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A Study of Timing in Two Louis Armstrong Solos

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For years musicians and critics have made statements about the nature of swing in jazz in general and the playing of Louis Armstrong in particular, based on the evidence of their ears. In order to quantify these issues, precise timing analyses of two mid-tempo solos by Louis Armstrong were analyzed, focusing in particular on stop-time sections. Two key elements of swing were analyzed; placement of the downbeats, and the swing or triplet ratio. For these solos, Armstrong played fairly close to on the beat, with a swing ratio of about 1.6 to 1.

FROM the beginning, it has been understood that a key characteristic of jazz is a certain rhythmic property that has generally been termed "swing." Inevitably, commentators have long attempted to discover what musical practices produce the swing effect. As early as 1917, when jazz was barely a decade old and Americans were just beginning to learn about it, a Columbia University professor said that it involved "the progressive retarding and acceleration guided by his sense of 'swing'" (Patterson, 1917, pp. 28–29), a startlingly early use of the term. In 1925 another early writer on jazz said that "the rhythm is angular, like the sporadic skidding of an automobile on a wet pavement" (Van Vechten, 1925, p. 57). In 1939, in the first good general book on jazz, the author said that in jazz most of the instruments "are playing rhythms variously suspended around the beat—as it were eccentric to it" (Hobson, 1939/1956, p. 30). A writer in the 1940s in a book highly regarded at the time said, "The subtle 'dragging' or 'pushing' of the beat is another characteristic of the 'hot style" (Finkelstein, 1948/1975, p. 42). Another important writer from the same period said

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that "the gifted player tends to place his notes a little away from the actual 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). A more recent writer, in a highly regarded work, said the musicians were "breaking away from the time framework of the ground beat to produce lines that are essentially rhythmically free" (J. L. Collier, 1978, p. 24). The author of one of the most widely used textbooks today says, "Syncopation often takes the form of accenting notes that occur just before or just after a beat. . . . Playing slightly after the beat can lend the music a soulful or laid back feeling . . ." (Gridley, 1985). Writing in 1995, yet another authority said, "at the most rarefied level of jazz performance . . . the melody remains in the vicinity of the beat but floats on either side, without restriction" (Kernfeld, 1995, pp. 24–25).

This is now the received wisdom in jazz studies: the jazz musician places his notes "around the beat." Inevitably, students of the work of Louis Armstrong have taken the same approach. Although it is not true, as is usually said, that Armstrong created the jazz solo, it is nonetheless the case that he so dominated the music in the period from the late 1920s to the late 1930s that certainly a majority of jazz musicians, and perhaps a large majority, were influenced by him. Danny Barker, a New Orleans guitarist well-known in the swing era said, "every other trumpet player . . . were copying Louis's style. . ." (Barker, 1986, p. 58). Jack Teagarden, considered by many observers to be the most significant trombonist of the "classic" period, said, "I guess that just about everywhere . . . musicians were listening to Louis' records" (Jones & Chilton, 1971, p. 99). The important swing trumpeter Bill Coleman said, "Armstrong was my first inspiration, and I listened to all of his records I could get hold of" (Jones & Chilton, 1971, p. 98). The swing band leader and vibraphonist Lionel Hampton said that Armstrong "influenced the whole music business" (Jones & Chilton, 1971, p. 110.)

In the past three-quarters of a century, Armstrong's solos have been subjected to countless thousands of hours of close study by musicians, musicologists, critics, and ordinary fans trying to discover his methods. Not surprisingly, a great many have concluded that Armstrong was playing "around" the beat, anticipating some notes, delaying others. The first important European jazz critic announced that "Louis has always surpassed other musicians in the manner in which he places and rests his notes," doing so by "slightly delaying or anticipating a few notes" (Panassie, 1942/1967, p. 83). A leading authority on New Orleans jazz says, "Armstrong has the right rhythm instinct and sense of time in 'swinging around and away from the regular beat' as he expresses it." A much-cited writer says that Armstrong would "condense or displace the melodic phrase a bit, rush this cadence, delay that one. . . . He would "dance around the beat" (Williams, 1993, pp. 54–55). A more recent writer said that he "alternately played ahead or behind a plodding, steady beat" (Peretti, 1992). One of the most venerated of jazz writers spoke of "the behind-the-beat delays and accents on which Armstrong based his innovations. . . ." (Williams, 1959/1975, p. 65).

Some writers have believed that Armstrong, rather than playing around the beat, was playing behind it. The author of the widely used textbook cited above refers to Armstrong's "slightly behind the beat rhythmic approach," (Gridley, 1985, p. 7), and a New Orleans authority said that he was "hesitating, always a little behind the beat" (Russell, 1939). A European critic claimed that Armstrong attacked on "the last third of the beat" (Hodeir, 1956, p. 205.). We have been able to find very few contrary opinions. One Armstrong biographer agreed that Armstrong played "around" the beat, but "he was more likely to place his notes ahead of than behind the beat," and the author of a 1999 book referred to Armstrong's "majestic on-the-beat phrasing" (Shipton, 1999, p. 51). These, however, are minority opinions. There is widespread agreement among jazz authorities that Armstrong plays either around the beat, behind it, or in the case of the venerated jazz writer, both.

A second important aspect of Armstrong's playing, and jazz in general, is the swing eighth, that is, the unequal accents of the first and second beat of each measure. This pattern is particularly evident in the treatment of the very common sequences of eighth notes present in jazz performances. These eighth notes are almost invariably paired, with the first of each pair weighted at the expense of the second. This weighting may be due to volume, sharpness of attack, or some other procedure, but it is widely understood that in most instances the first of these eighth note pairs, or "swing eighths" is longer than the second.

For some time jazz students have tried to determine how much the first of the swing eighths is weighted against the other—that is, what is the ratio between them? It is generally understood that this ratio may vary from player to player, even in the work of one player. However, there is widespread agreement that the ratio tends to be 2:1, in effect a tied triplet (e.g., Kernfeld, 1995, pp. 24–25). Some educators see this 2:1 triplet division of the beat to be a convention, and suspect that in practice it is more varied; others, however, appear to take it literally. In the past decade, several experimenters have attempted to determine the swing eighths ratio more exactly, using advanced electronic equipment (see Collier & Collier, 1997, for a review of the literature).

