Effects of instructed timing and tempo on snare drum sound in drum kit performance

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This paper reports on an experiment investigating the expressive means with which performers of groove-based musics signal the intended timing of a rhythmic event. Ten expert drummers were instructed to perform a rock pattern in three different tempi and three different timing styles: "laid-back," "on-the-beat," and "pushed." The results show that there were systematic differences in the intensity and timbre (i.e., sound-pressure level, temporal centroid, and spectral centroid) of series of snare strokes played with these different timing styles at the individual level. A common pattern was found across subjects concerning the effect of instructed timing on sound-pressure level: a majority of the drummers played laid-back strokes louder than on-the-beat strokes. Furthermore, when the tempo increased, there was a general increase in sound-pressure level and a decrease in spectral centroid across subjects. The results show that both temporal and sound-related features are important in order to indicate that a rhythmic event has been played intentionally early, late, or on-the-beat, and provide insight into the ways in which musicians communicate at the microrhythmic level in groove-based musics. © *2015 Acoustical Society of America*.

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I. INTRODUCTION

The interaction of timing with other parameters, such as timbre and loudness, is increasingly being considered fundamental to musical expression. In many groove-based genres, drummers' timing is thought to provide the backbone for rhythmic expressivity. Yet we know little about the extent to which drum *sound* is affected by timing in drumming. In what follows, we investigate the extent to which expert drummers systematically vary the sound of the drum stroke when intentionally performing a certain microtiming, such as early, late, or on-the-beat.

Several studies lend support to the assumption that there is a close relationship between timing and intensity in music performance at the expressive or micro level. In an early study of systematic expressive variation in performance, Sloboda (1983) found that experienced pianists used a combination of timing and intensity, as well as touch (staccato versus legato), to communicate meter. Several experiments have also shown that when pianists are instructed to emphasize one voice in a polyphonic piano performance, this voice is played both louder and earlier (i.e., melody lead) than the other voices (Palmer, 1996; Repp, 1996; Goebl, 2001). By testing the utility of timing versus intensity for the identification of the perceived melody lead, Palmer's (1996) study shows that dynamics is likely the most important aspect. Goebl and Parncutt (2002) also found that the relative perceptual salience of two tones in a piano chord depended primarily on their relative intensity, not on their asynchrony.

Numerous performance studies have also found a systematic relationship between intensity and duration in the production of accents in music. More precisely, accented beats tend to be lengthened in performance (see, for example, Clarke, 1988; Drake and Palmer, 1993; Gabrielsson, 1974, 1999). This relationship between accented beats and increased duration has also been found in research specifically into drum playing (Dahl, 2000, 2004; Waadeland, 2001, 2003, 2006). Regarding perception, already in 1909 Herbert Woodrow drew attention to the similar function of relative duration and relative intensity (loudness) in the formation of musical accents (Woodrow, 1909, p. 1), and this has been confirmed in several more recent perception studies (Povel and Okkerman, 1981; Tekman, 1995, 1997, 1998, 2001, 2002, 2003; Windsor 1993). Tekman demonstrated a similar function for relative pitch as well, and research by Gouyon *et al*. (2006) indicates that sudden changes of *timbre* over time also lead to perceived accents. Singh (1997) found that timbre and pitch changes dominated over a loudness-based accent structure. Various interaction effects between dynamic accents and perceived duration have also been found (Melara and Marks, 1990; Tekman, 2002): if the patterns indicated by these dimensions were compatible, the interaction effect was stronger—that is, there was a *redundancy gain*—whereas if the different cues were conflicting, the effect was neutralized or even negative [a *redundancy loss*; also reported by Woodrow (1909)].

Timing a stroke early or late can be regarded as an instance of temporal asynchrony between two rhythmic events. In the present experiment, one rhythmic event is an

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[a)] Electronic mail: anne.danielsen@imv.uio.no actual stroke on a drum, and the other a stroke on another part of the drum kit (for example, the hi-hat) or simply a metric expectation for a beat position generated by the internal pulse in the listener or musician. Looking further into the research on the perception of such asynchronous or multiple onsets, we find that humans generally have a very high sensitivity to the *order* of sounds (Warren, 1993), and that intensity and pitch tend to modulate the perception of this order. A study by Hove *et al.* (2007) shows that sensorimotor synchronization with chord sequences containing tone-onset asynchronies was affected by the pitch of the leading tone (high versus low). A different approach to the study of the relationship between temporal and sound-related features of microrhythm is found in a cluster of perception studies from Kungliga Tekniska Högskolan (KTH) in Stockholm. Here, different performative variations were added to computer-controlled performances and judged as to their perceived naturalness (later implemented in the so-called KTH Rule System for Musical Performance; see, for example, Friberg *et al.*, 2006). The KTH work demonstrates that patterns of change in one performative auditory dimension are related to particular variations in other dimensions.

Summing up, several experiments into both music performance and music perception point toward an intimate relationship between temporal and sound-related aspects of microrhythm. This is particularly true for the tripartite relationship between timing, intensity, and duration. Timing and intensity are both means of making a particular voice or event stand out from the surrounding events, and both affect duration: timing alters duration directly, and intensity affects our perception of duration. The aspect that is most effective in this regard is likely to vary with the musical context.

In groove-based music (see, for example, Alén, 1995; Bengtsson and Gabrielsson, 1983; Butterfield, 2010; Clarke, 1985, 1988; Danielsen, 2006; Desain and Honing, 1989; Friberg and Sundström, 2002; Iyer, 2002; Kvifte, 2007; Monson, 1996; Prögler, 1995), it is crucial to communicate in performance whether a beat is meant to be early, late, or on the expected beat position. At one level, this may seem like a straightforward task: in order to signal early or late timing, one places the beat early or late. However, we know that the tolerance for timing varies with genre and context, and that an actual early or late position of a beat measured in relation to a metric grid might be perceived by the listener as falling on-the-beat—that is, within the acceptable time window for on-the-beat playing (see, for example, Bjerke, 2010; Danielsen, 2010, 2012; Johansson, 2010). Communicating early or late timing thus concerns more than simply positioning the sounded beat early or late in relation to a pulse point on a metric grid. It is necessary to communicate that the rhythmic event *as a whole* stands out in relation to on-the-beat playing in the given musical context. Thus, and also in the context of groove-based music, it is likely to be the case that intensity, and possibly also other sound-related aspects, is important to both expressing (in performance) and identifying (when listening) a beat as standing out from the rest of the rhythmic texture.

"Laid-back" and "pushed" are terms often used to denote microtemporal relations in rock performances. In the former, the stroke is performed slightly late compared to the temporal reference for the beat, whereas in the latter, the stroke is performed slightly early. These notions are well known among drummers and represent qualities of microtiming that many drummers spend years practicing in order to be able to incorporate them into their playing. The present study investigates the expressive means with which drummers signal that the timing of a rhythmic event is meant to be perceived as early or late. We hypothesize that both temporal and sound-related features are important in communicating this quality to listeners. Pursuing this end, we conducted a study that investigates the effects of instructed timing on various sound parameters in rhythm performance. We focused our empirical investigation on the performance of drummers and hypothesized that in the process of achieving early, late, or on-the-beat timing, the drummer leaves a sonic "stamp" on the drum sound that is systematically related to the timing profile. Based on previous research showing that drummers often use highly consistent but individual strategies in their playing (Dahl, 2011), we focused on systematic patterns at the level of each individual drummer as well as for the drummers as a group. We explored this possibility by measuring changes in loudness [sound-pressure level (SPL)] and timbre [temporal centroid (TC) and spectral centroid (SC)] of drum strokes after instructing drummers to play a rock groove under different timing and tempo constraints, addressing the following question:

(1) To what extent are there systematic differences in the acoustic signal between drumbeats played with different intended *timing* (a) at the individual level and (b) across subjects?

Various performance studies indicate that tempo has an effect on timing. For example, a uniform effect of tempo on the swing ratio has been found (Collier and Collier, 1996; Friberg and Sundström, 2002; Honing and De Haas, 2008; Waadeland, 2006, 2011). Each of these studies documents a clear decrease in the swing ratio (a less swung subdivision) at faster tempi. Repp (1995) found a similar interaction between tempo and expressive timing in romantic and impressionistic piano music, and investigations of the performance of *notes inégales* in French baroque music indicate the same effect (Moelants, 2011). Moreover, Johansson (2010) has documented how tempo influences timing in Scandinavian folk fiddling, and various examples of tempo-specific timing have also been reported (Desain and Honing, 1994; Honing, 2006; Repp *et al.*, 2002). Thus we also asked:

(2) To what extent are there systematic differences in the acoustic signal between drumbeats played in different *tempi*, and to what extent does tempo interact with instructed timing?

