The effect of nearby timpani strokes on horn playing

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(Received 20 June 2013; revised 22 October 2013; accepted 28 October 2013)

Horn players have observed that timpani strokes can interfere disruptively with their playing, especially when they are seated close to the timpani. Measuring the horn's transfer function in the bell-to-mouthpiece direction reveals that the horn behaves as an acoustic impedance matching device, capable of transmitting waves with pressure gains of at least 20 dB near horn playing resonances. During moderate to loud timpani strokes, the horn transmits an overall impulse gain response of at least 16 dB from the bell to the mouthpiece, while evidence of non-linear bore propagation can be observed for louder strokes. If the timpani is tuned near a horn resonance, as is usually the case, further bore resonance interactions may be observed leading to gains of ~26 dB from bell to mouthpiece. Finally, measurements of horn playing made under conditions approximating playing reveal that timpani strokes sounding near the horn bell are capable of disrupting horn playing by affecting the amplitude, periodicity, and frequency of the pressure signal generated at the horn player's lips.
[http://dx.doi.org/10.1121/1.4829533]

PACS number(s): 43.75.Fg, 43.75.Hi, 43.75.St [AH] Pages: 472–478

I. INTRODUCTION

The bell of a horn is an impedance matcher—in both directions. In the outwards direction, it radiates high frequencies well and thus contributes to the loudness and characteristic timbre of the instrument. In the inwards direction, one would expect the bell to increase the pressure amplitude of the high frequency components of waves traveling into the instrument's bore from the outside. Some orchestral horn players and teachers (Schuller, 1962; Hill, 2001; Buckle, 2008) have observed that, when the horns are seated close to the timpani, and especially when the bell of the horn faces the timpani, timpani strokes seem to interfere disruptively with horn playing. The aim of this paper is to investigate how timpani strokes produce pressure waves in the mouthpiece of nearby horns, and how these affect playing.

Gunther Schuller (b. 1925), an influential horn player, writes: "The timpani's spreading wave-lengths back up through the horn, violently jarring the player's lips. Under these conditions split notes abound and what notes can be played develop a strong rasp. A half minute of this and the horn player will retain no sensitivity in his lips" (1962).

On the placement of horn players in the orchestra, horn soloist and composer Douglas Hill (b. 1946), professor of horn at the University of Wisconsin–Madison, further stipulates: "Never put the horns in front of the percussion, especially the timpani and bass drum. The intense vibrations projected by these larger drums literally become a concentrated, focused blast of air pressure that enters the bells and can affect the aperture's control of a note" (2001).

This proximity effect with the timpani has also been highlighted as a potential source of injury to horn players (Horvath, 2010), where "the impact of the timpani on the horn is an extremely direct and painful one" (Schuller, 1962), "like being hit in the mouth" (Buckle, 2008), and "will also negatively affect endurance" (Hill, 2001). The fact that the bell of the horn points back, behind the player, makes this instrument particularly susceptible to this problem: Trombones are sometimes seated in front of the bass drum, but the bell of the trombone points forwards. Horns are usually seated away from the bass drum, but sometimes in front of the timpani, particularly in small venues such as orchestra pits for opera.

To the authors' knowledge, there have been no previous acoustical studies on this matter so far, although the phenomenon is the subject of discussion and speculation in the horn-playing community (e.g., Online horn forum, 2012). This paper reports measurements of the transfer function of the horn: The ratio of pressure measured in the mouthpiece of the horn to that incident at the bell. It then reports the sounds at the mouthpiece produced by timpani strokes near the bell of the horn and their interaction with the signal from normal playing.[1]

II. MATERIALS AND METHODS

All experiments are conducted in a chamber treated to reduce reverberation and noise.

A. Measurement of horn transfer function

To measure the horn transfer function bell-to-mouthpiece, a Yamaha YHR-664 double horn (Yamaha Corp., Hamamatsu, Shizuoka, Japan) is suspended over a 12-in. loudspeaker (KF-1240R, Jaycar Electronics, Rydalmere, NSW, Australia) with its bell coaxial with and facing the loudspeaker, at a separation of one bell radius, as shown in Fig. 1(A). ("Double horn" means that a valve converts it from F to B♭: In each configuration three valves allow chromatic scales.)