There is now good reason to believe that the swing eighths ratio is not a 2:1 triplet, but ranges between 1.4 to 1 and 1.7 to 1, that is to say, the first of the swing pairs occupies, roughly, between 58% and 63% of the beat. We assumed that Armstrong's swing eighths would follow this pattern.

To test these theories, we have subjected two of Armstrong's most famous early solos, in "Cornet Chop Suey" (1926, henceforth "Chop Suey") and "Potato Head Blues" (1927, henceforth "Potato Head") to detailed analysis. We have chosen these solos in part because they are played in "stop-time," a device frequently used during the period, in which the band, or some members of it, played only on certain selected beats, leaving the soloist free to go as he wished. In fact, during stop-time passages soloists almost invariably fol1owed the chord patterns and rhythmic structure of the original piece, as Armstrong does here.

We have chosen to examine these stop-time passages because they allowed us to electronically isolate Armstrong's notes, except where they fell on the first beat of a each measure ("Chop Suey") or every other measure ("Potato Head"), which the band also played. We have therefore eliminated all notes played on the first beat from the analysis. Several other segments were also eliminated. The last two measures of "Potato Head" were eliminated, because the band returns and the stop time ends. The last two notes of "Chop Suey" were omitted from the analyses because this is where the tune ends and they are played rubato. We have also eliminated from our calculations bar 34 of "Chop Suey," which is atypically rushed. Armstrong hits a clam at the opening high B of this phrase; either he tensed at that point, or tensed because of the error, and rushed the phrase slightly.

In addition to studying the stop-time sections of each solo, we examined the non–stop-time section of "Chop Suey" (bars 17 to near the end in Figure 4). We wanted to see if his note placement in the stop-time section was different from his usual practice. We discovered, somewhat to our surprise, that it was possible to separate his notes by eye and ear from the surrounding noise of the band.

There was, however, a second reason for choosing these particular solos for examination, for they were among the most admired of all Armstrong recorded performances from this early period, which many commentators consider his most significant. "Chop Suey" in particular became a model for thousands of players. Thousands of jazz trumpet players learned it, and many still play it today. These solos were thought to epitomize jazz of the day.

Experiment 1: "Cornet Chop Suey" and "Potato Head Blues"

METHODS

Analysis of the waveforms were performed using a waveform editor (Cool Edit 96). The solos were digitized at 44 kHz 16 bits (CD quality) and truncated at the onset of the first note, providing a zero reference. Event onset times were then computed for each note. Because waveforms for note onsets gradually increase, there is inevitably a certain measure of arbitrariness introduced in the selection of the onset times, but all onset times were selected to be positive-going zero crossings at the points where the waveforms began to be discernibly differentiable from the background noise. The coder, who was neither of the authors, was instructed to be consistently conservative, that is, choosing onset times toward the beginning of each waveform. Although we did not attempt a complete replication of the coding of an entire song, one of the authors compared his estimates with those of the coder for a number of notes, and agreement was generally within two or three cycles of a waveform, or typically 2 ms or less, so the variance introduced by the use of subjective judgment was deemed to be unlikely to have a substantial effect on the final interpretations. This is about the same level of accuracy reported by Ashley in this issue of *Music Perception.*

Although theoretically it was possible to differentiate the note onset times of the band and Louis Armstrong on the first beats, this was not practically possible. Louis Armstrong and the band were fairly well coordinated on these beats, and furthermore, slowing down of the waveform revealed that the different instruments of the band were not necessarily coming in together, although not in any consistent order. The waveform in any case increased in amplitude as described earlier for the Armstrong solo notes, so that again a start point had to be selected by eye and ear.

Figures 1 and 2 give examples of waveforms from the stop-time of "Chop Suey" (Figure 1) and where Armstrong's note emerges from the band (Figure 2). Readers can see in Figure 1 that the determination of the exact onset point is arbitrary only within a few cycles of a waveform. Figure 2 presents a more complex picture. Although the point selected as the onset of measure 16 would appear to the eye to be about 40 ms after where the change in the waveform occurs, this visual impression is an illusion. This was determined by sweeping playback of a segment back and forth over the area seen here, from whence it was determined that note onset was where it is seen in the picture. In any case, recall that most of the analyses presented herein were based on the stop-time sections of the two pieces.

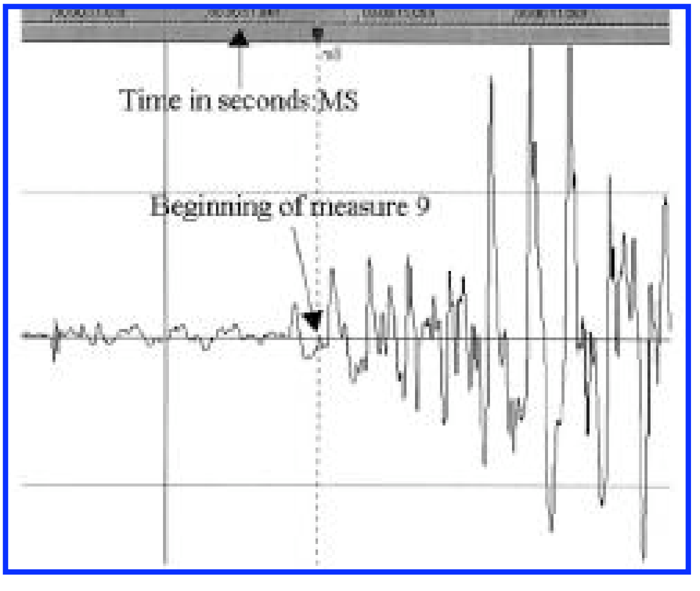

Fig. 1. Waveform from "Chop Suey." Armstrong's note emerges from silence.