II. METHOD

A. Participants, task, apparatus, and procedure

Ten male drumset players, 19–48 yrs of age [mean $= 27$, standard deviation (SD) $= 9$], participated in the experiment. All of them were semiprofessional or professional drummers acquainted with rock and jazz playing, and all were also former or current jazz students. They all participated in the experiment on a voluntary basis. The participants were asked to perform a rock pattern in 4/4 time that is commonly notated as in Fig. 1.

The upper notes in the score denote ride cymbal; the middle notes, the snare drum; the bottom notes, the bass drum. Variations upon this rhythmic pattern are used in a large number of rock/pop tunes. With regard to this pattern, the participants were presented with two different categories of performance conditions:

(1) Tempo conditions.
Play the rock pattern along with the clicks of a metronome at the following tempi:
  (a) 96 beats per minute (bpm) (medium tempo);
  (b) 148 bpm (fast tempo);
  (c) 64 bpm (slow tempo).

(2) Timing style conditions.
At each of the three tempi listed above, the participants were given the following instructions:
  (a) Play the pattern as *naturally* as possible (condition: Natural);
  (b) play the pattern in a *laid-back* manner (condition: Laid-back);
  (c) play the pattern in a *pushed* manner (condition: Pushed);
  (d) play the pattern synchronized with/*on-the-beat*s of the metronome (condition: On).

The recording was done at the MIT recording studio, Department of Music, Norwegian University of Science and Technology, Trondheim, Norway. Because our focus in this experiment was on possible variations in the sound of an acoustic snare drum, we decided to use a drum pad instead of an acoustic cymbal, in order to better isolate the sound of the snare. The picture in Fig. 2 illustrates the construction of the experimental situation.

For our setup, we used the following equipment: a Ludwig acoustic metal snare drum (Ludwig Drums, NC), 6.5 in. deep × 14 in. wide, with a Remo coated Ambassador drumhead (Remo, CA) (no muffler was used on the snare drum); a Gretsch 20-in. bass drum (Gretsch, SC) with Evans Eq1 batter drumhead (D'Addario, New York); a Roland PD-31 drum pad (Roland, Japan); an AKG 414B microphone (AKG, Austria) to record the snare drum sound, positioned on a microphone stand close to the side of the drum, 7 cm above the rim, pointing toward the drum head and slightly off center; a Sennheiser 602 microphone (Sennheiser, Germany) to record the bass drum; and an AKG 321 microphone (AKG, Germany) to record the sound of the cymbal strokes performed on the drum pad. The audio signals from the microphones were run through Soundcraft Vi4 preamplifiers (Soundcraft/Harman, CT) into an RME Madi sound card (RME/Audio AG, Germany) and were recorded with the audio software Logic 9 (Apple, CA), with a sampling frequency of 48 kHz and 24-bit resolution.

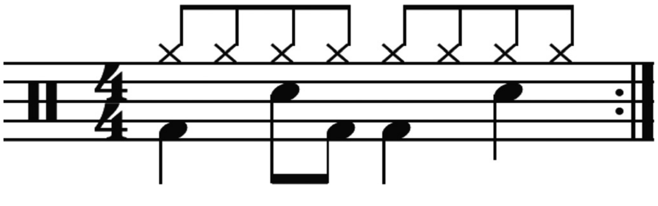


FIG. 1. Basic rock pattern in 4/4.

FIG. 2. Studio setup.

The participant was situated in a studio room with a headset, while the experimenters were positioned in a separate room with a mixer and the loudspeakers. We could see the participant through a window, and verbal communication was possible via microphones. In preparation for the performance of the task described above, each participant was given time to get acquainted with the instrumental setup. The experiment started when the participant reported that he was comfortable and ready to play. The experiment had a repeated-measures design. The Natural condition was used as a warm-up in each new tempo and began each session. The remaining performance conditions (Laid-back, On, and Pushed) were counterbalanced in order across participants. Prior to each performance, a participant was given verbal instructions for the next condition. Each condition was performed while accompanied by clicks from a metronome. The sound of the click was the sound of a wood block, which is very short and has a clear and well-defined attack. Every participant played each of the style conditions first at the tempo of 96 bpm, because we assumed that this tempo was comfortable for all drummers. The order of the tempi of 148 and 64 bpm was then randomized. For each series, a minimum of 20 strokes (10 bars) was recorded. All conditions in one tempo were performed before the participant was asked to switch to the next tempo.

After the performances, the participants were asked the following questions during an interview that was recorded as audio and digital video:

(a) Did you feel comfortable with the playing situation?
(b) Do you have any former experience with playing along with a metronome?

(c) Did you feel that you succeeded in performing the various tasks?
(d) Were any of the tasks more difficult than the others?
(e) What kind of strategy do you apply to play pushed versus laid-back versus on-the-beat?
(f) Have you practiced pushed versus laid-back versus on-the-beat drumming?
(g) How do you consider your own drumset timing: on-the-beat, laid-back, or pushed?

The reason for the interview was, on the one hand, to get feedback from the participants related to the experimental setup (that is, how did the experimental situation compare to a real performance situation?). On the other hand, we also sought insight into the participants' understanding of their own timing profiles and performance. An entire session for one participant lasted from 45 to 60 min.

B. Audio analysis

1. Selection of audio descriptors

Previous research has documented that SPL is the principal determining feature of experienced loudness (Rossing *et al.*, 2002); therefore, we decided to use SPL as the measure for loudness.

As to a measure for timbre, we used as our point of departure the ISO/IEC-defined MPEG standard's method for computing the similarity of percussive sounds, as well as previous studies of both subjective and automated classification of drum samples [see ISO/IEC 15938 (2002); Peeters *et al.* (2000)]. The MPEG standard includes three descriptors, log-attack time (LAT), SC, and TC, and builds in part on the three-dimensional perceptual model of timbre proposed by Grey (1977) and later revised by Krimphoff *et al.* (1994). The latter study suggested the following acoustic correlates for the three dimensions: (1) the centroid of the sound spectrum (SC); (2) the logarithm of the rise time (LAT); and (3) spectral flux. According to Lakatos (2000), for both percussive and harmonic instruments, dimensions 1 and 2 of Grey's three-dimensional perceptual model of timbre strongly correlate with SC and LAT, respectively, whereas the psychophysical nature of the third dimension appears to vary with the composition of the stimulus. Also, previous research documents that SC accounts well for the experienced brightness of sound, that is, for experienced spectral aspects of timbre (see Donnadieu, 1987, pp. 274–280; Schubert and Wolfe, 2006). In working out a computational model for the similarity of drum sounds, Pampalk *et al.* (2008) found both SC and TC, but not LAT, useful for the snare drum. Three descriptors, then, were selected for our analysis and defined as follows:

(1) SPL: Defined as the root-mean-square (rms) amplitude of the signal, measured in dB, with a 0 dB reference given as the average rms amplitude of all strokes in all series.
(2) TC: Defined as the energy-weighted mean of the time of the signal, in milliseconds relative to start at 2% of maximum signal value.
(3) SC: Defined as the amplitude-weighted mean of the power spectrum components of the signal.

The three dependent variables measure different aspects of sound. Regarding the relationships between them, it has been found that increased intensity tends to increase the amount of high-spectrum content of a signal, thus making the sound brighter (Beauchamp, 1982; Grey and Gordon, 1978). One might thus expect a positive correlation between SPL and SC. Interestingly, however, in an unpublished pilot study for the present experiment, we found indications of a *negative* correlation between SPL and SC.

2. Selection of time window for analysis

The analysis time window had to be carefully selected in order to avoid sound leakage from the strokes on the cymbal pad preceding and following the snare drum strokes (see Fig. 3). For SPL and TC, a time window covering the first 125 msec of each stroke was selected. Manual post-experiment inspections of amplitude/time envelopes revealed two distinguishable phases in the proceeding of the snare drum sound: a transient phase and a stable/sustain phase. For SC, we decided to investigate the signal separately in these two phase windows (SC1 and SC2), placed symmetrically around the mean TC of all strokes (27.4 msec), in order to capture the characteristics of each phase. For both SC1 and SC2, a 23.2 msec window was selected with a Hanning window.

