, 2005; MacCallum, Browne, & Cai, 1996; MacCallum Browne, & Sugawara, 1996; MacCallum & Hong, 1997). The data indicated that 397 units of analysis would be needed to achieve the desired power of .80, with $\alpha = .05$ and $df = 22$.

Method 1: Eighth note duration for solo recordings

The data designated by the variables of eighth note duration was collected using MATLAB, created by Mathworks™ with the utilization of MIR*toolbox* 1.3.3 (Lartillot & Toiviainen, 2007; Lartillot, Toiviainen, & Eerola, 2008). MIR*toolbox* is a software add-on written within MATLAB offering a specific set of functions that offers a set of computational approaches aiding in the feature extraction of audio files. Five salient algorithmic features were utilized in MIR*toolbox* for the data collection: (a) *mirenvelope;* (b) *mirspectrum*; (c) *mirpeaks*; and (d) *mironsets*. The resulting data included the duration of each analysed eighth note beyond a ten-thousandth of a second. The units were each rounded to a hundredth of a second and paired with the preceding and succeeding eighth note in order to compute the BUR and UBR data.

Method 2: Eighth note duration and ensemble synchronization for ensemble recording

Eighth note pairs were marked in sequential order. In order to digitally analyse the waveforms from the recorded material, the digital sound editor software Audacity 1.3.12 was used on an Apple™MacBook. Each solo was digitized at the CD quality of 44 kHz, 16-bit resolution (Ashley, 2002; Benadon, 2006; Collier & Collier, 2002) and was truncated at the onset of the first note of the soloist, providing a zero reference. Event onset times and offset times were computed for each eighth note by parsing the waveform of the recorded excerpt into its eighth note components by using the software's marker tool. These values were then transferred into a Microsoft Excel spreadsheet.

Results

A total of 949 eighth note samples from five improvised solos by Chris Potter were analysed: (a) *Confirmation* ($n = 165$); (b) *26-2* ($n = 219$); (c) *It Could Happen to You* ($n = 100$); (d) *Untitled Rhythm Changes* ($n = 267$); and (e) *Anthropology* ($n = 198$). Descriptive statistics for eighth note durations, BUR, and UBR are indicated in Table 1. Results of the four separate simultaneous regression procedures are presented in Table 2.

Beat-upbeat ratio (BUR)

The beat-upbeat ratio (BUR) value was defined as the temporal proportion between two subsequent eighth notes starting on the downbeat and ending on the upbeat. It was quantified by

Table 1. Descriptive statistics for eighth note duration, BUR, and UBR ($N = 949$).

	Group means (*SD*)	
	Eighth note duration (*ms*)	BUR/UBR*
Downbeat 1	.75 (.83)	1.27 (.82)
Upbeat 1	.71 (.72)	.94 (.55)
Downbeat 2	.68 (.72)	1.09 (.63)
Upbeat 2	.61 (.66)	1.05 (.12)
Downbeat 3	.56 (.71)	1.33 (.65)
Upbeat 3	.58 (.69)	.90 (.80)
Downbeat 4	.56 (.68)	1.78 (.90)
Upbeat 4	.64 (.70)	1.08 (.64)

Note. * BUR value is indicated on all downbeats. UBR value is indicated on all upbeats.

calculating the proportion between two consecutive eighth notes by dividing the durational value of the eighth note occurring on the downbeat (measured in milliseconds) by the durational value of the eighth note occurring on the upbeat (measured in milliseconds). In this study, BUR values served to quantify the linear time-feel measurement and were referred to as "eighth note durations." In this subset, BUR value ($N = 184$) was simultaneously regressed on metrical placement of the beat, melodic character, intervals, articulation, range, underlying harmony, and tempo. The omnibus test was not statistically significant, $R^2 = .068$, $F(9, 174) = 1.42$, $p = 1.80$ (Table available upon request).