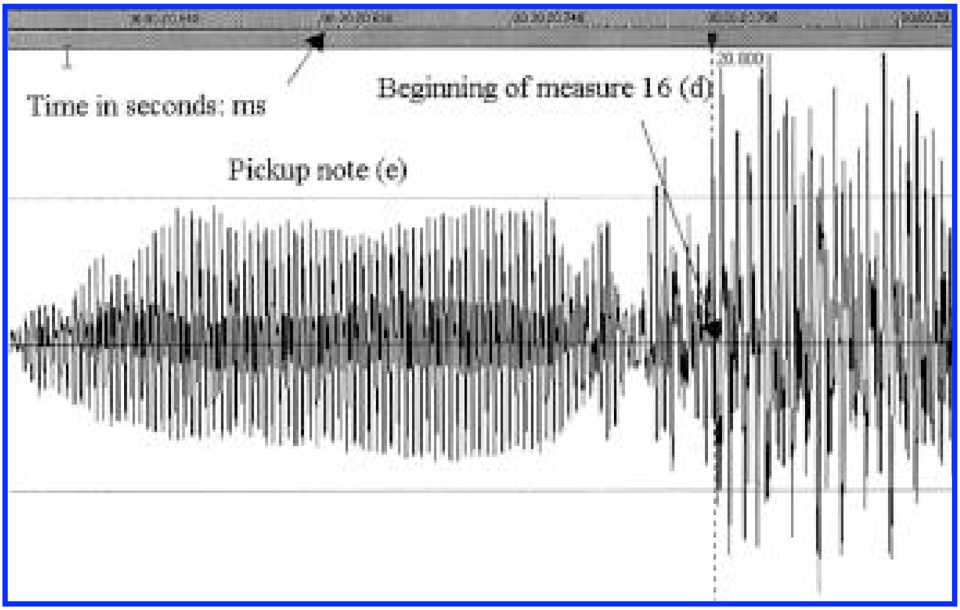

Fig. 2. Waveform from "Chop Suey." Armstrong's note emerges from the band.

METHODS OF ANALYSIS

The resulting event timings were in continuous absolute time, relative to the beginning of each song. These were converted into several dependent measures. Because we felt that the measure was a fundamental reference unit, each time was computed as time elapsed since the beginning of its measure. Thus, the first event in each measure always occurred at time 0, by definition, and was thus omitted from analyses. For the stop-time in "Chop Suey," each bar was marked by a band attack, and this event was therefore the reference. For the regular choruses (non–stop-time), Louis Armstrong's attacks on beat one were the reference points. In "Potato Head," the band accents occurred only every other bar, so Armstrong's attacks were used as the reference when there was no band attack. On the measures in which there was no attack on the downbeat, the attack time was estimated by linear interpolating between analogous eighths in the current and preceding measures, where both events were available, and then averaging these estimates. In a few cases, no downbeat interpolation estimates were available so that these measures were omitted from the analysis.

These times were then converted into "discrepancy" scores, computed as the difference between each note's onset time relative to the beginning of the bar, and its expected time had Armstrong been playing metronomic eighth notes. The expected note onsets were computed by multiplying the bar durations times 1/8, 2/8, 3/8, and so forth. Discrepancy was then defined as the actual minus the expected, so that positive discrepancies indicate playing late and negative discrepancies indicated playing early.

The third dependent variable was proportional discrepancy, which was the discrepancy divided by the bar duration. We felt this to be the most appropriate discrepancy metric for many analyses, because we wanted to normalize by the bar durations to take into account bar-to-bar tempo fluctuations. Proportional discrepancy tended to be less variable a measure than discrepancy. However, virtually all analyses came out the same whether discrepancy or proportional discrepancy was used, so the analyses presented herein were based on absolute discrepancy scores.

Finally, we computed the swing ratio. The interonset times of each note were obtained, and the ratios of the first and second eighth of each beat were computed, where both were available.

The time measurements are depicted in Figures 3 and 4. Note that because even eighths were used as the reference, the off-beats were expected to have substantial negative discrepancy scores (playing late) if Armstrong were to swing them at all, and this is indeed seen in the figures.

AHEAD OF THE BEAT/BEHIND THE BEAT ANALYSES

We first looked to see where Armstrong placed his notes relative to the downbeats. Recall that the first beats of the measures were used as reference points for the others and were thus eliminated from the analyses. We were, however, aware that Armstrong might have "shifted phase," that is, moved his own metric structure away from that of the band. That is, if his sense of where the downbeat was differed consistently from that of the band, then referencing all of Armstrong's non-downbeat notes to the band's downbeat would have been in error. We examined a number of downbeats and found no evidence that Armstrong was coming in at a point that differed systematically from the rest of the band. Indeed, when informally inspected at the submillisecond level it appeared that the different instruments entered at slightly different and apparently random points. Clearly, random variability in entry points will occur on the order of several milliseconds, if not more, even discounting the effect of randomness in rise times within and between instruments.

The average placement of Armstrong's notes for "Chop Suey" is seen in Figure 5 (left-hand figure), with percentiles in Table 1. The discrepancy scores for downbeats 2, 3, and 4 did not differ significantly from 0, $t(110) = -.80$, $p = .43$. The downbeats did not differ significantly among themselves, $F(2,108) = 1.69$, $p = .19$. For the downbeats in "Potato Head" (Figure 5, right-hand figure, beats 2, 3, and 4), he is virtually right on the beat. His mean was 2 ms ahead of the beat (median was 4 behind the beat, Table 1), $t\ (53) = .56$, $p = .58$. His downbeats did not differ among themselves, $F(2,50) = .117$, $p = .89$.

Fig. 3. Transcription of "Potato Head Blues" (from Peter Ecklund). Large superimposed numbers are the bar durations in seconds. Smaller numbers are the discrepancies from metronomic timing in milliseconds, where negative scores indicates that he is early relative to metronomic timing and positive scores indicate that he is late. The first notes of each measure are unmarked, as they were the reference points. Stars indicate band attacks, which occurred every two measures for "Potato Head." Because of error inherent in attempting to determine note onset times from waveforms, readers are cautioned against making too much of discrepancy scores for individual notes. Accordingly, the emphasis herein is in timing patterns across each piece.