C. Preprocessing and statistical analysis

Data from 120 recorded series of drum strokes (10 participants; 3 tempi: 64, 96, and 148 bpm; and 4 tasks in each tempo: Natural, Laid-back, Pushed, On) were gathered. Because the Natural series was used as an adjustment to each new tempo, all data for these series were omitted from

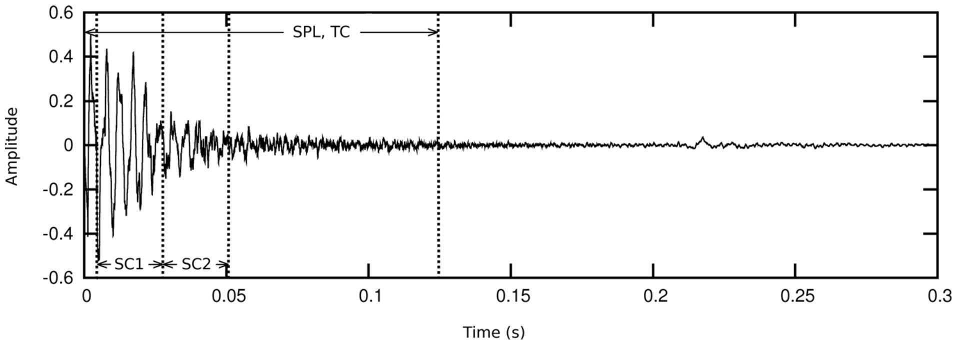


FIG. 3. Signal of a single stroke in tempo 148 bpm. Window indicated for each descriptor. Sound leakage from stroke on cymbal pad visible at 0.225 s. SPL = sound-pressure level, SC = spectral centroid, TC = temporal centroid.

the analyses. The first four and last two strokes of each series were also excluded from the analysis to eliminate any outlying data that might have been affected by the adjustment to the given task or the conclusion of the series. In addition, strokes on the rim of the snare drum and obvious mistakes were identified by listening to the recordings and removed from the sound files. The actual microtiming profile of each drum stroke was determined by manually measuring the distance from the onset (defined as first-zero crossing) of the drum stroke to the onset of the corresponding click in visual amplitude/time representations of the sound files in the software Amadeus Pro version 1.5.4 (HairerSoft).

Before statistical analysis, all series for the conditions Laid-back, Pushed, and On in all tempi were manually screened for normal distribution in *Q*-*Q* plots. Extreme outliers in the data sets (defined as values more than 3 times the interquartile range away from the median), probably produced by erroneous playing, were identified and removed. Many of the series of data for TC and SC2 did not display a normal distribution. We therefore decided to analyze the data in two steps:

(1) For the analysis of main and interaction effects of the two independent variables (instructed tempo and timing), we used only the measures with normally distributed data, that is, SPL and SC1.

(2) To get a better grasp of the full picture of the acoustic differences between drumbeats played with different intended timings, we analyzed instructed timing data for all descriptors (SPL, TC, SC1, and SC2) using non-parametric tests.

Though all of the participants reported performance experience with a metronome, they were likely to differ on a microtemporal level as to how successfully they were able to synchronize their strokes to the metronome. In order to ascertain the extent to which the drummers were able to play laid-back or pushed when instructed to do so—that is, to accomplish the performance task—we first compared the average (the arithmetic mean) *actual* microtiming profile of the Laid-back and Pushed series with the On series for each individual (the On series were the performances where the drummers were instructed to play in synchrony with the metronome). To check the statistical solidity of differences between means, repeated-measures two-way analysis of variances (ANOVAs) were conducted for each participant individually, using instructed timing and tempo as the independent variables and actual performed timing as the dependent variable. The repeated measures related to the repeated drum strokes within each participant's performance.

We then proceeded to the statistical analysis of the effect of instructed timing and tempo (independent variables) on the selected acoustic measure parameters for intensity and timbre (dependent variables). In the analysis of the data with normal distribution [see step (1) above], we first conducted Pearson's correlations, both at the individual level (single strokes) and across participants (based on the arithmetic means for each series), to test whether variations in SPLs were correlated with variations in values for SC. The variability in correlation was too large (see Sec. III) to justify the performance of a multivariate analysis of variance (MANOVA). We therefore decided to perform repeated-measures two-way ANOVAs.

Data for a given participant were first normalized over the average of all performances by that participant, in order to neutralize the effect of the differences in overall level between drummers. The average SPL and SC1 (arithmetic mean) for each series were then calculated. Manual inspection of the data revealed that one participant had an unusually large and non-systematic spread in SPL and SC1 and played considerably more softly than the other participants as well (see descriptive statistics in Tables III, IV, and V in the Appendix). These results might be interpreted as indications of uncertainty as to how to solve the task. It is interesting to note that, during the interview, this particular drummer reported that in his former practice he had not practiced pushed/laid-back/on-the-beat drumming as such. Moreover, he commented that he found both pushed and laid-back hard to perform, and that his ideal of drumming is to stay right on-the-beat. He also observed: "When I am asked to play with a click, my focus is often shifted from keeping a steady beat to listening for the click. I am not that focused on playing correctly; instead, I listen to the beat of the click." We came to regard this drummer as an outlier and excluded him from the analysis. Data for the outlier are reported in the descriptive statistics at the individual level (listed as participant No. 10).

We then conducted repeated-measures two-way ANOVAs on means of series to investigate whether there were main effects of instructed timing and tempo across participants ($N = 9$). *Post hoc* tests of pairwise comparisons were performed with Bonferroni corrections for multiple comparisons.

In step (2), we analyzed data for all audio descriptors (SPL, TC, SC1, and SC2) using non-parametric tests in order to better grasp the full picture of acoustic differences between drumbeats played with different intended timing. Because standard non-parametric tests do not allow for analyzing interactions, we focused in this part on the effect of the independent variable "instructed timing" only, using only data for one tempo. We chose tempo 96 because it is a comfortable tempo for drummers to perform the rock pattern. This was also the first tempo to be performed for all drummers in the experiment. We therefore concluded that this tempo was most suited for investigating the effect of instructed timing independent of tempo constraints. Friedman tests of differences among laid-back, pushed, and on-the-beat strokes were performed on each participant's data individually. Next, we wanted to investigate whether there were significant differences in median across participants ($N = 9$). Non-parametric Friedman tests were thus performed on differences among medians of all series in tempo 96. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons.

Descriptive statistics are provided in the Appendix (Tables III, IV, and V). All statistical analyses were performed using SPSS version 19 (IBM, Inc., New York).

III. RESULTS

A. Ability to accomplish the performance tasks

We found that for 78 out of 81 Laid-back, Pushed, and On series (participant [9] × style [3] × tempo [3]), the average actual microtiming profile corresponded to the given timing instructions—that is, when asked to play pushed strokes, for example, the drummer actually did so in comparison to the corresponding On series (that is, the average of the Pushed series was ahead of the average of the On series, while the average of the Laid-back series was behind). For one particular participant (No. 3), however, all of the series (Laid-back, Pushed, On) in tempo 64 bpm had an incorrect actual timing profile (the participant also reported difficulty in accomplishing the task at that tempo in the interview). Descriptive statistics of the microtiming profiles of all series by all drummers are given in Table I (the outlier is listed as participant No. 10).

A significant main effect of instructed timing on actual timing for all participants was found at $p < 0.001$ (see Table VI in the Appendix). Contrasts revealed statistically significant differences between timing style series Laid-back and

TABLE I. Descriptive statistics of microtiming (TIM). Note*:* Timing in msec.

		64 bpm			96 bpm			148 bpm		
Participant	Style	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
1	*N*	−26	18.4	17	8	7.2	23	2	8.8	28
	B	19	23.1	18	43	13.4	24	6	12.3	28
	P	−65	13.1	14	−44	15.4	23	−18	10.1	26
	O	−36	15.0	19	−1	10.8	24	−1	6.7	30
2	*N*	−25	14.3	32	−20	11.7	38	−6	9.6	50
	B	−9	14.7	31	−4	14.0	38	12	8.3	50
	P	−36	11.9	32	−36	12.7	38	−20	9.3	50
	O	−21	16.7	32	−3	13.3	38	−13	8.4	50
3	*N*	−52	14.0	28	−13	10.5	34	−1	7.4	41
	B	−5	17.5	27	5	14.5	34	8	10.4	41
	P	−2	12.8	30	−37	11.5	34	−23	12.2	41
	O	9	17.9	34	−7	8.4	34	−1	5.6	41
4	*N*	9	8.5	26	−8	6.9	42	2	7.9	42
	B	51	13.1	24	24	10.9	36	34	10.8	44
	P	−45	10.7	24	−64	17.5	30	−29	7.4	46
	O	2	8.2	26	−15	7.3	36	−5	5.2	46
5	*N*	−4	12.6	18	−15	13.4	36	−18	14.7	36
	B	31	15.5	18	16	14.9	26	32	13.9	38
	P	−77	16.5	18	−120	20.3	20	−77	22.9	34
	O	4	12.5	18	−11	12.0	34	−8	11.0	34
6	*N*	−10	16.7	26	−30	8.8	45	−22	9.1	46
	B	9	15.7	26	2	12.0	42	14	9.8	46
	P	−28	18.5	27	−48	8.9	42	−32	8.1	50
	O	−12	15.8	28	−30	7.7	42	−17	9.6	52
7	*N*	−5	14.1	26	−7	8.8	36	−4	7.9	41
	B	10	18.4	28	32	9.6	34	19	9.0	46
	P	−58	11.0	26	−47	11.4	34	−32	7.8	42
	O	−23	13.3	26	−17	7.2	31	−5	8.1	42
8	*N*	−26	14.8	28	−21	10.1	46	−21	13.3	44
	B	9	20.9	26	20	14.4	34	13	12.5	44
	P	−75	23.9	26	−67	10.3	38	−43	8.2	44
	O	−16	15.6	28	−18	10.2	38	−11	7.8	44
9	*N*	−14	17.2	28	−12	16.6	34	3	7.8	42
	B	19	23.0	28	25	17.1	34	25	13.8	46
	P	−55	25.5	30	−45	23.1	34	−35	14.4	46
	O	−3	16.3	26	−6	10.4	34	4	5.7	50
10	*N*	−14	17.5	26	−17	10.3	38	−4	8.6	46
	B	19	20.8	26	11	16.0	34	23	14.5	49
	P	−44	25.7	26	−66	13.8	34	−14	13.2	50
	O	−1	12.4	26	−6	9.8	34	−6	8.9	48