Upbeat-beat ratio (UBR)

The upbeat-beat ratio (UBR) value was defined as the temporal proportion between two subsequent eighth notes starting on the upbeat and ending on the downbeat. It was quantified by calculating the proportion between two consecutive eighth notes by dividing the durational value of eighth note occurring on the upbeat (measured in milliseconds) divided by the durational value of the eighth note occurring on the downbeat (measured in milliseconds). In this study, UBR values served to quantify the linear time-feel measurement and are referred to as "eighth note durations." In this subset, UBR value ($N = 173$) was simultaneously regressed on metrical placement of the beat, melodic character, intervals, articulation, range, underlying harmony, and tempo. The omnibus test was statistically significant, $R^2 = .128$, $F(9, 163)$, $p = .007$. Metrical placement of the beat, melodic character, interval, articulation, range, underlying harmony, and tempo accounted for 12.8% of the variance in UBR. Note articulation, $\beta = -.361$, $t(-2.99)$, $p = .021$, had a statistically significant effect on UBR. Table 3 provides the results from the Pearson product-moment bivariate correlation of range, metrical placement, interval, melodic character, articulation and tempo as a function of UBR.

Eighth note duration

Eighth note durations were defined as the distance between the onset of a note and its relative offset. It was calculated as offset-onset in milliseconds (*ms*). Eighth note durations were measured for each downbeat and each upbeat of eighth note pairs performed by the soloist. In this subset, eighth note duration ($N = 949$) was simultaneously regressed on metrical placement of the beat, melodic character, intervals, articulation, range, underlying harmony, and tempo.

Table 2. Summary of the simultaneous regression analyses.

Variable	*b*	*SE*	*β*	*p*	*VIF*
Variables predicting BUR values					
Metrical placement	.010	.031	.024	.750	1.052
Underlying harmony	−.041	.088	−.036	.636	1.102
Interval preceding	−.023	.035	−.053	.516	1.231
Interval succeeding	.041	.043	.075	.340	1.145
Melodic character preceding	−.160	.105	−.125	.516	1.250
Melodic character succeeding	.161	.125	.097	.340	1.066
Articulation	−.361	.155	−.178	**.021**	1.089
Tempo	−.002	.003	−.060	.437	1.097
Variables predicting UBR values					
Metrical placement	−.032	.022	−.108	.156	1.065
Underlying harmony	.071	.062	.089	.254	1.127
Interval preceding	−.035	.030	−.098	.247	1.321
Interval succeeding	−.007	.025	−.020	.793	1.091
Melodic character preceding	−.050	.075	−.060	.507	1.539
Melodic character succeeding	.089	.089	.081	.320	1.233
Articulation	−.400	.134	−.248	**.003**	1.294
Tempo	−.004	.002	−.131	.092	1.122
Variables predicting eighth note duration					
Metrical placement	−.038	.017	−.113	.065	1.045
Underlying harmony	.075	.047	.081	.112	1.062
Interval preceding	−.061	.020	−.162	**.003**	1.210
Interval succeeding	−.062	.019	−.161	**.002**	1.048
Melodic character preceding	−.108	.054	−.108	**.049**	1.227
Melodic character succeeding	−.008	.062	−.006	.898	1.056
Articulation	.091	.077	.061	.240	1.102
Variables predicting beat placement					
Metrical placement	−.004	.014	−.032	.765	1.076
Interval preceding	−.005	.022	−.021	.851	1.157
Interval succeeding	−.017	.024	−.082	.459	1.139
Melodic character preceding	−.059	.068	−.107	.356	1.252
Melodic character succeeding	−.017	.067	.116	.310	1.218
Articulation	−.058	.074	−.091	.438	1.283
Tempo	−.001	.004	−.435	.664	1.120

Note. R^2 = .068 (p = 1.8) for BUR, R^2 = .128 (p = .007) for UBR, R^2 = .067 (p < .001) for eighth note duration, R^2 = .052 (p = .760) for beat placement, Bold p values indicate significance, p<.05.