Autocorrelational analyses of "Cornet Chop Suey" (Figure 6) generally showed positive correlations among the different eighth notes of a measure. This means that Armstrong displayed short regions of similar discrepancy scores. In other words, notes that were a little bit behind tended to come in patches, as were notes that were a little bit ahead. However, we could find no obvious musical interpretation of these patches (readers are invited to inspect Figure 3 on this point). Some of the patches may have been due to fluffs, which can easily be heard. Furthermore, Figure 6 shows

Fig. 4. Transcription of "Cornet Chop Suey" (from Peter Ecklund). Because this is in the trumpet key, and changes in turntable speeds over the years may have intruded, the audible key is about E♭. During the stop time (through measure 16), the band attacked on the first beat of each measure. Timings obtained for the nonstop time section of the solo are inherently less reliable than ones before that, where Armstrong was playing by himself.

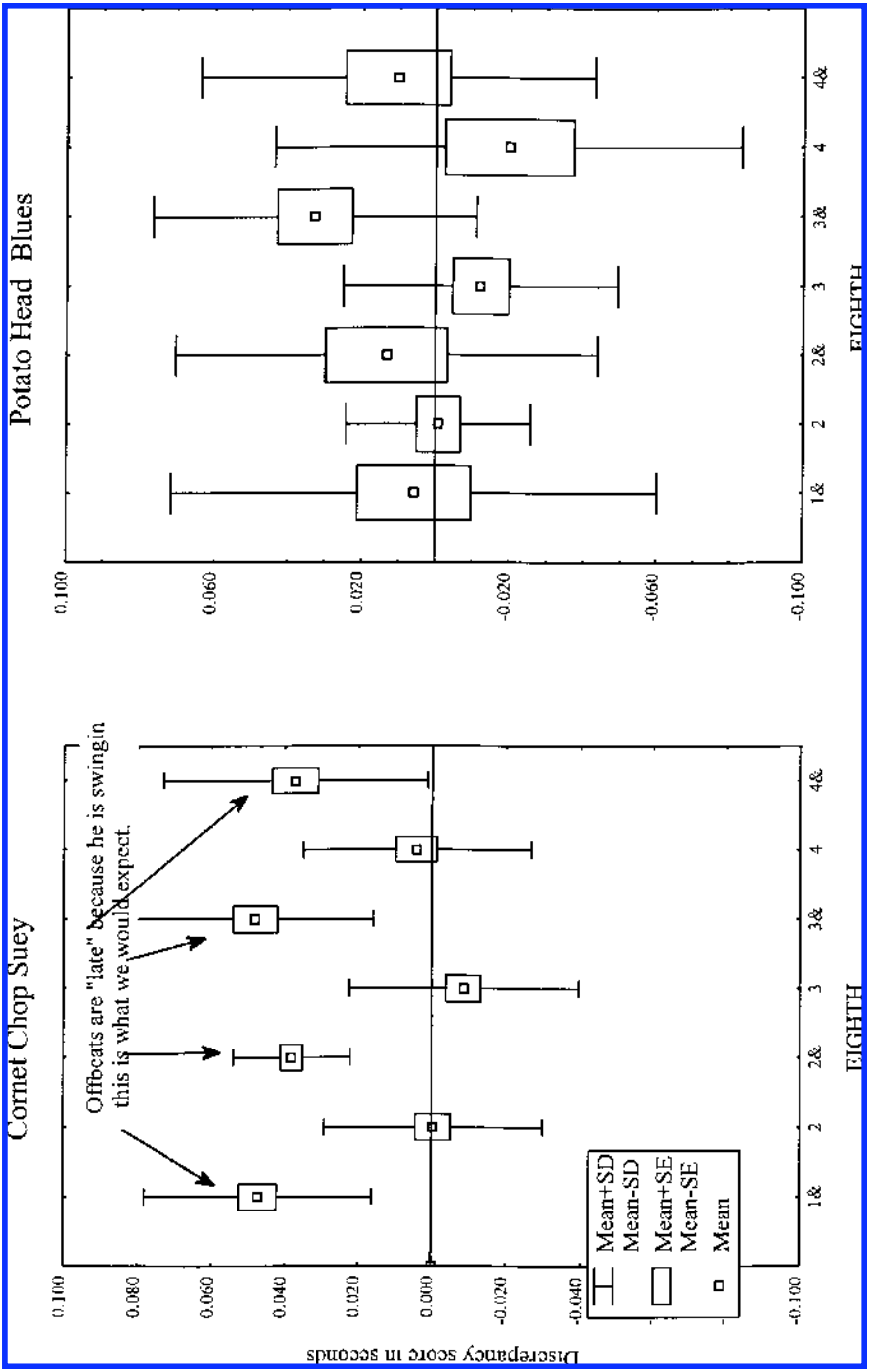

Fig. 5. Means and distributions of the discrepancies from metronomic timing for both downbeats and off-beats, for both songs.

TABLE 1
Percentile Table for the Discrepancy Metric in Milliseconds, Downbeats Only

Percentile	"Potato Head Blues" Corrected (MM 186)	"Cornet Chop Suey" (MM 173)
90th	29	38
75th	13	11
50th	4	-6
25th	-12	-18
10th	-33	-31

that the results from our classical trumpet player (introduced below) had a similar pattern. Coupled with the fact that Armstrong's beat discrepancies are mostly small in absolute terms (Table 1), we find it hard to reject the interpretation that this patchiness is more mechanical than interpretive. We return to the issue of how much was intentional in the general discussion.

SWING RATIO

Armstrong's swing ratio did not differ between the stop-time and playing with the band in "Chop Suey," $t(45) = .479$, $p = .63$, so analyses were performed on both sections collapsed together.

There are really two null hypotheses against which we would want to compare anyone's swing ratio. The first is that Armstrong was indeed playing even eighth notes, that is, not swinging. This would almost certainly be the case if the performance were fast enough, owing merely to technical difficulties.

At slower tempos, though, we would be surprised by even eighth notes. The second null hypothesis arises from prior work (G. L. Collier & Wright, 1995) that demonstrated that musicians, including those with no jazz background, play triplets at a ratio less than 2:1. This ratio is tempo dependent, becoming more even as the tempo increases (but at tempos not so fast that this limitation is likely to be purely physical). The reasons for this discrepancy between a strict 2:1 ratio and the ratio as actually performed (which we call the "natural" 2:1) are beyond the scope of this article, but we take this to have nothing to do with swing time. Nonetheless, we might hypothesize that the swing ratio is nothing more than this "natural" 2:1 ratio, as it is actually performed by jazz and classical musicians alike. In other words, when jazz musicians swing, perhaps they are doing nothing more than playing these distorted natural triplets.