On, and Pushed and On, for all participants in all tempi at $p < 0.001$, except for the comparison Laid-back versus On for the participant mentioned above. When the 64 bpm series were excluded for this participant, the Laid-back versus On series contrast was significant at $p < 0.001$. There was also a significant main effect of instructed tempo on actual timing for all participants at $p < 0.001$ (see Table VI in the Appendix). Bonferroni corrected pairwise comparisons between tempi revealed significant or almost significant ($p = 0.05$) differences between all tempi for five participants. For two participants, fast was significantly different from medium and slow; for one participant, slow was significantly different from medium and fast tempo; for the last participant, medium tempo was significantly different from slow and fast. As to the interaction between tempo and timing style, this was significant for all participants individually (8 at $p < 0.005$, 1 at $p < 0.05$), but the patterns varied from participant to participant.

To summarize, the results for actual timing show that the drummers were successful in accomplishing the tasks. The average of all series is, with the exception of the three series in 64 bpm by the 1 drummer mentioned previously, in compliance with the instructed timing style, and the differences between the series are significant.

B. Effects and interaction of instructed timing and tempo on SPL and transient-phase SC across participants

In step (1) of the statistical analysis of the effect of instructed timing and tempo on the audio descriptors, we investigated the main and interaction effects of the two independent variables (instructed tempo and timing) using the normally distributed data—that is, data for the measures SPL and SC1. The Pearson's correlations test at the level of single strokes is reported in Table II, where we see that 79 out of 120 possible correlations (participant [10] × style [4]× tempo [3]) were statistically significant: 68 were negative correlations, while 11 were positive correlations. For 8 out of 10 participants, all significant correlations were negative (68 significant negative correlations out of 96 possible). For the remaining 2 participants, all significant correlations were positive (11 significant positive correlations out of 24 possible). This indicates that, for eight participants (seven if excluding the outlier), as the SPL in the snare drum strokes increased, the SC1 tended to decrease. For two participants, the opposite was the case, but this trend is weaker (fewer significant correlations per participant).

The Pearson's correlations test across participants (outlier excluded, $N = 9$) based on the arithmetic mean for each series showed that 2 out of 12 possible correlations were statistically significant. Both were strong negative correlations (Pearson's R/effect >0.5).

The results of the repeated-measures two-way ANOVAS across participants ($N = 9$) show that there is a trend toward a significant effect of instructed timing on SPL, $F(3, 24) = 2.654$, $p = 0.071$, but not on SC1, $F(3, 24) = 1.793$, $p = 0.175$. There was a main effect of instructed tempo on SPL, $F(2, 18) = 7.567$, $p < 0.005$, and on SC1, $F(2, 18) = 10.498$, $p < 0.005$, but no significant interaction for SPL, $F(6, 48) = 1.288$, $p = 0.281$, or SC1, $F(6, 48) = 1.698$, $p = 0.142$.

1. Effects of instructed timing on SPL and transient-phase SC across participants

Post hoc comparisons revealed that there was a close-to-significant difference in SPL between laid-back strokes and on-the-beat strokes across participants ($p = 0.054$, Bonferroni corrected for multiple comparisons). As Fig. 4 illustrates, this trend is present at tempi 64 and 96 bpm, but not very salient at tempo 148 bpm. The series comparisons Pushed versus On and Laid-back versus Pushed were not significant ($p = 1.000$ and $p = 0.761$, respectively).

2. Effects of tempo on SPL and transient-phase SC across participants

Post hoc comparisons ($N = 9$) showed that tempo 96 bpm was played significantly louder than tempo 64 bpm ($p < 0.05$) and indicated a similar trend for 148 bpm versus 64 bpm ($p = 0.082$); see Fig. 5. The difference between 96 and 148 bpm was not significant ($p = 1.000$).

Post hoc comparisons ($N = 9$) also showed that strokes in tempo 96 bpm had on average a significantly lower SC than those in tempo 64 bpm ($p < 0.01$) and indicated a close-to-significant trend for 148 bpm versus 64 bpm ($p = 0.057$). The difference between tempi 96 and 148 bpm was not significant ($p = 0.753$).

C. Non-parametric tests of effects of instructed timing on all audio descriptors

In step (2) of the statistical analysis we investigated the main effect of the independent variable instructed timing on all audio descriptors in tempo 96. Regarding intensity, the results of the Friedman tests showed that there were significant differences in SPL between conditions for all participants individually. Regarding timbre-related measures, for TC there were significant differences for 8 out of 9 participants; for SC1, 7 out of 9; and for SC2, 6 out of 9. Chi-square and p values for all tests are reported in Table VII in the Appendix. In the following, we will examine the *post hoc* pairwise comparisons for intensity- and timbre-related measures, respectively.

1. Effects of instructed timing on SPL for each participant individually

Post hoc analysis ($N = 9$) revealed statistically significant differences for the series pairs Laid-back versus On, Pushed versus On, and Laid-back versus Pushed. The results are summarized in Fig. 6. Unless otherwise stated, differences are reported significant at $p < 0.05$. The results show that a majority of the participants played laid-back (7 out of 7 significant comparisons) and pushed (5 out of 6 significant comparisons) strokes more loudly than strokes on-the-beat ($x > y$). As to the comparison laid-back versus pushed strokes, there was no clear pattern.

TABLE II. Pearson's correlations between SPL (dB) and SC (Hz) for snare drum strokes within participants. Note: $^{*}p < 0.05$, $^{**}p < 0.01$.

		64 bpm				96 bpm				148 bpm			
Participant		Natural	Laid-Back	Pushed	On-the-beat	Natural	Laid-Back	Pushed	On-the-beat	Natural	Laid-Back	Pushed	On-the-beat
1	Pearson's Cor.	0.330	0.653**	0.059	0.470*	0.557*	0.561*	0.138	0.307	0.299	−0.228	−0.077	0.408*
	Sig.	0.167	0.003	0.821	0.042	0.011	0.015	0.598	0.215	0.123	0.244	0.707	0.025
	N	19	18	17	19	20	18	17	18	28	28	26	30
2	Pearson's Cor.	−0.648**	−0.707**	−0.618**	−0.592**	−0.716**	−0.493**	−0.733**	−0.359*	−0.367**	−0.428**	−0.802**	−0.374**
	Sig.	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.027	0.008	0.002	0.000	0.007
	N	32	30	32	32	39	38	38	38	51	50	50	50
3	Pearson's Cor.	−0.229	0.331	−0.654**	−0.674**	−0.526**	−0.339*	−0.353*	−0.355*	−0.417**	−0.181	−0.515**	0.052
	Sig.	0.242	0.092	0.000	0.000	0.001	0.050	0.041	0.039	0.006	0.244	0.000	0.741
	N	28	27	28	34	34	34	34	34	42	43	42	43
4	Pearson's Cor.	−0.367	−0.449*	−0.093	−0.234	−0.160	−0.115	−0.363*	−0.354*	−0.291	−0.123	−0.137	−0.067
	Sig.	0.065	0.028	0.667	0.250	0.313	0.505	0.049	0.034	0.062	0.426	0.364	0.659
	N	26	24	24	26	42	36	30	36	42	44	46	46
5	Pearson's Cor.	−0.875**	−0.001	−0.550*	−0.767**	−0.496**	−0.486*	−0.535*	−0.875**	−0.423*	0.181	−0.747**	−0.705**
	Sig.	0.000	0.997	0.018	0.000	0.002	0.012	0.015	0.000	0.010	0.285	0.000	0.000
	N	18	18	18	18	36	26	20	34	36	37	34	34
6	Pearson's Cor.	−0.724**	−0.304	−0.361	−0.836**	−0.203	−0.380*	−0.362*	−0.434*	−0.362*	−0.487**	−0.107	−0.634**
	Sig.	0.000	0.131	0.064	0.000	0.182	0.013	0.018	0.004	0.013	0.001	0.460	0.000
	N	26	26	27	28	45	42	42	42	46	46	50	52
7	Pearson's Cor.	−0.786**	−0.669**	−0.500**	−0.568**	−0.352*	−0.464**	−0.384*	−0.432*	0.087	0.188	−0.246	−0.366*
	Sig.	0.000	0.000	0.009	0.002	0.035	0.006	0.025	0.015	0.584	0.234	0.116	0.017
	N	26	28	26	26	36	24	34	31	42	42	42	42
8	Pearson's Cor.	0.708**	0.382	0.100	0.717**	0.527**	0.578**	0.128	0.311	0.241	0.124	0.478**	0.434**
	Sig.	0.000	0.054	0.628	0.000	0.000	0.000	0.443	0.057	0.115	0.423	0.001	0.003
	N	28	26	26	28	46	34	38	38	44	44	44	44
9	Pearson's Cor.	−0.449*	−0.113	−0.231	0.053	−0.690**	−0.640**	−0.115	−0.281	−0.828**	0.114	−0.353*	−0.364**
	Sig.	0.017	0.567	0.218	0.796	0.000	0.000	0.517	0.108	0.000	0.449	0.015	0.009
	N	28	28	30	26	34	34	34	34	42	46	47	50
10	Pearson's Cor.	−0.909**	−0.890**	−0.851**	−0.815**	−0.709**	−0.836**	−0.656**	−0.725**	−0.903**	−0.755**	−0.731**	−0.563**
	Sig.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	N	26	26	26	26	38	34	34	34	46	49	50	48

