

Dynamic temporal behaviour of the keyboard action on the Hammond organ and its perceptual significance

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The Hammond organ is one of earliest electronic instruments and is still used widely in contemporary popular music. One of its main sonic features is the “key-click”, a transient that occurs upon note onset, caused by the mechanical bouncing of the nine electric contacts actuated during each key press. A study of the dynamic mechanical behaviour of the contact bounces is presented, showing that the velocity, the type of touch and, more in general, the temporal evolution of the key position, all affect different characteristics of the contact bounces. A second study focuses on the listener’s perception of the generated sound and finds that listeners can classify sounds produced on the Hammond organ according to the type of touch and velocity used. It is concluded that the Hammond organ is a touch-responsive instrument and that the gesture used to produce a note affects the generated sound across multiple dimensions. The control available at the fingertips of the musician is therefore such that it cannot be easily reduced to a single scalar velocity parameter, as is common practice in modern digital emulations of the instrument.

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I. INTRODUCTION

The Hammond organ occupies a prominent position in popular music. After its introduction in the 1930’s, it was widely used in popular music since the 1950’s and its sound has been heard on countless recordings.

Where the piano and most digital keyboards have a clear relation between velocity and the produced sound, the Hammond shows a more subtle effect: the key-click, a distinctive transient in the sound at the beginning of every note. This click is the result of the behaviour of nine different contacts embedded in the keyboard mechanism. As we show in this paper, these contacts are not ideal switches: they do not close at the same time and they exhibit bouncing. These characteristics change in response to both the speed and the quality of the key press, giving the instrument its own distinctive form of touch response.

We conduct two studies to characterise the behaviour of the Hammond organ keyboard. Our first study analyses the dynamic electromechanical behaviour of the key action and its main components. Through position and electronic measurements we show that the moving parts in the action react to the details of the key press, producing measurable differences in the timing and characteristics of the onset transient. The second study is a listening test to assess to what extent the measured differences in contact behaviour are relevant to the listener. We find that, although the key-click is a short burst of a few milliseconds at the note onset, a statistically significant number of participants are able to correctly infer the type of touch used to generate a note.

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II. THE HAMMOND ORGAN

A. History

Laurens Hammond started prototyping the Hammond organ in 1929, patented it in 1934 and first made it available to the general public in 1935, making it one of the first commercial pipeless electronic organs (Hammond, 1934; Roads, 1996).

The Hammond organ was originally designed and sold as a cheaper substitute for church organs. While offering a wide palette of sounds, its timbre was less rich in harmonics than pipe organs and the attack of the note on the Hammond was much faster and sharper, somehow limiting its realism as an emulation. Regardless, many church communities were willing to accept this trade-off given the lower cost of the new instrument (Ng, 2015, 23-24). Since the moment of its introduction, the Hammond organ was used in a variety of genres, far beyond the original aims of his inventor. It was used in classical, gospel, rock, jazz and all sorts of popular music, as well as radio and TV shows, theatres, stadiums and other public venues, cruise ships (Vail, 2002, 13-24). Some of the reasons for this success can be traced back to the attack sound itself: the fast attack allows playing faster tempi with accurate rhythmic precision (Ng, 2015, 36-37).

B. Principle of operation

The Hammond organ, as patented by Laurens Hammond, is an electromechanical keyboard music instrument. The principle of use is that of a polyphonic additive synthesizer, whose oscillator bank consists of 91 quasi-sinusoidal signals. Each of these is generated by a mechanical dented wheel (tonewheel), spinning driven by a synchronous AC-motor. Each tonewheel induces a sinusoidal signal at the output of an electromagnetic

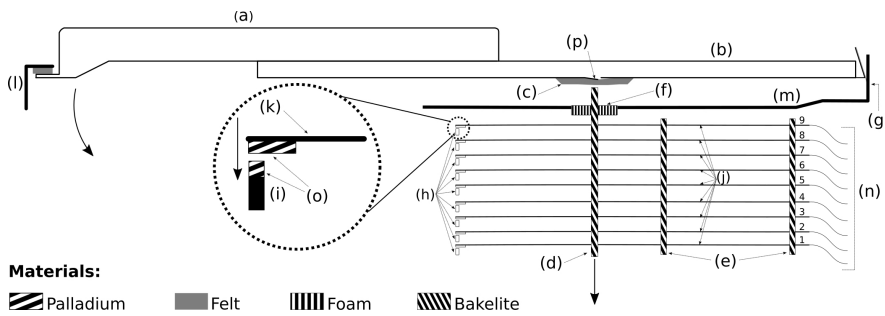


FIG. 1. Schematic representation of a typical tonewheel Hammond key and the underlying contacts. Solid arrows indicate the directions of the motion of the key, the contact pusher and the tip of the spring contact. (a) plastic key, (b) metal shaft, (c) contact pusher felt, (d) contact pusher, (e) insulated support, (f) foam, (g) pivotal point, (i) and (h) busbar, (j) and (k) contact spring, (l) and (m) support frame, (n) resistive wires from generator, (o) precious metal points, (p) adjusting tab