The omnibus test was statistically significant, $R^2 = .067$, $F(8, 385) = 3.48$, $p = .001$. Metrical placement of the beat, melodic character preceding, melodic character succeeding, interval preceding, interval succeeding, articulation, range, underlying harmony, and tempo combined to account for 6.7% of the variance in note duration. Interval preceding, $\beta = -.361$, $t(-2.99)$, $p = .021$, and interval succeeding, $\beta = -.16$, $t(-3.20)$, $p = .002$), had a statistically significant effect on note duration. Table 4 provides the results from the Pearson product-moment bivariate correlation of range, metrical placement, interval, melodic character, and articulation as a function of eighth note duration.

Table 3. Summary of intercorrelations, means, and standard deviations for scores of range, metrical placement of the beat, underlying harmony melodic character, interval and articulation as a function of upbeat beat ratio (*N* = 173).

Measure	1	2	3	4	5	6	7	8
1. Note duration	–	0.061	−0.08	−0.022	0.033	0.173	−0.293	−0.149
2. Metrical placement		–	0.027	−0.095	−0.142	0.053	0.063	0.017
3. Underlying harmony			–	0.023	0.015	−0.034	−0.016	−0.119
4. Interval preceding				–	−0.412	0.081	0.083	−0.003
5. Interval succeeding					–	−0.015	0.116	−0.206
6. Melodic character preceding						–	0.011	−0.154
7. Melodic character succeeding							–	−0.113
8. Articulation								–
M	1.058	1.97	3.65	3.94	1.74	1.62	1.21	224.37
SD	0.662	0.831	1.873	1.995	0.804	0.604	0.441	22.144

Note. * No correlations were significant beyond the .05 level.

Table 4. Summary of intercorrelations, means, and standard deviations for scores of range, metrical placement of the beat, underlying harmony melodic character, interval and articulation as a function of eighth note duration (*N* = 949).

Measure	1	2	3	4	5	6	7	8
1. Note duration	–	−0.086	0.04	−0.126	−0.154	−0.043	−0.022	0.052
2. Metrical placement		–	0.104	−0.036	−0.082	−0.061	0.085	−0.096
3. Underlying harmony			–	0.103	0.102	−0.007	−0.01	−0.012
4. Interval preceding				–	0.11	−0.382	0.022	−0.004
5. Interval succeeding					–	−0.01	−0.08	0.114
6. Melodic character preceding						–	0.014	−0.02
7. Melodic character succeeding							–	−0.204
8. Articulation								–
M	0.723	4.57	1.97	3.74	3.97	1.71	1.63	1.47
SD	0.744	2.251	0.808	1.984	1.934	0.747	0.606	0.5

Note. * No correlations were significant beyond the .05 level.

Beat placement

Beat placement was defined as measurement that quantifies the asynchronous timing between ensemble members relative to the underlying perceptual pulse of the music. Beat placement was quantified through a four-step process: (a) calculation of the downbeat onset time of each eighth note pair for the saxophone, bass, and drums; (b) calculation of the Mean Onset Time (MOS) for each downbeat of the eighth note pair; (c) calculation of the Relative Onset Time (ROT) for each downbeat of the eighth note pair; and (d) calculation of the Onset Difference Time (ODT) for each downbeat of the eighth note pair (for full conceptual and mathematical descriptions, see Rasch, 1988). In this subset, 198 eighth note units were sampled. Quarter

Table 5. Summary of intercorrelations, means, and standard deviations for scores of ROT_Sax, ROT_Bass, and ROT_Drums (N = 99).

Measure	1	2	3	4
1. ROT_sax	–	–.612**	–.523**	–1.000**
2. ROT_bass		–	–.353**	.612**
3. ROT_drums			–	.523**
M	–.383	–.023	.406	.191
SD	.231	.210	.195	.115

Note. ** Correlation is significant at the 0.01 level (2-tailed).

note beat placement ($N = 99$) was simultaneously regressed on metrical placement of the beat, melodic character, intervals, articulation, range, underlying harmony, and tempo. The omnibus test was not statistically significant, $R^2 = .067$, $F(8, 385) = 3.48$, $p = .001$.