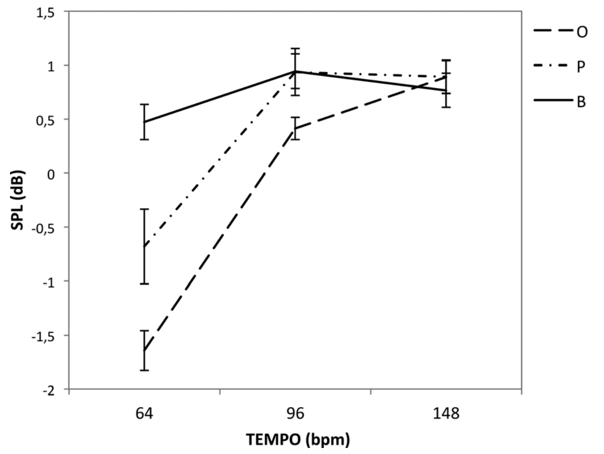


FIG. 4. Average SPL (dB) in different timing styles across participants in all tempi. Arithmetic means of series normalized over each participant's average SPL (outlier excluded, $N = 9$). B = Laid-back, O = On, and P = Pushed; bpm = beats per minute.

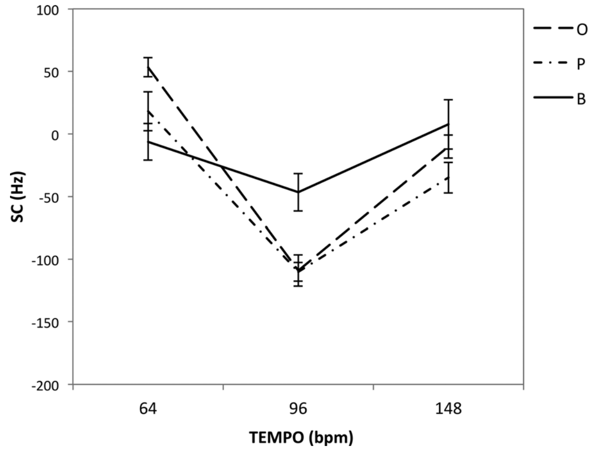
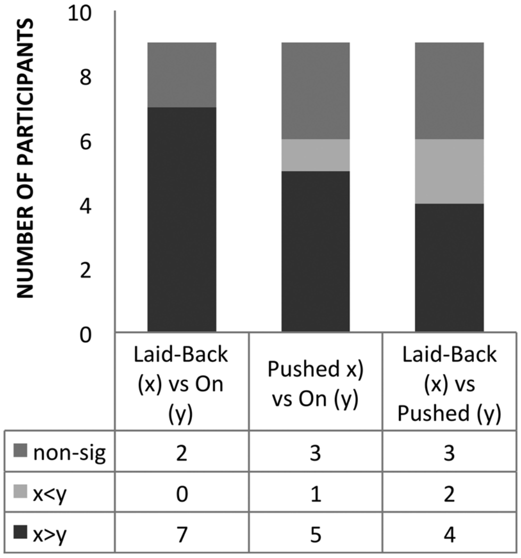


FIG. 5. Average SC1 (Hz) in different tempi across participants. Means of series normalized over each participant's average SC1. Negative values reflect the normalization process and indicate a lower SC than the average for all strokes by all participants (outlier excluded, $N = 9$). B = Laid-back, O = On, and P = Pushed; bpm = beats per minute.



	Laid-Back (x) vs On (y)	Pushed x) vs On (y)	Laid-Back (x) vs Pushed (y)
■ non-sig	2	3	3
■ x<y	0	1	2
■ x>y	7	5	4

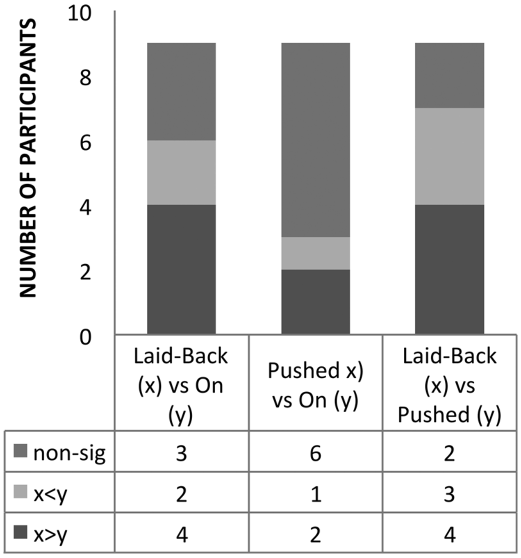
FIG. 6. Summary of significant pairwise comparisons of median SPL between series of drum strokes for each participant individually at tempo 96 bpm. Bonferroni corrected for multiple comparisons.

2. Effects of instructed timing on temporal and SC for each participant individually

For eight participants there were significant differences for TC and either SC1 or SC2 or both. For the remaining participant (No. 4), instructed timing did not affect any of the timbre-related measures (which might be because this drummer, as reported in the interview, pursues a homogeneous sound ideal in his drumming). *Post hoc* analysis revealed statistically significant differences for the series pairs Laid-back versus On, Pushed versus On, and Laid-back versus Pushed. The results are summarized in Figs. 7 (TC) and 8 (SC1 and SC2). Unless otherwise stated, differences are reported significant at $p < 0.05$. Regarding TC, of the six significant comparisons for Laid-back versus On series, the median TC was later for B than O ($x > y$) for four participants. There were few significant comparisons for Pushed versus On, whereas for Laid-back versus Pushed, there was a high number of significant comparisons (7/9), but they go in both directions. As to the results for transient-phase spectral centroid (SC1), there were no clear trends and few significant comparisons, with the exception of Laid-back versus On with six significant comparisons whereof four showed B having a lower SC than O ($x < y$). For stable-phase spectral centroid (SC2), there were few significant comparisons and no clear patterns.

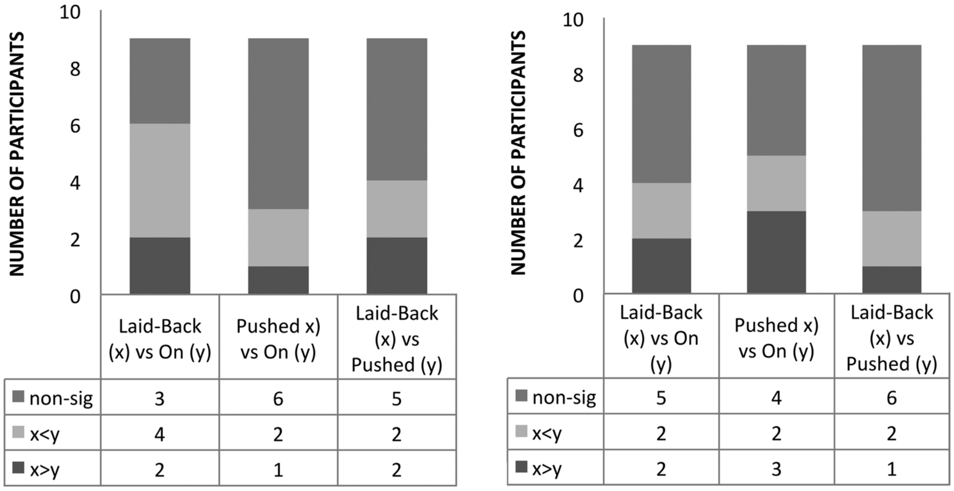
3. Effects of instructed timing on SPL and temporal and SC across participants

The results of the Friedman tests on paired differences among medians of all series at tempo 96 across participants ($N = 9$) showed a significant effect of instructed timing on SPL, $\chi^2(2) = 6.889$, $p = 0.032$. *Post hoc* analysis revealed a statistically significant difference between Laid-back ($Mdn = 2.01$ dB) and On ($Mdn = -0.11$ dB) ($p = 0.029$). The difference between Pushed ($Mdn = 0.450$ dB) and On was not significant ($p = 0.297$), nor was the difference between Laid-back and Pushed ($p = 1.000$).