Contact number	Harmonic	Interval
9	eighth	+3 octaves
8	sixth	perfect fifth +2 octaves
7	fifth	major third +2 octaves
6	fourth	+2 octaves
5	third	perfect fifth +1 octave
4	second	+1 octave
3	fundamental	unison
2	sub-third	perfect fifth
1	sub-fundamental	- 1 octave

TABLE I. Harmonic ratios and intervals of the frequencies routed to the contact switches of each playing key.

pickup placed in front of it ¹.

The Hammond C-3 used in this study, one of the most popular models, has two 61-note (C_2 to C_7) keyboard manuals, as well as pedals and an expression pedal. Each key on the keyboard manuals closes multiple contacts: seven were present in the original patent, but there are nine in most tonewheel Hammonds, including the C-3. Each contact is connected to one of the sinusoids from the tone generator, and each of these corresponds to the frequency of one of the harmonics or sub-harmonics of the note, as outlined in Table I (Hammond Instrument Company, 1987, sec. 2, p. 17-19). The bottom 12 tonewheels from the generator are reserved for the pedals, and only 79 are routed to the playing manuals. As these do not cover the entire range of frequencies needed for the playing manuals, some of the keys from the bottom octave and some from the topmost two octaves use the signal from a tonewheel one octave below or one or two octaves above the nominal frequency (“foldback”) (Wiltshire, 2008). An intricate web of 549 resistive wires for each of the two manuals routes the generator tones to the contact switches.

Every time a key is pressed, this causes each contact to close against one metal bar (“busbars”). When a contact is closed, this connects the signal from the generator to the busbar through the resistive wire, which allows for passive summation of several signals on the same busbar. The output of each busbar is connected to one tap of a matching transformer which sums the signals coming from the busbars before feeding them to the pre-amplifier. The relative levels of the harmonics of the notes

on each manual are adjusted by selecting the tap of the matching transformer used by each busbar. Ten “preset keys” (reverse-colored keys with locking mechanism at the left end of each playing manuals) allow quick access to predefined harmonic combinations, while a set of nine² levers (“drawbars”) allows the performer to adjust the harmonic mix to taste.

A general overview of the routing mechanism can be found in Wiltshire (2008); a detailed technical description is in the service manual (Hammond Instrument Company, 1987, p. 17-19), while a simplified mathematical model can be found in Werner and Abel (2016).

C. Key mechanics

Here and in the remainder of this paper we will refer to a 1967 Hammond C-3 available at our lab, which we used for the measurements and recordings throughout this paper. The organ was in good working order and was recently serviced by a specialised technician.

A diagram of the key action can be found in Fig. 1. The keyboard action features square-front (“waterfall”) key caps mounted on metallic shafts, equipped with a return spring which is responsible for returning the key to the home position once it is released. A bakelite contact pusher is positioned vertically below the key shaft, at about 3cm from the pivotal point at the back of the key. Where the bottom of the key shaft makes contact with the contact pusher there is a tiny strip of felt which couples the metal key shaft to the bakelite strip. A metal tab is cut out on the bottom of the key shaft and allows adjustment of the distance at which the felt engages the contact pusher. The contact pusher has nine horizontal openings, each holding one bronze contact spring. Each contact spring is connected via a resistive wire to one tone from the generator. The busbar and the spring contact are covered in palladium to ensure optimal conductivity (Hammond Instrument Company, 1987, sec. 2, p.17). The top of the contact pusher is inserted in a slot cut out from a layer of foam which prevents it from moving sideways in the horizontal plane.

The pivotal motion of the key is transformed in a vertical motion of the contact pusher and of the spring contacts, with the key assembly effectively acting as a 9-pole-single-throw switch. When the key is at rest, the felt is

resting about 2mm above the contact pusher. During the key travel, the felt engages the contact pusher and pushes it down. This in turn actuates the stack of spring contacts by pushing each of them against its corresponding busbar, thus connecting the tones from the generator to the output. The maximum displacement of the front of a white key is 9mm, while the maximum displacement of the shaft at the felt is about 4mm. We did not investigate the mechanical details of the contact switches, however more details on their design can be found in Hammond (1934, p. 7-8).