A bivariate correlation was run on ROT_sax, ROT_bass, and ROT_drums using the Pearson product-moment correlation coefficient. The relationships between all three variables yielded statistically significant results. There was a large, negative correlation between ROT_sax and ROT_bass ($r(77) = -.612$, $p < .001$), a large negative correlation between ROT_sax and ROT_drums ($r(77) = -.523$, $p < .001$) a moderate, negative correlation between ROT_bass and ROT_drums ($r(77) = -.353$, $p < .001$), and a large, negative correlation between ROT sax and average_bass-drums ($r(77) = -1.00$, $p < .001$). These results support the claims by Friberg and Sundström (2002) and Butterfield (2010). Table 5 provides the results from the Pearson product-moment bivariate correlation of onset timing measures from the saxophone, bass, drums, and mean of the bass and drums.

The average onset difference time between bass and drums (bass–drums) was −0.218 seconds. The average onset difference time between saxophone and bass (sax–bass) was −0.369 seconds. The average onset difference time between saxophone and drums (sax–drums) was −0.405 seconds. It should be noted that the onset discrimination threshold by the ear for the simultaneous playing of musical tones is approximately 20 ms (Hirsh, 1959). The statistically significant correlations challenge the claim that "the distribution of onset differences is practically random" (Rasch, 1988, p. 80).

Discussion

The purpose of this study was to examine the relationships of selected musical variables on horizontal and vertical timing deviations in jazz performance. The statistical evidence gleaned from this study suggests that articulation and intervals preceding and succeeding the sample eighth notes had a statistically significant effect on both eighth note duration and upbeat–beat ratio. Additionally, clear leader–follower relationships were demonstrated (i.e., drums first, bass second, saxophone third). The results accounted for low amounts of variance and some dependence, as indicated by the statistically significant omnibus tests, R-values, and correlation coefficients. In this case study, evidence supports Thaut's (2005) argument that fluctuations in timing deviations are random with some dependence and are not purely chaotic. Perhaps future research can empirically describe the random fluctuations in timing more reliably through probabilistic models similar to Brownian motion, Donsker's theorem, or Rasch modeling. Furthermore, it may be possible that timing deviations in jazz performance are a unique, intrapersonal construct that is subject to some (or possibly no) variability in joint action performance contexts. At the moment, this is speculative, as more data needs to be collected and

Table 6. Comparison of test results with previous research claims.

Variables	Claim	This study
Note duration and metrical placement		
	Beats 2 and 4 are generally lengthened and beats 1 and 3 are generally shortened (Rose, 1989).	There is no significant correlation between note duration and metrical placement, $r(394) = .088$, $p = .088$.
Note duration and metrical placement		
	83.5% of eighth note pairs displayed longer durations of the first note (Collier & Collier, 2002).	There is no significant correlation between note duration and metrical placement, $r(394) = .088$, $p = .088$.
Note duration and metrical placement		
	Notes of the downbeats tended to be performed with longer duration than notes on the upbeat (Busse, 2002).	There is no significant correlation between note duration and metrical placement, $r(394) = .088$, $p = .088$.
Note duration and tempo		
	As tempo increases, performers elongate note durations (Busse, 2002).	There is a strong, positive correlation between tempo and note duration, $r(394) = .008$, $p < .001$.
BUR and tempo		
	Swing ratio and tempo are indirectly proportional. As tempo increases, the swing ratio decreases and becomes closer to straight eighth notes (Cholakis & Parsons, 1995; Ellis, 1991; Friberg & Sundström, 2002).	There is no significant correlation between BUR and tempo, $r(184) = -.083$, $p = .265$.
	Swing ratio is tempo-dependent (Collier & Collier, 1996).	There is no significant correlation between BUR and tempo, $r(184) = -.083$, $p = .265$.
	Swing ratio and tempo are not indirectly proportional (Benadon, 2006; Collier & Collier, 1996; Honing & de Haas, 2008).	There is no significant correlation between BUR and tempo, $r(184) = -.083$, $p = .265$).
BUR and metrical placement		
	Higher BUR values occur at cadential phrase endings (Benadon, 2006).	There is no significant correlation between BUR and metrical placement, $r(184) = .562$, $p = .562$.
BUR and metrical placement		
	BUR ratios are not uniform within a phrase. They oscillate considerably, from beat to beat (Benadon, 2006).	There is no significant correlation between BUR and metrical placement, demonstrating considerable oscillation, $r(184) = .562$, $p = .562$.
BUR and melodic character		
	Shifts in melodic character sometimes correlate to changes in BUR values (Benadon, 2006).	There is no significant correlation between BUR and melodic character preceding, $r(184) = -.083$, $p = .263$, or melodic character succeeding, $r(184) = .090$, $p = .224$.