Two 1/4-in. pressure-field microphones, type 4944A [(Brüel & Kjær, Nærum, Denmark), with upper limit of dynamic range: 169 dB] are employed. The positive polarity was determined by popping bubble-wrap and a balloon. One

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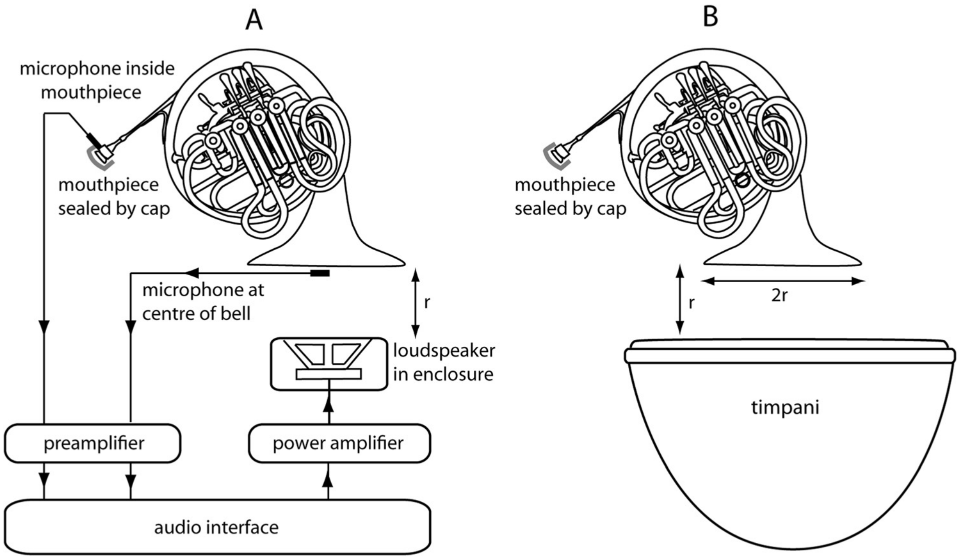

FIG. 1. Schematic diagram (not to scale) showing the experimental apparatus. (A) shows the configuration used for measuring the bell to mouthpiece transfer function. (B) shows the configuration used to measure the effect of timpani strokes on the pressure in the mouthpiece. For clarity the microphones in the mouthpiece and bell have not been shown in (B).

microphone is mounted on a modified horn mouthpiece with a 1 mm hole drilled into the cup to measure the pressure inside the mouthpiece. (The air between the microphone and this 1 mm coupling hole, together with the compliance of the microphone, is estimated to produce a Helmholtz resonance around 7 kHz, well above the frequencies of interest in this study.) The mouthpiece is sealed in the plane of the rim and isolated from the radiation field using a block of nylon with a recess that fits tightly over the mouthpiece. The other microphone is positioned in the plane of the bell close to its center.

A broadband signal is synthesized as a sum of sine waves from 25 to 1000 Hz, at 2.7 Hz spacing, amplified and output to the loudspeaker over several seconds. This signal is generated using an iterative approach (Smith *et al.*, 1997) such that the pressure spectrum introduced at the bell is independent of frequency. The Fourier transform of both the bell and mouthpiece pressure signals measured are time-averaged and divided to yield the transfer function of the horn.

For both the F and B♭ horns, measurements were made for the fingerings 000, 0X0, X00, and XX0, where X indicates a depressed valve for the index, middle, and ring fingers, respectively.

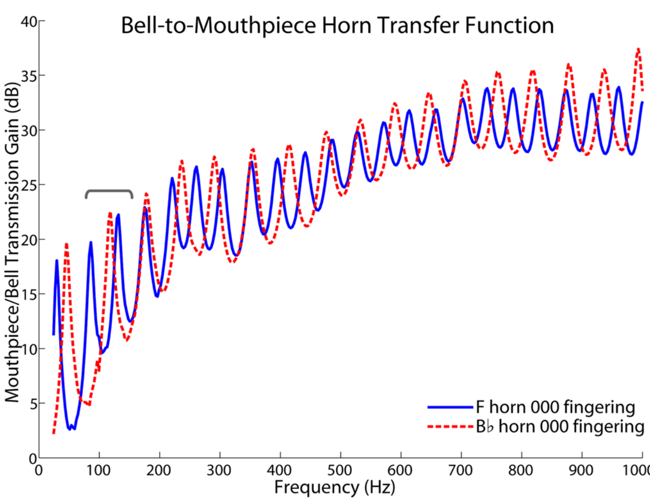

FIG. 2. (Color online) Bell-to-mouthpiece horn transfer function measured for the 000 fingering on the F and B♭ horn (solid and dashed lines, respectively). The pale horizontal bracket indicates the nominal sounding range (F2-E3) of the 26 in. timpani used. Experimental configuration as shown in Fig. 1(A).