In spite of the precious metal coating, dirt, oxide and dust will often make the contact less than ideal over time (Vail, 2002). Additionally, contacts may not close simultaneously and each of them may bounce multiple times. When the signal at the input of the contact is non-zero and the contact is switched, this causes a transient in the output signal, thus giving rise to the key-click. A computationally-efficient emulation of the key-click sound was proposed in (Pekonen *et al.*, 2011) using an Attack-Decay-Sustain-Release envelope applied to the sixth harmonic of the fundamental note.

III. TOUCH ON KEYBOARD INSTRUMENTS

No formal study on the player’s touch on the Hammond organ can be found in the literature. On the other hand, the literature on the effect of touch on the piano and its effects on the produced sound is abundant and is here reviewed as it will later be used as a starting point for the analysis of the Hammond. For an extensive review of the studies on piano touch, see MacRitchie (2015).

Touch has also been studied on other keyboard instrument, such as the Ondes Martenot (Quartier *et al.*, 2015) and the harpsichord (Gingras *et al.*, 2009). MacRitchie and Nuti (2015) investigate the effect of touch on the harpsichord, which is often regarded as an instrument which is not touch-sensitive. They find measurable differences in the amplitude of the harmonics of harpsichord notes, depending on the type of touch used.

Some basic concepts on the Hammond organ are introduced here in comparison with the piano.

A. Touch on the piano

When discussing the effect of piano touch, most of the literature focuses on the distinction between:

- pressed (also called legato, non-percussive) touch, when the finger is resting on the surface of the key before pressing it.
- struck (also called staccato, percussive) touch, when the finger is moving when it engages the surface of the key.

An early study on the effect of touch showed that the psychological factors involved in different types of key press are different, but concluded that ultimately there is a one-to-one correspondence between the intensity of the

touch and the tonal quality of the produced sound (Ortmann, 1925). This correspondence is strictly true only for the sound produced by the string, but a key press is often accompanied by additional sound components. During a struck onset, for instance, an “early noise” is produced by the finger hitting the key. A listening test showed that when the early noise, which precedes the actual note onset, is excluded from a recording, a listener cannot infer the type (pressed or struck) of touch used to produce the tone (Goebel *et al.*, 2004). In real playing conditions, this noise will be part of the sound of the acoustic instrument, and will to some extent reach the listener. However, being much quieter than the tone produced by the string, and very close to it in time, it may be hard to distinguish it as a distinct event (Kinoshita *et al.*, 2007). In Goebel *et al.* (2014), the early noise, along with the more subtle “key-bottom” noise, caused by the key hitting the felt on the keybed, are shown to be perceptually relevant to the listener in a controlled experimental situation.

The acceleration of the key during a key press is continuously under the control of the player. Even non-professional players can vary the way they distribute the acceleration, in order to control parameters other than simple velocity, such as percussiveness, weight and depth of a key press (McPherson and Kim, 2011). Trained pianists, on the other hand, routinely semi-unconsciously control these dimensions as part of an expressive performance (McPherson and Kim, 2013). These studies suggest that reducing gesture on the piano to a single scalar parameter, such as the velocity of the key or of the hammer, does not fully represent the expressive intention of the performer.

Goebel *et al.* (2005) conducted a thorough study on the relative timings of different sections of piano action as they relate to the type of touch used. The time between the finger-key actuation and the production of the sound changes greatly with the velocity of the touch, with pressed notes exhibiting a longer delay than struck notes with a similar hammer velocity. Birkett (2014) suggests that the key-to-hammer-to-string interaction is consistently repeatable, in that a given key motion will consistently produce very similar sonic results.

When testing the response of an instrument to the performer’s key press, there is need to find a strategy to create a dataset large enough to be statistically meaningful and to reproduce the exact gesture multiple times. Typical self-playing pianos use solenoids to press the tail of the key. Goebel *et al.* (2003) used multiple recordings of a human player pressing the key, while Hayashi *et al.* (1999) designed an active, voice-coil motor driven, mechanical finger which presses the front of the key, but is unsuitable for percussive touch. Askenfelt and Jansson (1990) used a rubber-tipped pendulum which occasionally causes undesired rebounds of the tip on the key.