Table 6. (Continued)

Variables	Claim	This study
BUR and underlying harmony		
	Shifts in harmony sometimes correlate to changes in BUR values (Benadon, 2006).	There is no significant correlation between BUR and underlying harmony, $r(184) = -.025$, $p = .738$.
Beat placement		
	Asynchronization of nominally simultaneous tones by different instruments occurred. Tendency was for the drums to hit first, the piano to hit second, and the bass to hit last (Rose, 1989).	There was a large, negative correlation between ROT_sax and ROT_bass, $r(77) = -.612$, $p < .001$, a large negative correlation between ROT_sax and ROT_drums, $r(77) = -.523$, $p < .001$, a moderate, negative correlation between ROT_bass and ROT_drums, $r(77) = -.353$, $p < .001$.
	Discrepancies in ensemble beat placement are contextual (Prögler, 1995).	The omnibus test for beat placement was statistically insignificant and demonstrate no significant context, $R^2 = .052$, $F(8, 90)$, $p = .760$.
	Upbeat note placements were generally performed later than the traditional swing feel (Prögler, 1995).	The average BUR measurement ($N = 184$) was 1.28, placing the average upbeat .72 units earlier than the traditional triplet swing feel of 2.00.
	Soloists' downbeats note placements were generally performed behind the beat at all tempi (Prögler, 1995).	The average onset difference time between the saxophone and the average of the bass and drums was −0.786 seconds.
	Jazz musicians swing their eighth notes to produce anacrusis on the offbeats, an effect that generates motional energy directed toward the ensuing downbeat as a consequence (Butterfield, 2011)	Interval preceding, $\beta = -.162$, $t(-3.00)$, $p = .002$, and interval succeeding, $\beta = -.16$, $t(-3.20)$, $p = .002$, had a statistically significant effect on eighth note duration
Beat placement and tempo		
	Beat placement is not proportional to tempo. As tempo increases, beat placement tends to become more behind the beat (Ellis, 1991).	There is no significant correlation between beat placement and tempo, $r(99) = -.023$, $p = .821$.
	There was no relationship between upbeat note placement and tempo (Busse, 2002).	There is no significant correlation between beat placement and tempo, $r(99) = -.023$, $p = .821$.

Note. Shaded rows indicate accordance with previous research literature claims.

analysed for relationships between other individual performers, multiple performers in joint performance contexts, instrument groupings, sub-genres, and cultures. However solidly defended in this article, the results cannot be generalized outside of the subject studied. Table 6 displays prior research claims along with the statistically validated significance levels and correlations from this study. Due to the aforementioned data analysis problems related to previous research and the design limitation of this study, conclusive evidence of certainty cannot be demonstrated. However, both the statistically significant and non-significant results in the context of this study provide further insight into the structure of jazz rhythm.

An understanding of the relationship between the perception of jazz rhythm and the mechanics of jazz rhythm may play an important part of the advancing the understanding jazz rhythm. Early musicological discourse relating to jazz was based upon the perception of swing and groove. Perception seems to be guided by the notion of what "swings" and what "does not swing." However, there is no empirical support demonstrating the relationship between the perception of jazz rhythm and timing deviations. As an example, Liebman (2003) writes, "Every jazz musician knows that 'two' and 'four' are the swinging beats and in fact it is the four that really swings, while the upbeat of four swings even more" (p. 21). However, this research study demonstrated that there is no statistically significant relationship of metrical placement to beat-upbeat ratio ($r(184) = .043$, $p = .562$), upbeat–beat ratio ($r(199) = -.040$, $p = .572$), eighth note duration ($r(394) = -.086$, $p = .088$), or beat placement ($r(99) = -.004$, $p = .967$). The question remains as to what mechanical aspects of a jazz performance direct performers' and listeners' ears to particular metrical placements as important elements of groove. Further investigation into the relationships between the perception and mechanics of a jazz performance may broaden our understanding of what defines a "swinging" jazz performance. In addition, parsing out perceptually "swinging" performances from perceptually "non-swinging" performances and analysing timing deviations of these performances may clarify the relationship of perception to acoustical mechanics. Such information may be retrieved through various experimental designs that examine the empirical boundaries of such performances.