B. Impulse measurement using timpani strokes

To investigate the effect of timpani strokes on the pressure in the mouthpiece, the loudspeaker is replaced by a single timpani (26 in., Evans Drumheads, Dodge City, KS, plastic skin with nominal sounding range F2-E3, i.e., 87 to 165 Hz) with its skin facing the bell coaxially, as shown in Fig. 1(B). The drum skin and the plane of the horn bell are separated by one bell radius. The timpani was struck manually at about 10 cm from the rim, a position usually used by timpanists that is mainly expected to excite the (1,1), (2,1), and (3,1) modes, which decay slowly, and the (0,1) mode, which decays more rapidly (Fletcher and Rossing, 1998). In the (n,m) notation, n and m, respectively, represent the number of nodes that are diameters and circles.

Although the horn transfer function measured bell-to-mouthpiece is not simply the inverse of that measured mouthpiece-to-bell, the peaks in the transfer function measured nevertheless still correspond closely with the sounding frequencies of the horn. Local maxima and minima in the transfer function (Fig. 2) that fall within the musical range of the timpani are determined, and are as follows.

For the 000 fingering on the F horn:

(1) 2nd transfer function maximum, 86.1 Hz (F2-23 cents).
(2) 3rd maximum, 131.9 Hz (C3 + 14 cents).
(3) Minimum between the 2nd and 3rd maxima, 107.7 Hz (A2-37 cents).

For the 000 fingering on the B♭ horn:

(1) 2nd transfer function maximum, 118.4 Hz (B♭2 + 27 cents).
(2) Minimum between the 2nd and 3rd maxima, 145.3 Hz (D3-18 cents).
(3) The 3rd maximum on the B♭ horn and higher maxima on both horns fall above the range of the timpani, and so are not considered.

The timpani was tuned to each of the frequencies listed above. It was also tuned to a range of pitches deviating up to

±100 cents from each of the frequencies of interest identified above. For each tuning, it was struck at varying dynamic levels ranging from *mp* to *f*, and the resulting pressure signals at the bell and in the mouthpiece recorded by the two microphones and analyzed. (To ensure reproducibility, measurements in this series were made without a hand in the bell.)

C. Timpani strokes during horn playing

To investigate further the effect of timpani strokes sounded during horn playing, two experienced horn players volunteered to be experimental subjects. Both have decades of experience playing the horn, and one has experience playing with a large national orchestra. The horn remains positioned as before (the nylon block that sealed the mouthpiece is now removed so the instrument can be played). For these measurements, the player does not place his hand in the bell. To cope with the greater sound pressure levels now expected in the mouthpiece, the microphone at the mouthpiece is now replaced with a piezoresistive pressure transducer, 8507 c-2 (Endevco, San Juan Capistrano, CA), with upper limit of dynamic range: 177 dB).

The players were asked to play sustained, steady notes at the horn resonances identified earlier (sounding F2, C3, and B♭2, but written C3, G3, and F3, respectively, for the horn) at *p* and *mf* dynamic levels, while the timpani (tuned to these notes, and also tuned ±70 cents) was struck at dynamic levels ranging from *mf* to *ff*, and the pressure at the mouthpiece and bell recorded and analyzed.

Last, to mimic conditions that might be encountered on a small stage or orchestra pit, with the horn and timpani in close proximity, an "ecological" measurement is made with the horn player sitting and holding the horn in the normal concert position, hand in bell, and the bell pointing at the timpani as it is struck 1 m away.

III. RESULTS AND DISCUSSION

A. Bell-to-mouthpiece transfer function

Figure 2 shows an acoustic transfer function measured bell-to-mouthpiece for the 000 fingering on the F and B♭ horn. For both fingerings, the transmission pressure gain (mouthpiece/bell) increases globally with frequency, with the local maxima corresponding closely to playing resonances of the horn. (The first horn resonance is below the pedal note and is not played.)

For the F horn, the second resonance has a pressure gain of 20 dB. Gains at resonance then rise steadily to 27 dB by the sixth resonance. Similarly, the second resonance on the B♭ horn has a gain of 23 dB, while the gain at resonance increases to 28 dB by the sixth resonance. The B♭ horn is a shorter pipe than the F horn and so is expected to have somewhat smaller bore losses, particularly at higher frequencies. The transfer functions of the other fingerings measured show comparable gain profiles, and so are not included in Fig. 2.