	Laid-Back (x) vs On (y)	Pushed x) vs On (y)	Laid-Back (x) vs Pushed (y)
■ non-sig	3	6	2
■ x<y	2	1	3
■ x>y	4	2	4

FIG. 7. Summary of pairwise comparisons of median TC between series of drum strokes for each participant individually at tempo 96 bpm. Bonferroni corrected for multiple comparisons.



	Laid-Back (x) vs On (y)	Pushed x) vs On (y)	Laid-Back (x) vs Pushed (y)
■ non-sig	3	6	5
■ x<y	4	2	2
■ x>y	2	1	2

	Laid-Back (x) vs On (y)	Pushed x) vs On (y)	Laid-Back (x) vs Pushed (y)
■ non-sig	5	4	6
■ x<y	2	2	2
■ x>y	2	3	1

FIG. 8. Summary of pairwise comparisons of median SC1 (left) and SC2 (right) between series of drum strokes for each participant individually at tempo 96 bpm. Bonferroni corrected for multiple comparisons.

Friedman tests were also run for the timbre-related measures across participants. The differences in median TC between conditions were all less than 1 msec and were not significant, $\chi^2(2) = 0.889$, $p = 0.641$. The median transient-phase spectral centroids (SC1) were lower for Laid-back ($Mdn = 1239$ Hz) and Pushed ($Mdn = 1241$ Hz) than for On ($Mdn = 1264$ Hz), but the differences were not statistically significant, $\chi^2(2) = 3.600$, $p = 0.165$. For stable-phase spectral centroid (SC2), there were only minor differences between Laid-back ($Mdn = 2989$ Hz), Pushed ($Mdn = 2975$ Hz), and On ($Mdn = 2986$ Hz), and none of them were statistically significant, $\chi^2(2) = 0.222$, $p = 0.895$.

IV. DISCUSSION

The analyses show that there are systematic differences in the acoustic signal among drumbeats played with different instructed timing styles. The results support our main hypothesis—namely, that expert drummers use both temporal- and sound-related features to solve the timing task. In the following, we will discuss the findings in more detail.

The results are most salient for SPL, where instructed timing style had a significant impact on all participants' performance at the individual level, across all tempi. We also identified a shared pattern across participants: a majority of participants played laid-back strokes significantly louder than strokes on-the-beat. This result was clearly significant across participants in tempo 96 and close to significant when analyzing the effect of instructed timing style on SPL across tempi. This combined *late and loud* playing across participants could be interpreted as indicative of the possibility that the drummers shared a common understanding of how a laid-back stroke should be performed in relation to an on-beat stroke. In the interviews, some of the drummers stated that, when playing laid-back, the snare is "given more weight" and the hand is "lifted higher" in preparation for the snare stroke. One drummer said, "I play more relaxed"; another directly stated, "I think I play louder when playing laid-back." When looking at the results for each drummer individually, we found that five drummers (six if we include the outlier) also played pushed strokes louder than on-the-beat strokes, but this pattern did not prove significant across participants, which might be a consequence of the relatively low number of participants.

There was no significant interaction effect between tempo and instructed timing across participants. However, Fig. 4 indicates that the shared tendency to play late strokes louder than strokes on-the-beat is very salient at tempo 64 bpm; less so, but still salient, at tempo 96 bpm; and absent at tempo 148 bpm. At the faster tempo, in fact, all differences between conditions tend to disappear. This could be regarded as parallel to the ways in which the amount of swing decreases at faster tempi (see Collier and Collier, 1996; Friberg and Sundström, 2002; Honing and De Haas, 2008; Waadeland, 2006, 2011) and can be explained by the particular challenges of playing a rock pattern at fast tempi. The motoric constraints caused by such a fast tempo probably make it difficult to shape the drum strokes in any particular way.

In the previously discussed research on piano performance, several studies found that a combination of early timing and heightened intensity is commonly used to emphasize the melody (Goebl, 2001; Palmer, 1996; Repp, 1996). Early or late timing of a melody in relation to its accompaniment could be regarded as an instance of asynchronous onset, and Goebl and Parncutt (2002) found that such asynchrony in timing was harder to detect when the louder tone began earlier (the "melody-lead condition"). They explain this as a consequence of either reduced sensitivity to synchrony due to forward masking or musicians perceiving familiar combinations of asynchrony and intensity difference as more synchronous than unfamiliar combinations. In our study, on the contrary, we found a systematic relationship between *late* timing and loud sound. As opposed to the melody-lead research process, in which participants were instructed to emphasize the melody, we asked in the laid-back condition that participants produce an asynchronous onset (compared to a position on-the-beat). The common tendency among our participants to make use of this particular combination of intensity difference and asynchrony (*late and loud*) might then be explained by the way in which it makes the asynchronous onset more detectable or apparent in relation to on-the-beat playing.

For nine out of ten participants, instructed timing also had a significant impact on timbre (TC and SC1/SC2). Generally, the patterns for the timbre-related audio descriptors seem to be consistent, though they are highly individual. This is in accordance with previous research into drummers' performance of accents (Dahl, 2011), which demonstrates that a player's individual strategy tends to be used consistently. TC seems to be particularly important for the difference between laid-back and pushed strokes (significant for nine out of ten participants; the remaining participant showed no significant differences whatsoever for timbre-related aspects). Regarding SC, there are generally fewer significant pairwise comparisons, with the exception of Laid-Back versus On series for SC1, where seven out of ten are significant. In terms of the results for the different audio descriptors at the individual level, it is interesting to note that, when comparing the individual results for SC1 with those for SPL, we see that the same participants who play laid-back with a *darker* sound (lower transient-phase SC) also play laid-back significantly *louder* (higher SPL) than on-the-beat. This correlation between loud sound and dark sound was salient also in the correlation test for the audio descriptors SPL and SC1 (it was, moreover, also found in an unpublished pilot experiment for the present study). In sum, this means that several drummers systematically play late timing not only louder but also with a darker sound than strokes on-the-beat. In a study from 2007, Hove *et al*. showed that sensorimotor synchronization with chord sequences containing tone-onset asynchronies was affected by the pitch of the leading tone (high versus low). Taps were generally drawn toward the second (late) onset, but this was especially so when it was lower in pitch than the first. In addition to the combination late and loud, then, *late and dark* may also be particularly effective in catching the listener's attention.

The indication of a negative correlation between SPL and transient-phase SC also seems to be contrary to previous studies (Beauchamp, 1982; Grey and Gordon, 1978), which have generally found a positive correlation between SPL and timbre in various woodwind, brass, and string instruments. The tendency toward a negative correlation between SPL and SC1 in our experiment could be related to acoustical properties of the drum. In addition, there are reasons to assume that there is a specific performance strategy involved in playing laid-back strokes (which is easily employed at slow and medium tempi but difficult to maintain at tempo 148 bpm). Important factors that might influence the sound of the snare are the location where the drumstick hits the drumhead, the angle of the stick, and whether the stick is allowed to rebound or not. Regarding the former, several drummers corroborated this during the interviews: "When I play pushed, I am more up on the drum; when I am laid-back, I am more down on the drum, or I pull my stick up a little bit; when I play on-the-beat, I am more in the middle of the drum"; "When I play pushed, I play further up on the drum, more rigid, controlled"; and furthermore: "When I play on-the-beat, I turn into a machine straight away." Regarding the latter, a study by Dahl and Altenmüller (2008) of the ways in which a drummer's striking gesture influences the sound that is produced reports that "controlled" strokes (where the drummer was asked to stop the drumstick as close as possible to the drumhead after the stroke) were generally played with more striking force (a higher peak force) than "natural" strokes (which were allowed to rebound freely off the drumhead afterward), and, moreover, that natural strokes were rated by listeners to have a fuller timbre (that is, a higher SC) than controlled strokes. This means that the laid-back strokes in our experiment seem to share some important characteristics (loud and dark sound) with the controlled strokes in Dahl and Altenmüller's experiment. It remains to be investigated whether this can be explained by a similarity in performance strategy. It also remains to study the effect of the angle of the stick.

Regarding the effect of tempo, we found that strokes in the faster tempi were overall significantly louder and had a darker sound than strokes in the slow tempo. More precisely, the results show that a medium tempo tended to be played louder than a slow tempo and indicated a similar trend for fast versus slow. This trend ("the faster you play, the louder it sounds") represents an example of a performance characteristic whereby the intensity level of one performance parameter (tempo) is inherited by the intensity level related to another performance parameter (loudness): if playing faster requires more effort in performance, this increase in effort might also affect the force applied to the drum strokes, making the drum strokes louder at faster tempi. It is interesting to note that this situation resembles one of the "Performance Rules" in the KTH Performance Rules System: "The higher the pitch, the louder" (see Friberg *et al*., 2000).