Implications for music education and pedagogy

Though basic to the perception and performance of jazz, educators and performers have difficulty describing the subtle, expressive nuances of jazz rhythm in concrete terms (Johnson, 2001; Liebman, 1997). Pedagogically, listening and emulating are often prescribed as the most important instructional methodologies for teaching and learning the expressive elements of jazz rhythm and time-feel (Dunscomb & Hill, 2002). The aural model in jazz pedagogy is essential to learning and teaching; however, its use as the single method for teaching jazz rhythm limits the ability to interpret and analyse performances related to contextual authenticity, precision, and overall perceptually pleasing qualities related to time-feel. Additionally, levels of cognitive agreement between teacher and student may limit a teacher's pedagogical strategy based upon listening and perception alone. At best, metaphoric illustrations are often used to pedagogically describe timing deviations in jazz rhythm:

> I use the term "rotary perception." If you get a mental picture of the beat existing within a circle you're more free (*sic*) to improvise. People used to think the notes had to fall on the centre (*sic*) of the beats in the bar at intervals like a metronome, with three or four men in the rhythm section accenting the same pulse. That's like parade music or dance music. But imagine a circle surrounding each beat- each guy can play his notes anywhere in that circle and it gives him a feeling he has more space. The notes fall anywhere inside the circle but the original feeling for the beat doesn't change. (Mingus, 1995, pp. 124–125)

In addition, Benward and Wildman (1984) explain:

> A beat can either be wide or narrow. For example, although each beat occurs as a "point" in time, try to envision the difference between the "point" made by an ultrafine-line pen and a magic marker. The ultrafine-line pen demonstrates the center of a beat, while the magic marker widens the possibilities, allowing a loose, swinging, personal approach to time on many different structural levels. A wide-beat concept is not just a haphazard reaction, however; it is idiomatic to the jazz style. (p. 127)

Although helpful as an instructional tool, metaphors do not describe expressive timing in jazz rhythm or its relationship to other musical variables as accurately or reliably as empirical investigations.

Empirical analysis of vertical timing deviations (i.e., ensemble synchronization) and horizontal timing deviations (i.e., eighth note duration) as well as their relationships with musical variables can provide empirical evidence that defines the structure of jazz rhythm. Bruner's (1960) theory of the role of structure in learning and teaching outlines its importance as a fundamental concept to understanding.

> The teaching and learning of structure, rather than simply the mastery of facts and techniques, is at the center of the classic problem of transfer… If earlier learning is to render later learning easier, it must do so by providing a general picture in terms of which the relations between things encountered earlier and later are made as clear as possible. (p. 12)

Bruner's theoretical framework for learning explains that a learner selects and transforms information, constructs hypotheses, and makes decisions based upon a cognitive structure. In addition, consideration is needed for the ways in which a body of knowledge can be structured in order to achieve and optimize student understanding. Instruction must be organized in order for the student to easily grasp information and designed to facilitate extrapolation of information and/or fill in the gaps with new information. Juslin (2003) suggests that different aspects of musical expression (i.e., structure, emotion, motor precision, human motion and gesture, timing deviations) should be taught separately at certain stages of learning. Breaking the myth that expression cannot be studied objectively and empirically (Juslin & Laukka, 2003) and educating students and teachers on empirical structures in jazz rhythm may (a) better inform verbal and written musical assessments related to jazz rhythm; (b) analyse and interpret performances in terms of contextual authenticity, precision, and overall perceptually pleasing qualities related to time-feel; and (c) deepen the understanding of aesthetics in jazz performance.