B. Pressure in the mouthpiece produced by timpani strokes

Figure 3 shows the initial pressure waveforms typical for a timpani stroke sounded outside the bell, measured at the bell and in the mouthpiece. The sound pressure in both cases initially goes negative, because the rarefaction of the air above the drum skin produced by the descending beater is radiated more effectively than the compression of the air inside the drum.

For this example, the timpani is tuned nominally to A2 + 25 cents, and the B♭ horn 000 fingering is used. The initial oscillation in each of the microphone signals has a qualitatively similar shape, but that in the mouthpiece has much greater amplitude. Further, the mouthpiece signal shows a delay of 8 ms, which corresponds to the time for sound to travel the ~2.75 m length of the B♭ horn. The first peak in the mouthpiece signal is 16 dB greater than that in the bell. The most negative part of the signal is 17 dB greater in the mouthpiece signal. Although the initial pressure oscillations in the two pressure signals are similar, their similarity decreases over time. This is attributed to the establishment of standing waves in the bore as the timpani pulse is reflected at mouthpiece and bell and as energy from subsequent oscillations of the drum is stored in those standing waves.

The impulse pressure gain responses measured for the 000 fingering on the F and B♭ horn are shown in Fig. 4. Each of the 420 data points was taken from the initial trough and peak pressure signals for a single timpani stroke. The mean value obtained for all strokes at each timpani tuning is indicated with a cross, while the pale horizontal line shows standard deviations. The pale vertical line shows the aggregated average gain over all timpani tunings used for that horn fingering.

Figure 4 shows that impulse pressure gain values are fairly consistent for each fingering across timpani tunings: They do not depend much on the frequency difference between the timpani's tuning and the horn's resonance: A consistent ~16 dB gain for the F horn 000 fingering, and a slightly higher gain of ~17.5 dB for the B♭ horn 000 fingering. The impulse gain on the F horn is generally lower than on the B♭ horn because the F horn is the longer pipe, and

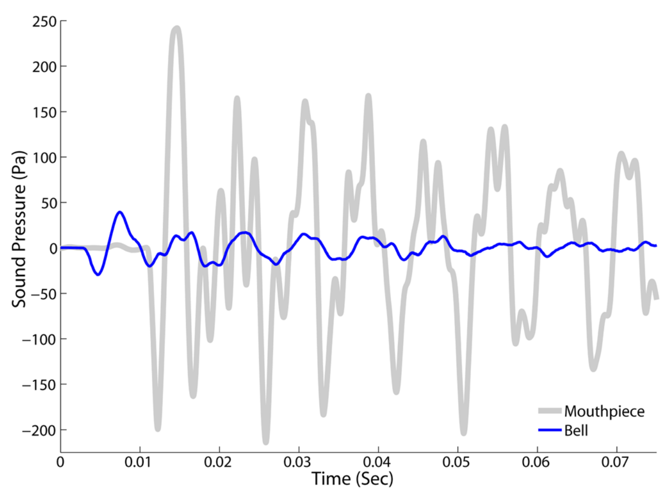

FIG. 3. (Color online) A typical waveform of the initial pressure pulse of a timpani stroke, nominally tuned A2 + 25 cents, measured in the bell (dark line) and in the mouthpiece (pale line) for the B♭ horn 000 fingering. Experimental configuration as shown in Fig. 1(B).

hence is expected to have greater wall loss. This is consistent with the smaller range in the impedance magnitude extrema measured on the F horn (Chen, 2009).

The independence of impulse gain on tuning is not surprising, because the initial timpani pressure impulses occur over time scales too short for reflections in the bore to occur, so resonances are irrelevant here: The gain results from the horn acting as an acoustic impedance-matching transformer that converts a signal at the bell having (relatively) large flow and small pressure into a signal at the (sealed) mouthpiece have negligible flow and large pressure.

For pressure amplitudes up to the linear limit of this transfer function, corresponding roughly with timpani strokes sounded up to *mf* (∼125 dB, measured at the bell), this gain is observed to be approximately independent of the magnitude of the pressure pulse and the timpani tuning used. This is true for the B♭ horn for most of the timpani strokes measured in this study. However, on the longer F horn, pressure pulses exceeding ∼1 kPa (∼150 dB) are sometimes measured in the mouthpiece if the external impulse signal measured at the bell is on the order of 100 Pa (∼130 dB) or greater. At these larger amplitudes (strokes > *mf*), the pressure pulse is observed to arrive at the mouthpiece with distorted waveform: e.g., peaks arrive on average 5% (0.6 ms) sooner than the trough. Further, the initial pulse has a slightly larger gain (17 dB for a 135 dB pressure pulse measured at the bell, compared with 16 dB for lower pressures). (These large pressure pulses measured at the mouthpiece are still well within the operating dynamic range of the Brüel & Kjær 4944A microphone used, whose stated upper limit is 169 dB at 3% total harmonic distortion.) It is interesting to note that the sound pressure of these strokes may be sufficiently high such that it produces nonlinear effects and thus, as observed, a gain that increases for large signals.