The results are seen in Figure 7, which show Armstrong's performances on "Potato Head" and "Chop Suey" compared with the results

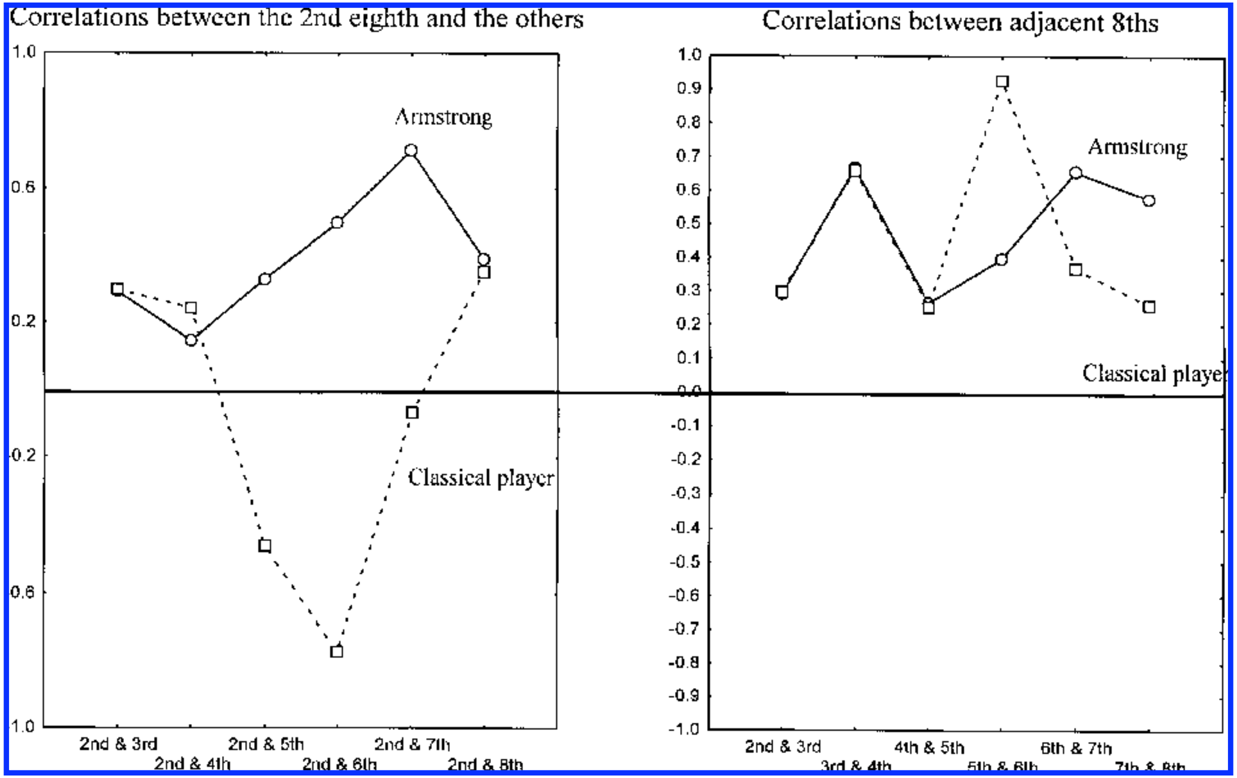

Fig. 6. Correlational analyses, "Cornet Chop Suey," both Armstrong and the classical musician. The left side of the figure gives the correlations between the second eighth note of each measure (1&) and each of the remaining eighth notes. The right figure gives the correlations between adjacent eighth notes, that is, the second and the third, the third and the fourth, and so on. Note that these subseries correlations (Pressing, 1999) are similar to but not the same as autocorrelations, as the vectors correlated do not overlap. Correlation denominators (standard deviations) were computed by using all available notes, and numerators (covariances) were computed by using all available notes where both pairs were available (S+ "available" method).

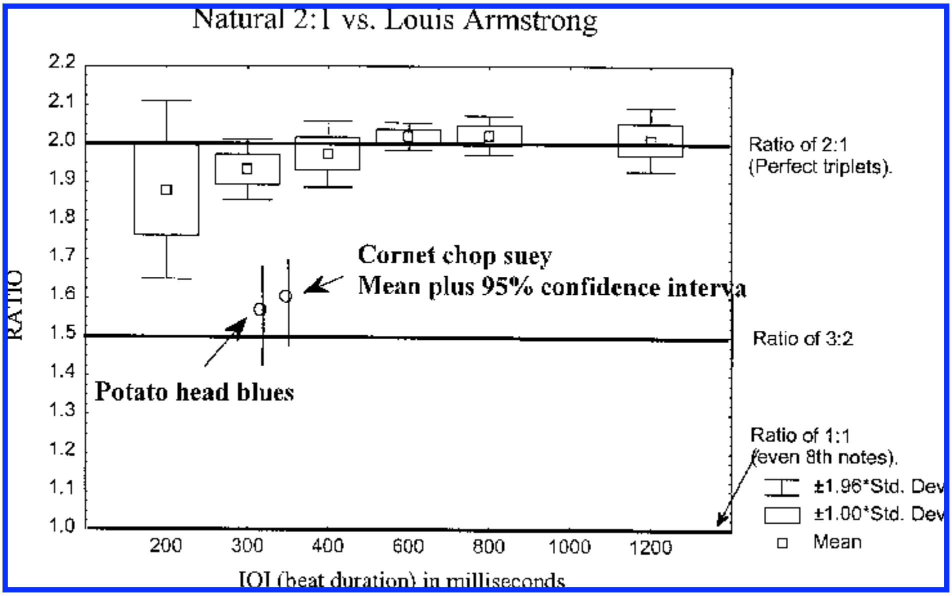

Fig. 7. Louis Armstrong's swing ratio, compared with 2:1 ratio of classically trained musicians. Because of error in the original recording speed, his actual tempo might have been slightly different from the tempi indicated here.