Future research in cognitive psychology

Human musical performances are always characterized by marked deviations from mechanical regularity due to human psychomotor limitations and perceptual timing limitations (Rasch, 1988). Several models explain these fluctuations (for reviews of literature, see Repp, 2005; Repp & Su, 2013). However, Iyer (2002) argues these models are unfit for analysis of jazz rhythm for two reasons: (a) the central clock pulse of these models is at the tactus/pulse level and the unit of expression in jazz performance is the subtactus/eighth note value; and (b) groove-based synchronization is an advanced skill utilizing precise temporal acuity that can potentially be developed with practice. Juslin (2003) argues that studies in psychomotor limitations must be included in studies of performance expression in order to demonstrate a holistic representation. Therefore, further investigation into perceptual and cognitive timing limitations appropriate for groove-based music (i.e., jazz performances) is needed to capture a more complete picture of expressive timing deviations in groove-based frameworks.

Additionally, several models have made an explicit connection between expressive timing and kinematics (Feldman et al., 1992; Friberg & Sundberg, 1999; Todd, 1992). Latest trends in the study of joint action have embraced motor cognition (i.e., embodied cognition) theories as a mechanism for investigating mental processing and expressive timing in cooperative performance (Jackson & Decety, 2004; Jacob & Jeannerod, 2005; Jeannerod, 2001). Analysis of kinesthetic motion/action in musical performance is supported by two theories: (a) performers' motions are shaped by psychological processes and task demands; and (b) motion is an indicator of emotional and communicative interpretation (Palmer, 2013). The focus on action underscores motor cognition inquiry and is proving to be a fruitful method for analysing motor patterns and sensory effects related to music making in a group context. Through applications of co-registration processes and functional data analyses techniques (Levitin, Nuzzo, Vines, & Ramsay, 2007), motion capture data can be precisely aligned with other types of data streams such as audio data, expressive performance cues such as timing deviations, and other related motor control data (Palmer, 2013). For example, recent analyses have been conducted on pianists' finger movements (Goebl & Palmer, 2008), clarinetists' ancillary gestures (Wanderley, Vines, Middleton, McCay, & Hatch, 2005), and percussionists' gestures (Bouenard, Wanderley, & Gibet, 2010). However, the gestures of musicians in timekeeper roles (e.g. bass and drums), improvisatory roles (e.g. jazz soloists, bass and drums), or performances with an underscoring isochronous pulse have not been investigated thoroughly. The analysis of ancillary body gestures and timing deviations in jazz and/or groove-based performances may demonstrate a more thorough account of musical expression.

Lastly, recent developments in the application of strain gauge sensor technology to musical instruments are proving to be a valuable method for quantifying human motor skills and expressive information in musical performance with extreme accuracy (Chatziioannou & Hofmann, 2013; Hofmann, Chatziioannou, Weilguni, Goebl, & Kausel, 2013; Hofmann & Goebl, 2014; Hofmann, Goebl, & Weilguni, 2013). The combination of strain gauge resistors, wavelet-based time series analysis, and state-of-the-art musical information retrieval algorithms may provide reliable empirical data that describe not only motor skills but expressive auditory performance cues such as timing deviations, intensity, articulation, timbre, and intonation. The utilization of musical information retrieval methodology, sensor data from strain gauge resistors, and infrared motion capture camera tracking systems to empirically capture expressive features of jazz and other groove-based performances in a controlled performance environment may provide valuable information towards a more holistic description of expressive elements in groove-based performances with extreme reliability and accuracy.

Jazz rhythm is complex and multi-faceted. This study provides an introduction to the intricate framework of jazz rhythm. An empirical answer to the operationalization of timing deviations in jazz performance is far from conception; however, quantitative research in the field has been expanded. Hopefully, the groundwork provided in this study inspires others to partake in jazz-related research utilizing empirical means in order to unravel the elaborate nature of perception, cognition, and action in jazz performance. Additional research of this nature will allow for the building of cognitive, educational, social, and cultural learning theories related to jazz and other groove-based performances.

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