For the gain of the initial pressure impulse, no significant dependence on the relative tuning of the timpani and horn is observed. In the latter part of the signal, however, there is time for energy input from the timpani to be stored in standing waves in the bore, and the effects of such tuning can be observed. Figure 5 shows this effect in two contrasting cases. Both measurements use the B♭ horn 000 fingering but, in one case, the timpani is tuned to the second horn resonance (top). In the other, the timpani is tuned to the transfer function minimum between the second and third maxima (bottom).

Both measurements in Fig. 5 begin with a large transient and oscillations, with the period roughly equal to that of the timpani fundamental and a pressure envelope that decays with a time constant of roughly 25 ms. The effect of tuning the timpani near a horn resonance is most clearly seen after about 100 ms. Where the timpani is tuned well away from a resonance, the envelopes of both bell and microphone signals decay gradually and nearly monotonically. In the case where the timpani is tuned to the horn resonance, however, both the mouthpiece and the bell signals show the amplitude of the quasi-periodic signal rise smoothly from about 0.1 to 0.3 s after the initial pulse, as more sound energy produced by the vibrating drum skin is stored in the standing wave in the bore of the horn. In this case, the mouthpiece signal increases proportionally more than that at the bell, and the gain at the mouthpiece rises to a maximum of ∼26 dB and remains near this level until about 0.5 s after the initial pulse. This contrasts with the behavior when the stroke is tuned away from the horn resonance. In that case (lower graph) energy from the timpani is not stored in standing waves and no delayed boost is observed in either the mouthpiece or the bell signal: Both envelopes decay nearly monotonically.

In typical orchestration, the timpani plays either the tonic or the fifth of the chord. Further, one or more of the horns will also play the notes of the chord, sometimes at the same pitch, sometimes an octave or more above. It follows that, in typical cases, one or more of the horns will use a fingering for which one of the resonances (and thus one of the