taken from G. L. Collier and Wright (1995). Qualitatively, in "Chop Suey," in 72% of the pairs of swing eighths, the first note is longer than the second. In "Potato Head," the first is longer than the second 95% of the time. Quantitatively, we can reject both null hypotheses: Armstrong's swing ratios are not even, yet they are more even than would be predicted by the natural ratios hypothesis, which suggests ratios closer to 2:1 in this tempo range, and differ significantly from

⇐ **Fig. 6.** (Continued) Data used were "proportional discrepancies," that is, the discrepancies between metronomic timing and actual timing, divided by the bar duration. With this approach, the autocorrelations do not include local similarities of durations due to fluctuating bar durations. However, differing beat duration expectations are included, so that the classical trumpeter's tendency to slow down in the middle of the measure and then speed back up is reflected in negative correlations at the appropriate lags, as we see in the left-hand figure. Note that the differing beat expectations induce positive correlations between adjacent eighths (right figure), swamping any negative correlations induced by motor delay (Wing & Kristofferson, 1973). Note also that negative correlations induced by motor delay cannot account for negative correlations at a distance of the sort seen in the left-hand figure (e.g., Vorberg & Wing, 1996).
The positive correlations for adjacent lags, seen in the right-hand side of the figure, demonstrate that in fact Armstrong and the classical player have roughly similar correlational patterns. These correlations were more positive when the durations were not normalized by bar length, thereby incorporating the effects of tempo drift.

Armstrong's ratios. Furthermore, the mean ratios for the two songs, which happen to be at similar tempos, are almost identical; 1.61 for "Cornet Chop Suey" (173 beats per minute) and 1.58 for "Potato Head Blues" (186 BPM) ($t(94) = .36$, $p = .72$). Therefore, Louis Armstrong's average swing ratio is closer to 3:2 (i.e., 1.5) than 2:2 (even) or 4:2 (strict triplets). We see that this is similar to ratios found to be workable in classical contexts for certain interpretative forms (Gabrielsson, 1987; Gabrielsson, Bengtsson, & Gabrielsson, 1983).

In addition to the pairs of swing eighths, there were other offbeat patterns of interest, especially eighth-quarter-eighth, and eighth rest-dotted quarter, which are exeedingly common in jazz. Does Armstrong treat these notes as he does the second, off-beat, note in swing pairs, by playing them substantially late? In fact, in "Chop Suey" he strikes these syncopated notes late relative to metronomic eighth notes 82% of the time, in "Potato Head" 88% of the time. Further, his distance from the beat for these notes is virtually the same as for the second note in the pairs of swing eighths. Thus, the delay of the second note of the beat pair appears to be part of a general practice of striking off-beat notes significantly late, whether or not they are preceded by a downbeat eighth.

DOES THE SWING RATIO VARY SYSTEMATICALLY?

An examination of whether the swing ratio depended systematically on musical factors yielded mostly negative results. The swing ratio did not depend on position in the bar for "Potato Head," $F(2,16) = 1.500$, $p = .25$ (although note the low power of the test), or "Chop Suey," $F(3, 50) = .915$, $p = .44$. For "Chop Suey," the ratio did not depend on whether he was playing stop-time or with the band, $F(1,65) = .23$, $p = .63$. There is, however, a slight tendency in "Potato Head" for the off-beats to be later when preceded by a down beat, but this is not significant, $F(1,44) = 1.694$, $p = .20$, nor was there any trend in this direction for "Chop Suey."

A NOTE ON THE ENDING TAG OF "CORNET CHOP SUEY"

Finally, we note the interesting ending tag in cornet (Figure 8). Armstrong plays five groups of eighth notes slurred together in groups of threes, mostly in a long-short-medium grouping pattern. This grouping pattern is reflected in the timing, as seen in Figure 7. It is interesting that when the musical phrasing is in three-note patterns rather than the standard swing eighths, that the swing eighth division does not apply. However, we see that as soon as he returns to eighth notes, he returns to the long-short pattern of swing eighth notes.

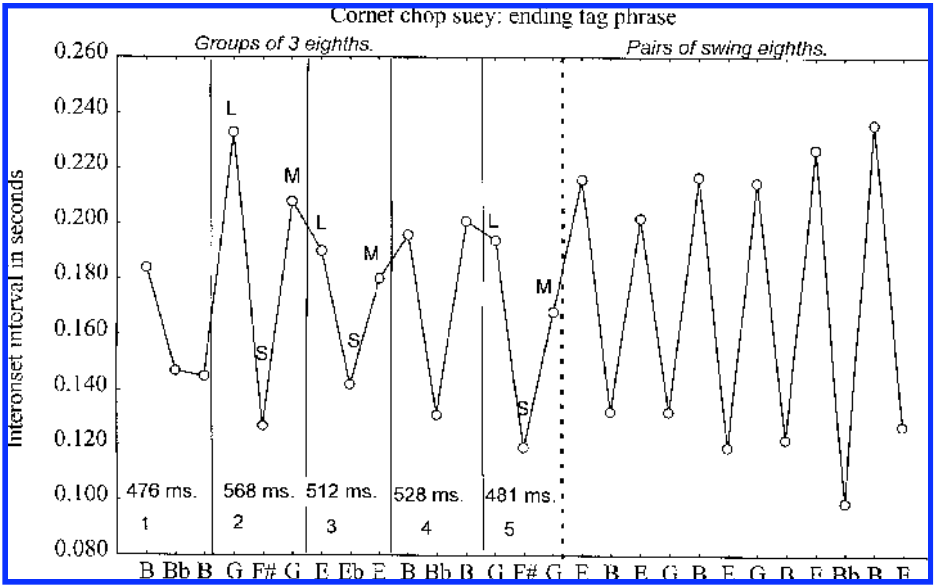

Fig. 8. Timing on the ending Tag, "Cornet Chop Suey."

Experiment 2: Classical Trumpet Player

It remains possible that Armstrong's approach to rhythm is not particular to him, but is universal, caused by factors not confined to jazz. We therefore turned to a classical performance to see if there were rhythmic similarities to jazz.