V. CONCLUSION

The results show that there were systematic differences in the intensity and timbre of series of snare strokes (that is, SPL, TC, and SC) played with different timing instructions (Laid-back, Pushed, and On-the-beat) at the individual level. In addition, we found a common pattern for intensity across participants—namely, that laid-back strokes are played louder than strokes on-the-beat. These results concur with previous works reporting an intimate relationship between intensity, timing, and duration at the micro level in music performance and perception, and they lend support to our hypothesis that both temporal and sound-related aspects are important for drummers in order to communicate an intended timing style. The results are strongest for intensity. Here, we find that when a drummer is asked to alter the timing of a beat, he or she will systematically alter its SPL as well. This supports our hypothesis that sound-related features are important in order to signal that a rhythmic event ought to stand out in relation to an on-the-beat position.

In future research, we would like to repeat the experiment with a second group of participants in order to establish stronger statistical reliability for the pattern and trends that are reported here. We also plan to conduct a perception experiment, using the recorded strokes as stimuli, to determine whether listeners are able to distinguish between early and late strokes on the basis of their sound only. Moreover, pursuing the hypothesis that there are different gestural strategies for how to *produce* the different timing profiles seems particularly tantalizing. We will therefore incorporate aspects of performance gestures, such as motion trajectories, stick rebound, stick angle, and location of the hit on the drumhead, into our future investigations, applying motion-capture systems to study how the drummers, through different movements, *control* their timing, and how this timing control influences the sound of the snare drum.

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APPENDIX

TABLE III. Descriptive statistics of SPL for each participant in all tempi. Note: SPL in dB. The reference for 0 dB is the average rms amplitude of all strokes in all series. Part. = Participant.

		64 bpm			96 bpm			148 bpm		
Part.	Style	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
1	*N*	1.34	0.56	19	0.81	0.58	20	0.91	0.48	28
	B	1.71	0.49	18	1.96	0.32	17	2.05	0.52	28
	P	−6.2	0.73	17	−3.05	0.74	17	−0.28	0.53	26
	O	−1.74	0.51	19	−1.03	0.49	18	1.42	0.31	30
2	*N*	−3.26	0.55	32	−1.45	0.85	39	−0.11	0.78	51
	B	−0.37	0.72	30	1.00	0.51	38	−0.19	0.61	51
	P	−2.70	0.74	31	−1.59	1.05	38	−3.13	0.92	51
	O	−1.62	0.55	32	−0.98	0.61	38	−0.86	0.61	49
3	*N*	−0.97	0.55	28	0.25	0.85	34	0.27	1.01	42
	B	−0.90	0.68	27	0.00	0.86	34	0.10	0.53	43
	P	−1.59	0.86	28	0.05	0.58	34	0.71	0.47	27
	O	−0.42	0.63	33	−0.96	0.75	34	0.17	0.62	43
4	*N*	2.51	0.40	26	3.00	0.27	42	3.55	0.32	42
	B	2.30	0.57	24	2.97	0.38	36	3.15	0.38	44
	P	2.89	0.38	24	3.66	0.28	30	3.48	0.39	46
	O	2.39	0.33	26	3.28	0.24	36	3.51	0.35	46
5	*N*	−1.09	0.78	18	1.02	1.27	35	0.61	0.87	36
	B	1.63	0.55	17	1.95	0.83	28	2.28	0.76	37
	P	−0.99	0.69	18	0.27	0.77	20	1.21	1.03	34
	O	−0.70	0.81	17	−0.52	1.44	34	−0.30	1.12	33
6	*N*	−3.07	1.11	26	0.28	0.76	45	0.15	0.70	46
	B	−1.48	0.67	26	−1.22	0.59	42	0.47	0.65	46
	P	−0.61	0.69	27	0.33	0.51	41	0.39	0.56	50
	O	−4.00	0.92	28	−2.5	0.44	42	−2.45	0.66	52
7	*N*	−0.16	0.65	24	0.42	0.69	36	0.84	0.70	42
	B	1.08	0.52	28	2.43	0.58	34	1.07	0.54	46
	P	1.20	0.59	24	2.27	0.51	34	1.20	0.45	42
	O	0.85	0.62	26	0.79	0.44	31	0.17	0.66	26
8	*N*	2.25	0.73	27	1.37	0.76	46	0.29	0.77	44
	B	2.14	0.55	26	1.25	0.84	34	0.28	0.78	44
	P	1.87	0.71	26	1.46	0.67	38	0.85	0.62	44
	O	1.89	0.99	28	0.71	0.52	38	1.04	1.03	44
9	*N*	−0.57	0.50	28	0.16	0.73	34	1.22	1.30	42
	B	3.75	0.86	27	3.59	0.70	34	3.01	0.95	46
	P	1.33	1.05	30	1.92	0.94	34	2.97	1.14	26
	O	0.42	0.51	26	1.87	0.84	34	2.63	0.62	49
10	*N*	−3.94	1.00	26	−3.88	0.66	38	−4.64	0.85	46
	B	−6.33	1.19	26	−6.71	1.40	34	−7.78	1.12	49
	P	−7.23	0.94	26	−1.12	0.77	33	−3.85	1.12	26
	O	−4.85	0.69	26	−3.12	0.54	34	−4.55	0.70	48

TABLE IV. Descriptive statistics of transient-phase spectral centroid (SC1) for each participant in all tempi. Note: SC in Hz. Part. = Participant.

		64 bpm			96 bpm			148 bpm		
Part.	Style	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
1	*N*	1033	38	19	1015	39	20	970	33	28
	B	1071	36	18	1067	46	18	986	31	28
	P	783	37	17	824	18	17	832	22	25
	O	908	29	19	855	30	18	918	27	30
2	*N*	1739	126	32	1542	103	39	1463	105	51
	B	1405	94	30	1400	65	38	1466	83	50
	P	1605	157	32	1456	139	38	1616	169	50
	O	1527	80	32	1516	113	38	1526	101	50
3	*N*	1509	101	28	1485	100	34	1465	87	42
	B	1479	79	27	1443	83	34	1419	85	43
	P	1612	115	28	1415	110	34	1336	87	27
	O	1484	105	33	1500	77	34	1426	76	43
4	*N*	1247	68	26	1238	65	42	1224	65	42
	B	1292	60	24	1257	61	36	1239	69	44
	P	1252	71	24	1211	65	30	1224	60	46
	O	1264	79	26	1254	63	36	1246	54	46
5	*N*	1491	124	18	1264	138	36	1266	99	36
	B	1202	119	18	1241	68	26	1237	89	33
	P	1418	68	18	1322	90	20	1299	114	34
	O	1371	170	18	1399	136	34	1400	120	34
6	*N*	1566	141	25	1382	94	44	1380	101	46
	B	1428	101	26	1350	89	42	1319	85	46
	P	1389	76	27	1288	83	41	1280	79	50
	O	1772	145	28	1576	88	42	1579	107	52
7	*N*	1336	81	24	1272	80	36	1279	66	42
	B	1274	80	28	1144	62	34	1268	83	46
	P	1238	112	26	1148	81	33	1247	70	42
	O	1304	87	26	1256	85	31	1315	76	26
8	*N*	1094	44	28	1078	46	46	1062	37	44
	B	1117	28	26	1112	36	34	1075	30	44
	P	1100	42	26	1081	40	38	1078	46	44
	O	1078	46	28	1068	39	38	1078	44	44
9	*N*	1401	102	28	1354	113	34	1345	138	42
	B	1178	91	27	1168	75	34	1224	74	46
	P	1267	114	28	1263	70	33	1286	126	26
	O	1374	115	24	1186	58	34	1326	73	50
10	*N*	1646	182	26	1610	108	38	1740	154	46
	B	1931	163	26	1927	192	34	2125	210	49
	P	2246	213	26	1347	125	33	1690	152	26
	O	1772	141	26	1547	93	34	1751	113	48

TABLE V. Median and quartiles for SPL, TC, transient-phase spectral centroid (SC1), and stable-phase spectral centroid (SC2) for each participant in tempo 96.