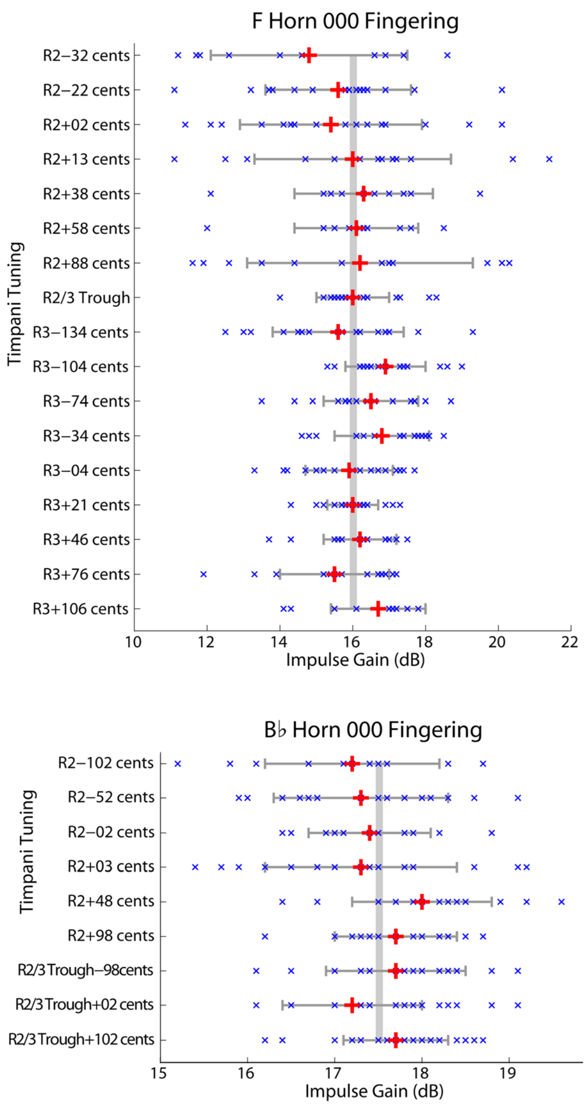

FIG. 4. (Color online) The pressure gain of the pressure measured in the mouthpiece with respect to that in the bell for each timpani stroke for the F and B♭ horn 000 fingering (*top* and *bottom*, respectively). Measurements were made at the initial peak and trough of the pressure impulse for a range of timpani pitches tuned near a corresponding maximum (resonance) and minimum of the measured horn transfer function. Each of the 420 measurements is indicated by a small "×." The mean obtained for each separate tuning of the timpani is indicated with a large cross. Pale horizontal bars show ± one standard deviation, while the pale thick vertical line shows the average for all of the measurements for that fingering. Experimental configuration as shown in Fig. 1(B).

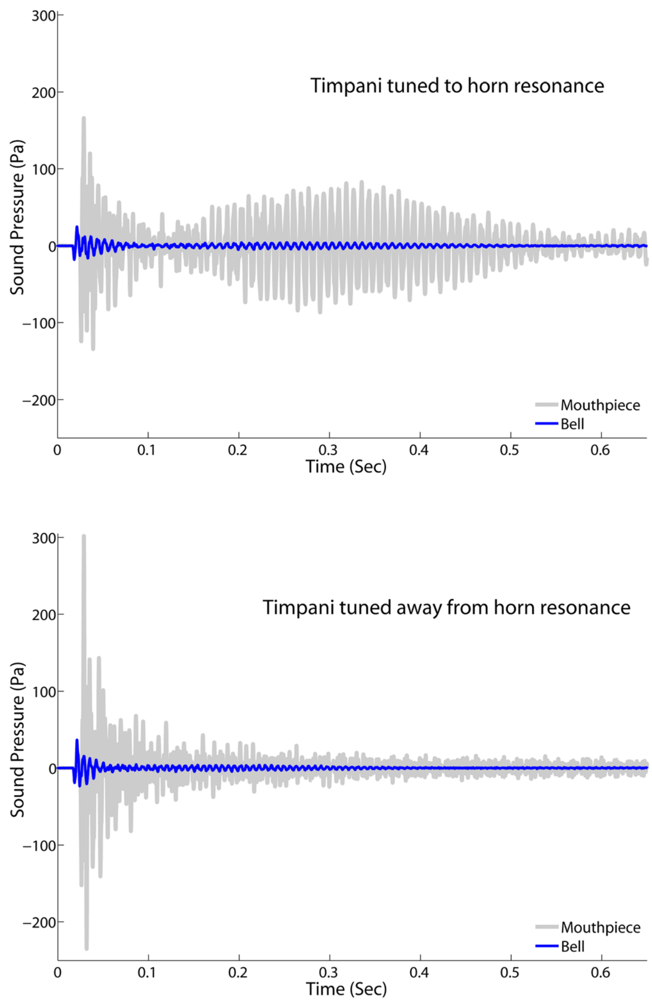

FIG. 5. (Color online) The sound pressure signals due to timpani strokes at two different pitches. Both are measured using the B♭ horn 000 fingering, showing the signal recorded at the bell (dark line) and in the mouthpiece (pale line). *Top*: Timpani tuned to B♭2 + 25 cents to coincide with the 2nd maximum in the horn transfer function. *Bottom*: Timpani tuned to D3-20 cents to coincide with the transfer function minimum between the 2nd and 3rd maxima. The experimental configuration is shown in Fig. 1(B) and the horn is not being played.

transfer function maxima) will fall close to the frequency of the principal resonance of the timpani. This creates two problems for the horn players.

First, the high-pressure pulse from the initial timpani stroke arrives at the mouthpiece during the initial transient of the horn players' notes. Suppose that the bell is 1 m from the timpani and the horn bore is 3 m long. The pulse arrives at the mouthpiece about 12 ms after the beater-drum skin impact. The initial horn transient lasts longer than this. One of the difficulties associated with playing an instrument with a bore that is rather longer than the wavelength of typical notes played is that the horn player must "buzz" her lips for several cycles—the time for at least two round trips from mouthpiece to horn—before the lip vibrations receive suitably phased positive feedback from the standing waves induced by lip vibration, hence the player's fear of "cracking" or "splitting" a note: Playing a note with a noticeably long transient before producing the intended note. The disruptive effect of a timpani pulse arriving at the mouthpiece is likely to be greatest during this less stable starting transient.