METHODS

Mary Hastings sight-read the solo to "Chop Suey." Hastings has a Master's degree in music from The Julliard School. She is primarily interested in classical music, has no experience in the playing of jazz, and little listening experience, except what is routinely unavoidable in public music (Peter Ecklund, personal communication).

She was instructed to play it straight and not attempt to swing it. She played it twice through, once without and once with a metronome. Her timekeeping with the metronome was poor, so that the version without the metronome was analyzed. This performance was played in three segments, so the three segments had to be sewn together for the analysis.

The methods of analysis were the same as in the preceding experiments, with one exception. Because there was no metronome or band, measures that had no note on the first beat failed to provide a first beat reference that was the basis of the analyses previously described. In these cases, the expected onset of the first beat was interpolated as we had done for the non–stop-time Armstrong sections, as described earlier. In several cases, no interpolated estimates were available, and these measures were omitted. One measure with triplets was excluded, as was one poorly timed measure in a segment transition.

SWING RATIO

Because the trumpet player was told to play metronomically (i.e., was not instructed to swing), the expected eighth ratio was 1:1, in contrast to Louis Armstrong's clear swing ratio. The mean swing ratio was 0.997, with a minimum of 0.68 and a maximum of 2.13, not significantly different from 1. When broken down by position in the bar, means for positions 1, 3, and 7 were 1.00, with position 5 at 0.99 (no significant difference among them). Thus, when told to play metronomically, the trumpeter varied greatly from beat to beat, but showed no evidence of swinging or any other systematic deviation from evenness.

DISCREPANCY SCORES

Figure 9 shows the proportional discrepancy for each beat. The trumpeter is consistently ahead of the beat relative to where she starts each

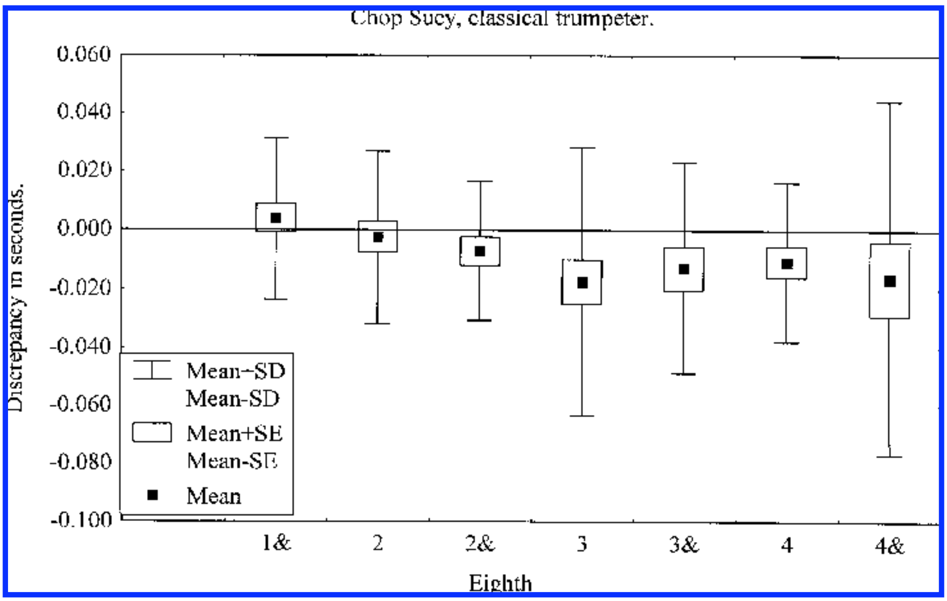

Fig. 9. Mean discrepancies from metronomic timing, classical trumpeter, "Cornet Chop Suey."

measure (t = -3.41, df = 191, p < .001). Although the differences among the discrepancies are not significant (F (6,185) = 1.24, p = .29), the graph leads us to speculate that she had a tendency to "rush" throughout the measure and then slow down as she comes to the beginning of the new measure. Because she is playing without an external metronome, she appears to be catching up with her own internal bar length-time keeper, arguing for the presence of hierarchical timing-keeping. We see a bit of this pattern in Armstrong's downbeats for "Chop Suey" (Figure 5, left-hand side). It is slightly true for "Potato Head" as well, where he doesn't catch up until he restarts the measure (Figure 5, right-hand side). In the latter case, he appears to be falling more and more behind the beat, although because we have defined the first beat as the reference point, he too catches up by the beginning.

It is not safe, of course, to generalize from one example. However, it does not appear that Armstrong's rhythmic method is employed by all classical players. As Armstrong's delay of the second eighth is found even when not preceded by the first eighth, we can conclude that this swing style has nothing to do with mechanical limitations, but rather is indeed a stylistic matter.

General Discussion

Does Armstrong, then play his notes ahead of the beat, behind it, "around" it, or as one of the early commentators suggested, "eccentric" to it? As far as the off-beat notes are concerned, we can safely conclude that as a general rule Armstrong places these notes significantly behind the beat, rather than in some fashion "around" it, at the 1.6 to 1 ratio, with considerable variation. This, given what is understood about swing eighths in jazz playing, is what we had expected.

What, then, about the placement of the downbeat notes? Is Armstrong playing ahead of the beat, behind the beat, or "around" the beat? If Armstrong were actually playing around the beat, as many observers have suggested, the effect would be obscured by averaging. Autocorrelational analyses showed that Armstrong was weaving around the beat, but as we have discussed, there were reasons to suspect that this was more mechanical than expressive. With respect to his average deviation from the downbeat, Armstrong did not differ significantly from being right on the beat in either song. In absolute size, his deviations from the downbeat are small. The median deviation from the beat for these notes in "Potato Head" was 0 ms, and for "Chop Suey" it was –6 ms. In "Chop Suey," the 75th percentile is 11 ms, and the 25th percentile is –18 ms. Similarly, in "Potato Head," the 75th percentile is 13 ms and the 25th percentile is –12 ms. Thus, 50% of the deviations have a range of 29 ms or less for both songs. Translating these ranges into musical terms, at the song's tempi, a 64th note would be about 20 ms and a 32nd note about 40 ms.