		SPL (dB)	TC (msec)	SC1 (Hz)	SC2 (Hz)
Part.	Instr. timing	Median[a] [*Q1*, *Q3*]	Median [*Q1*, *Q3*]	Median [*Q1*, *Q3*]	Median [*Q1*, *Q3*]
1	*N*	0.91 [0.40, 1.28]	24.8 [23.9, 28.1]	1017 [999, 1049]	3006 [2871, 3131]
	B	2.07 [1.72, 2.19]	26.7 [25.8, 28.7]	1081 [1026, 1103]	2679 [2496, 2875]
	P	−3.06 [−3.43, −2.53]	25.1 [24.5, 25.5]	825 [811, 837]	2948 [2816, 3022]
	O	−1.09 [−1.31, −0.56]	25.5 [24.4, 26.3]	851 [830, 881]	2630 [2454, 2912]
2	*N*	−1.23 [−2.17, −1.23]	24.5 [24.2, 25.0]	1540 [1478, 1615]	3166 [2999, 3261]
	B	0.92 [0.59, 1.36]	24.7 [24.2, 25.9]	1402 [1347, 1453]	3200 [3112, 3287]
	P	−1.39 [−2.50, −0.90]	29.6 [27.2, 31.7]	1443 [1370, 1552]	2975 [2797, 3149]
	O	−1.11 [−1.33, −0.64]	24.5 [24.3, 25.3]	1533 [1440, 1576]	3021 [2811, 3164]

TABLE V. (*Continued.*)

		SPL (dB)	TC (msec)	SC1 (Hz)	SC2 (Hz)
Part.	Instr. timing	Median[a] [*Q1*, *Q3*]	Median [*Q1*, *Q3*]	Median [*Q1*, *Q3*]	Median [*Q1*, *Q3*]
3	*N*	0.56 [−0.32, 0.79]	25.2 [24.8, 25.5]	1496 [1402, 1547]	3172 [2983, 3274]
	B	0.09 [−0.46, 0.63]	25.2 [24.8, 25.5]	1437 [1383, 1505]	3118 [3037, 3271]
	P	0.05 [−0.42, 0.57]	25.7 [25.2, 26.5]	1383 [1337, 1512]	3083 [2981, 3247]
	O	−0.99 [−1.46, −0.38]	27.6 [25.8, 28.3]	1505 [1450,1536]	2884 [2722, 3169]
4	*N*	3.00 [2.75, 3.16]	24.2 [23.9, 24.4]	1242 [1179, 1285]	3091 [2924, 3200]
	B	3.08 [2.65, 3.23]	24.3 [24.1, 24.6]	1254 [1221, 1299]	3145 [2986, 3244]
	P	3.67 [3.43, 3.81]	24.3 [24.0, 24.9]	1216 [1162, 1270]	3082 [2899, 3158]
	O	3.27 [3.13, 3.46]	24.1 [23.9, 24.5]	1254 [1225, 1288]	3089 [2956, 3259]
5	*N*	1.23 [0.35, 2.20]	29.9 [28.3, 32.6]	1254 [1148, 1363]	3071 [2908, 3241]
	B	2.01 [1.47, 2.71]	27.6 [26.0, 31.3]	1239 [1193, 1287]	3010 [2885, 3091]
	P	0.26 [0.01, 0.59]	33.2 [29.3, 35.6]	1339 [1261, 1364]	3025 [2793, 3193]
	O	−0.11 [−1.69, 0.45]	30.0 [28.1, 32.0]	1386 [1292, 1449]	2965 [2768, 3149]
6	*N*	0.39 [−0.22, 0.79]	25.5 [24.5, 26.6]	1402 [1342, 1440]	3155 [3022, 3364]
	B	−1.24 [−1.57, −0.81]	30.2 [28.9, 31.4]	1343 [1284, 1408]	2989 [2882, 3113]
	P	0.45 [−0.01, 0.74]	28.5 [27.4, 29.7]	1281 [1236, 1349]	3081 [2977, 3243]
	O	−2.53 [−2.84, −2.26]	25.9 [25.3, 26.7]	1582 [1518, 1638]	2691 [2666, 2817]
7	*N*	0.52 [−0.19, 0.86]	29.4 [28.0, 29.4]	1270 [1229, 1311]	3096 [2950, 3232]
	B	2.43 [1.88, 2.85]	37.2 [36.1, 38.3]	1147 [1100, 1197]	2522 [2453, 2603]
	P	2.28 [1.91, 2.55]	28.4 [26.3, 30.4]	1149 [1089, 1199]	2887 [2768, 3005]
	O	0.85 [0.42, 1.16]	27.1 [26.6, 28.1]	1264 [1198, 1318]	3150 [3067, 3294]
8	*N*	1.42 [0.94, 1,81]	27.8 [25.7, 30.2]	1082 [1039, 1105]	2818 [2741, 2961]
	B	1.15 [0.49, 1.97]	30.1 [28.1, 32.1]	1108 [1090, 1137]	2649 [2545, 2741]
	P	1.55 [1.08, 1.85]	25.3 [24.4, 26.5]	1081 [1058, 1111]	2775 [2611, 2839]
	O	0.66 [0.33, 1.07]	26.1 [25.5, 27.5]	1070 [1046, 1093]	2991 [2833, 3256]
9	*N*	0.38 [−0.37, 0.78]	25.7 [25.1, 26.8]	1362 [1262, 1427]	2981 [2810, 3093]
	B	3.59 [3.20, 4.13]	25.1 [24.6, 26.6]	1188 [1113, 1216]	2910 [2802, 3038]
	P	1.90 [1.34, 2.61]	26.4 [25.5, 27.6]	1241 [1217, 1333]	2851 [2666, 3094]
	O	1.66 [1.37, 2.53]	27.5 [26.0, 28.5]	1197 [1139, 1226]	2986 [2879, 3173]
10	*N*	−3,93 [−4.40, −3.32]	29,9 [28.5, 31.0]	1616 [1515, 1683]	2870 [2647, 3193]
	B	−6.50 [−7.81, −5.77]	41,9 [40.1, 42.8]	1931 [1795, 2063]	2293 [2223, 2520]
	P	−0.95 [−1.49, −0.56]	27,5 [26.4, 30.6]	1338 [1267, 1426]	2881 [2689, 3008]
	O	−3.13 [−3.43, −2.75]	30,7 [29.5, 31.9]	1562 [1467, 1619]	3071 [2871, 3256]

[a] The reference for 0 dB is the average rms amplitude of all strokes in all series.

TABLE VI. Main effects of style and tempo on timing (TIM). Note: Part. = Participants. Style includes all four timing styles (*N*, *B*, *P*, and *O*).

		Style			Tempo			Style* Tempo		
Part.	*N*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
1	14	277.051	3,39	<0.001	75.593	2,26	<0.001	145.520	2.867, 37.268[a]	<0.001
2	31	95.641	3,90	<0.001	65.736	1.551, 46.541[a]	<0.001	12.442	4.357, 130.714[a]	<0.001
3	27	117.708	3,78	<0.001	13.223	1.626, 42.271[a]	<0.001	69.899	6,156	<0.001
3[b]	33	187.376	3,96	<0.001	32.611	1,32	<0.001	4.979	3,96	0.003
4	24	826.486	3,69	<0.001	93.602	2,46	<0.001	15.786	6,138	<0.001
5	18	506.204	3,51	<0.001	29.661	2,34	<0.001	16.837	6,102	<0.001
6	26	144.686	3,75	<0.001	44.171	2,50	<0.001	5.490	3.806, 95.141[a]	0.001
7	26	555.494	3,75	<0.001	46.202	2,50	<0.001	14.565	4.049, 101.215[a]	<0.001
8	26	401.524	3,75	0.007	18.110	2,50	<0.001	10.266	3.404, 85.112[a]	<0.001
9	26	210.896	3,75	<0.001	19.092	2,50	<0.001	2.512	3.985, 99.634[a]	0.047

[a] Degrees of freedom (*df*) corrected using Greenhouse-Geisser estimates of sphericity.
[b] Series in tempo 64 excluded.

TABLE VII. Friedman tests of the effect of instructed timing on SPL, TC, transient-phase spectral centroid (SC1), and stable-phase spectral centroid (SC2) for each participant in tempo 96. Note: Part. = Participants.

		SPL			TC			SC1			SC2		
Part.	*N*	χ^2	*df*	*p*	χ^2	*df*	*p*	χ^2	*df*	*p*	χ^2	*df*	*p*
1	17	34.000	2	<0.001	17.294	2	<0.001	29.059	2	<0.001	12.824	2	0.002
2	38	58.895	2	<0.001	49.784	2	<0.001	18.053	2	<0.001	8.579	2	0.014
3	30	30.353	2	<0.001	46.294	2	<0.001	4.941	2	0.085	16.294	2	<0.001
4	30	33.067	2	<0.001	4.267	2	0.118	5.067	2	0.079	4.067	2	0.131
5	20	30.000	2	<0.001	7.300	2	0.026	19.900	2	<0.001	0.300	2	0.861
6	41	80.149	2	<0.001	53.476	2	<0.001	47.561	2	<0.001	50.537	2	<0.001
7	31	46.516	2	<0.001	40.258	2	<0.001	17.613	2	<0.001	52.452	2	<0.001
8	34	11.118	2	0.004	41.176	2	<0.001	11.294	2	0.004	39.515	2	<0.001
9	34	42.765	2	<0.001	18.059	2	<0.001	22.545	2	<0.001	4.471	2	0.107

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