Second, the continuing vibration of the drum skin sets up a superposed standing wave in the bore, whose amplitude rises over the first few tenths of a second (see Fig. 5). This wave has a frequency that is harmonically related to the desired frequency of vibration of the horn player's lips, but the relative phase of its arrival at the mouthpiece depends on the precise timing of the timpani stroke and the spatial separation of the players: Its phase could be such that it causes maximum disruption to the positive feedback usually provided during a steady note.

C. Timpani strokes during horn playing

When the horn played at *p* and *mf* dynamic levels, sound pressure levels of ∼152 and ∼158 dB are measured in the mouthpiece. In both cases, the arrival of the pressure impulse signal from the timpani stroke sounded outside the bell can usually be easily observed at the mouthpiece. Soon after the timpani pulse arrives at the bell, the periodic pressure oscillation in the mouthpiece is disrupted for times up to a few tenths of a second: The amplitude and the apparent period are seen to vary substantially.

Figure 6 shows an example of a measurement made while the horn player played the note B♭2 + 20 cents (on the B♭ horn 000 fingering) at the *p* dynamic level (149 dB, measured at the mouthpiece). The player is seated in the normal concert position with his hand in the bell. The bell of the horn is pointing at the timpani situated 1 m away, which is also tuned nominally at B♭2 + 20 cents and struck at *mf* dynamic level.

Before the arrival of the timpani pulse, the pressure in the mouthpiece is almost completely periodic. Eight milliseconds after the timpani pulse arrives at the bell, the quiescent oscillation in the mouthpiece is significantly perturbed: The amplitude and apparent period are significantly changed and subsidiary peaks appear. Amplitude variations are as large as 4.5 dB. The irregularity persists for several tenths of a second before the quiescent vibration is completely restored.

With the same spatial arrangement of the two instruments, other perturbations in the horn note were also observed. Sometimes the horn's pitch is affected; sometimes its timbre becomes unpleasant (described as "raspy" by one of the players). Sound examples are available online (Music Acoustics, 2013).

The degree of disruption depends also on the relative tuning of the instruments. When the timpani is tuned slightly away from the horn note (less likely in practice), interference beats can be observed (Fig. 7). In other cases, the lip vibration frequency was briefly driven near the timpani frequency: In examples where the pitch of the timpani was about 95 cents flatter than the horn note, the horn pitch was sometimes "pulled" 85 cents flat for some tenths of a second after the stroke (example online; Music Acoustics, 2013).

The example cited in Fig. 6 is a little exaggerated: The horn is playing *p* and the timpani *mf*, and the separation of 1 m would only be encountered on a small stage or perhaps in an orchestra pit. Nevertheless, the extreme perturbation

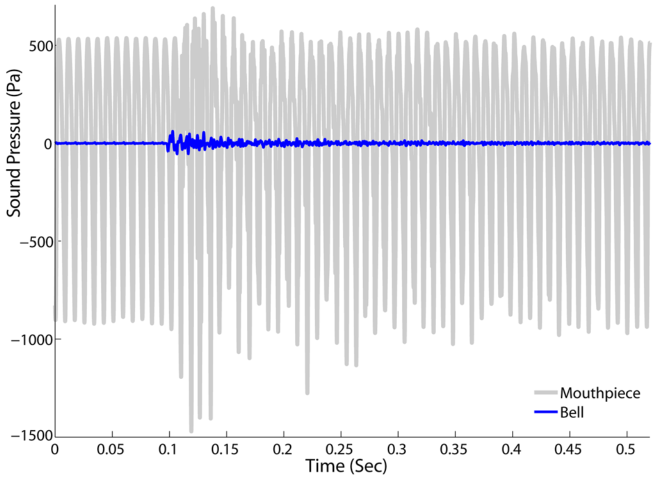

FIG. 6. (Color online) The disruptive effect of a timpani stroke: The mouthpiece pressure measured during horn playing, before, during, and after the pulse of a timpani stroke. Both instruments here play B♭2 + 20 cents, with the 000 fingering on the B♭ horn used. The pressure measured in the bell is the dark line, while the pressure measured in the mouthpiece is the pale line. The horn is played *piano* in the normal concert position (hand in the bell), with the bell pointing at the timpani, 1 m away and struck at *mf*.

observed in this case supports the arguments of certain horn players stipulating that they be seated at least 6 ft (∼2 m) from the timpani (Online horn forum, 2012), in an effort to minimize the timpani's impact on the horn's playability. Is it possible then to specify quantitatively what a "safe" timpani-horn distance might be? This is difficult because it depends on the relative magnitudes of the pressure produced by horn player and timpanist, and thus possibly on the music performed and the players' interpretations of loudness markings. It could also vary among horn players, according to their sensitivity to perturbation. However, using the far field isotropic radiation approximation, a 2 m separation would halve the timpani:horn pressure ratio at the mouthpiece from that shown in Fig. 6, under similar playing conditions, and may sufficiently reduce the perturbation from the timpani for most cases.