So, Armstrong is, on average, on the beat on both songs. Couple this with the tight range of Armstrong's deviations around the beat, and we are led to a question: are the deviations intentional, or are they simply the result of a mechanical limit? That is, in these cases was Armstrong in fact not trying to play ahead, behind, or around the beat, but trying to hit the notes as close to the beat as it was possible for him to do?

The upper limit of jazz performance appears to be around 320 beats per minute (metronome tempo [MM]; Collier & Collier, 1994), a tempo at which only a few jazz musicians can play at all. At that tempo an eighth note has a duration of 94 ms, suggesting that in performance musicians have difficulty handling intervals this short. Friberg and Sundstrom (1997), in their study of jazz drummers' swing eighths, found that in tempos above about 150 MM the short second note of the eighth pairs remained at about 100 ms in duration, even when tempos reached 300.

This again suggests that jazz players have difficulty manipulating time durations of about 100 ms or less. Looking at it from a musician's viewpoint, we can understand why: at 160 MM, roughly the tempo of the solos under study, a note 94 ms in duration would be the equivalent of a sixteenth note. A technically gifted pianist could manage streams of these, but they would be beyond the ability of most wind players, especially brass players, as in the case of Armstrong. Obviously, the physical limitation will vary among instruments, and at least one reviewer suggested that some jazz players can play notes faster than eighths at MM 320. We grant that extremely fast passages occur in, for example, "sheets of sound," fast trills, and rough triplets, particularly when the fingers are pressed sequentially or in other simple patterns. However, we doubt that players can play a controlled series of notes of arbitrary fingerings at these rates. One hundred milliseconds is a well-known (rough) limit on arbitrary fingering alternations in motor control. It may also be true, as Friberg and Sundstrom (1997) suggest, that there is a perceptual limitation in roughly the same range, but that does not obviate the possibility of a physical limitation as well.

The foregoing refers to absolute rates of production, but when talking about anyone's interpretive timing variations, we are talking about controlled variation in the rate of production, which is a bit different. The Weber fraction (standard deviation/mean, the production equivalent of the just-noticeable difference, or JND) for production is typically 3–5% for simple isochronous (even) finger tapping for musicians, worse for nonmusicians. At the tempo of "Potato Head," this is 16 ms. To our knowledge, this has never been tested on a wind instrument. However, we believe that increasing the complexity of the task, as would be the case when the lips and fingers must be coordinated, and different notes require different finger patterns and muscular tension in the lips, would surely decrease the accuracy.

As we have seen, the bulk of Armstrong's deviations from the beat were substantially less than 100 ms. We strongly doubt that any musician could intentionally, whether consciously or not, place a note the equivalent to a 64th note away from a beat at the tempos jazz musicians usually play. It seems to us, then, that Armstrong, rather than playing ahead, behind, or around the beat as has so often been suggested, was attempting to place these downbeat notes exactly on the beat as he perceived it, and did so with remarkable accuracy.

A perhaps even more significant question is whether auditors could have perceived these deviations from the beat, even if Armstrong had intended them. The literature on the JND in temporal durations is inconclusive. For an isochronous sequence, the JND is about 5% (Friberg & Sundberg, 1995). In another instance, in a laboratory setting, the same research found the JND to be about 10 ms (for additional discussion of the JND in this context, see Reinholdson, 1987, p. 113). However, one problem is that perceptual acuity is highly context dependent: what may be a noticeable difference in a laboratory may not be even close to it in a real-life performance. Indeed, Friberg found the JND to be about 20% in a musical example at 170 MM (Friberg, 1995; Friberg, Sundberg, & Frydén, 1994). A second problem is that in a real musical example, it is hard to know what the reference for the computation of the JND should be: the measure, quarter note, eighth, etc.?

Armstrong's pieces were certainly a real-world context, and in the case of the stop-time portions, there were reference points only every four beats. Even using the quarter note as a reference point, 10% of a quarter note for the two Armstrong pieces is about 33 ms. Table 1 indicates that this would cover the majority of Armstrong's deviations from the beat, many of which were much smaller.

In sum, we find it highly questionable that even well-trained observers would be able to regularly detect these small discrepancies. And in fact, historically they did not: many skilled musicians have spent thousands of hours attempting to determine where Louis Armstrong placed his notes, and as we observed in the introduction, came up with varying conclusions. Too, we question whether these deviations could have been part of some intentional musical scheme. We could find no systematicity in the deviations.

Taken as a whole, it is clear that, in these pieces at least, Armstrong employed a consistent rhythmic system in which he struck down beat notes as close to the beat as could be reasonably expected, and played his offbeat notes swing eighths at a ratio of about 1.6, or about 30–40 ms later than even eighths would dictate, but with considerable variation.

We suspect that this finding can be generalized to Armstrong's work during the 1920s at similar tempi, when he was (according to many jazz critics) recording his most significant work. At slower tempi, such as *West End Blues,* he plays in a looser rhythmic style, and different rules might apply. In that case, it may well be appropriate to describe his playing as "eccentric to the beat" (Hobson, 1939/1956). Also, after about 1930 Armstrong adopted, for a variety of reasons, a simpler style using more open space, fewer and longer notes, and he may have changed his approach to rhythm as well. Further, at extreme tempos jazz musicians generally alter their way of playing swing eighths, and this may be the case with Armstrong.

Nor would it be safe to generalize these findings to jazz in general. It will be necessary to study the playing of a substantial number of jazz musicians, working in a variety of styles, before we can conclude anything about the swing effect. Nonetheless, given Armstrong's importance as a model and influence in the formative years of jazz, this study suggests that the accepted ideas about how jazz players place their notes in respect to the beat must be rethought. It should be clear that analyses of the details of jazz rhythm by the unaided ear should be viewed with suspicion.[1]

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1. The solos discussed in this paper can be found on the CD, *This Is Jazz 1* (Louis Armstrong, Sony Records, 1996), as well as other Armstrong collections. We are grateful to Peter Ecklund for permission to use portions of his Armstrong transcriptions of the solos analyzed herein. We also thank him for conducting the experiment with Mary Hastings, to whom thanks are also owed. We also thank research assistant Jocelyn James for tireless transcription of the Armstrong timings from the .wav files, and Jeff Pressing and Anders Friberg for informative reviews.

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