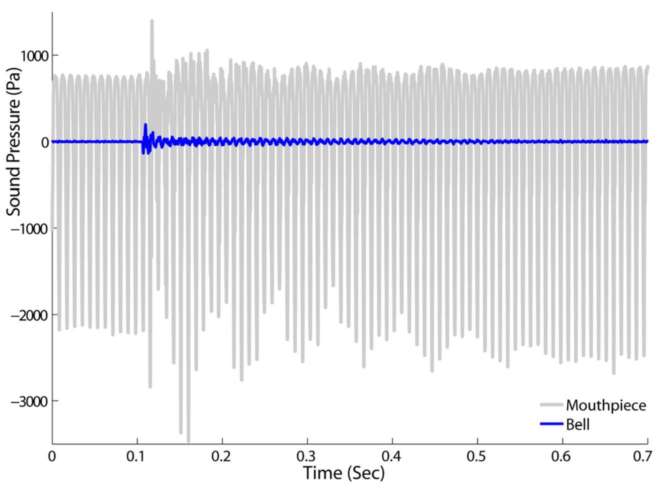

FIG. 7. (Color online) Interference beats measured in the mouthpiece during horn playing, due to a timpani stroke with a mismatched tuning. The horn here is initially sounding 113 Hz while the timpani stroke is tuned to 124 Hz, resulting in interference beating (∼11 Hz) in the mouthpiece signal after the timpani is struck. The pressure measured in the bell is the dark line, while the pressure measured in the mouthpiece is the pale line. The horn is played using the experimental configuration shown in Fig. 1(B).

A related disruptive effect has been reported when horn players are seated closely together and playing a high passage at a loud dynamic level in unison (a fairly common occurrence in an orchestral climax). Under these conditions, players sometimes report that it can become difficult for the players to sustain the notes (Schuller, 1962; Horvath, 2010). The relative phase of the waves produced by a player and his/her neighbors has no predictable relationship, therefore potentially disruptive interference might also be possible.

IV. CONCLUSIONS

Measurements of the bell-to-mouthpiece transfer function of the horn for various fingerings show that gains of at least ∼20 dB at the mouthpiece are possible around resonances of the horn.

For impulsive external excitation produced by timpani strokes played near the bell of the horn, the overall impulse gain response at the mouthpiece is at least ∼16 dB, because the horn is behaving as an acoustic impedance matching receiver. When the timpani is tuned near to a maximum in the transfer function (a situation that would be common in orchestral performance), the vibrations from the drum skin can produce standing waves in the horn bore that lead to a gain of ∼26 dB from bell to mouthpiece. Behavior consistent with nonlinear wave propagation in the bell-to-mouthpiece direction has been observed, allowing proportionally greater transmission to the mouthpiece for signals producing pressures at the bell of about 100 Pa (∼130 dB) or greater.

Measurements of the acoustic pressure in the mouthpiece during horn playing show that the response to a loud timpani stroke nearby disrupts the periodic oscillation in the mouthpiece and that the disruption may continue for tenths of a second—the timescale of the horn's resonant response to the timpani input. Both the impulsive and sustained input from the nearby, loud timpani are sufficient to disrupt horn playing.

Generally the horn is played with the bell pointing behind the player, and so only instruments in the near vicinity and to the rear (often the timpani) might be expected to be disruptive. Interestingly, in most orchestral stage configurations, the bass drum is usually positioned on the other side of the percussion section, away from the horns (unlike the timpani), and so is not expected to give much trouble to horn players. Although other orchestral instruments may indeed generate larger average sound power than the timpani, the nature of their sound is quiescent rather than transient, and they are positioned elsewhere on the stage, so they are less likely to interfere with horn playing.

ACKNOWLEDGMENTS

We thank the Australian Research Council for support, our volunteer horn players, and Emery Schubert for loan of his instruments.

[1]A report of a preliminary version of this study, including Fig. 2, was presented to the Stockholm Music Acoustics Conference 2013 (Chen *et al.*, 2013).

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