Key position is usually measured with optical reflectance sensors (McPherson, 2015), while moving parts in the piano action are measured in the works mentioned above with a combination of accelerometers, optical interference sensors, conductive surfaces, force-sensitive resistors and high-speed imaging. Solutions based on optics are preferable as they do not interfere in any way with

the mechanics of the instruments.

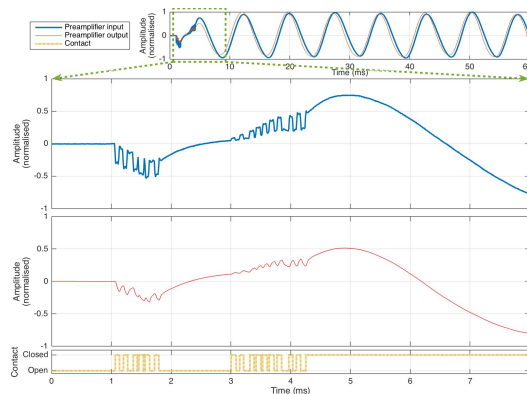
B. Touch on the Hammond organ

When a key is pressed, the key contacts are connected to the busbars, generating an onset transient, after which the amplitude and harmonic characteristics of the sound remain constant for the entire duration of the note. As soon as the key is released, the contacts are disconnected from the busbars and the note terminates with an offset transient. The sound produced by a key press has - as a first approximation - a rectangular amplitude envelope, with the key-click marking the beginning and ending of the note. The volume of a note can be varied only through the use of the registration drawbars or the volume pedal, the former affecting all the notes on the corresponding manual and the latter affecting all the notes being played on the organ. The velocity at which a key is pressed will not affect the amplitude or the harmonic content of the steady-state part of a note.

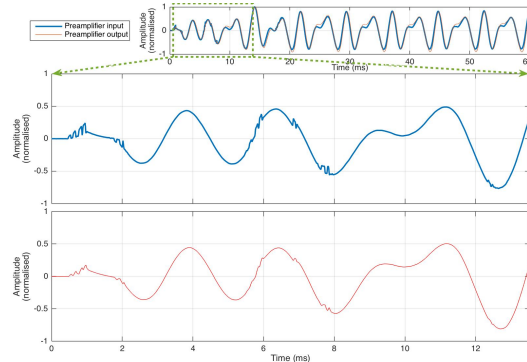
Laurens Hammond always considered the attack click of his instrument more as a defect, rather than as an expressive feature and tried to make it less prominent with low-pass filtering in the power amplifier and on dedicated speakers. Regardless of the designer’s opinion on the subject, the “key-click” is, to date, one of the most appreciated characteristics of the Hammond organ by players, so much that when newer technologies were introduced to completely eliminate the key-click from fully electronic organs, musicians objected to the consequent lack of articulation (Vail, 2002, p. 44-45).

The particular contact stack in use also allows some extended playing techniques. Progressive key presses consist in slowly depressing a key, so that individual harmonics will start playing one at a time, as soon as each contact touches the corresponding busbar. Partial key presses are also possible, when the key is not pressed all the way down and it does not trigger all of the harmonics. These are commonly used to obtain percussive “non-pitched” sounds. The squabbling technique consists in playing a chord with one hand where one or more of the intermediate keys are partially pressed³.

Many digital synthesizers are available on the market which are dedicated to reproducing the sound of the Hammond organ, though they often fall short of reproducing the feel of the original keyboard action. Most of these emulators use a standard keybed and compute the scalar velocity of the key press, which is then encoded in the MIDI velocity parameter and passed onto the synthesis engine. Only some of the synthesis engines would actually make use of this parameter to shape the key-click sound. Some two-contact keybeds can be set to trigger velocity-insensitive sounds early in the key throw, as soon as the first contact closes, thus disregarding the velocity parameter but giving a more immediate response, without having to wait for the key to reach the bottom of the keybed. Manufacturer Hammond-Suzuki, in their “B-3 mk2” model went as far as building a complete re-creation in hardware of the original 9-contact action, paired with a digital sound generator⁴(Vail, 2002, 226).



(a) Single drawbar



(b) Multiple drawbars

FIG. 2. (color online) Comparison of the signal at the output of the generator and the signal modulated by the key contact during an onset, measured at the output of the matching transformer. The note played is a C_3 , with a fundamental frequency of 131Hz. In (a) only the drawbar 1 was active, while in (b) drawbars 1, 2, 3 and 4 were active. The contact state at the bottom of (a) is inferred from the discontinuities in the audio signal.

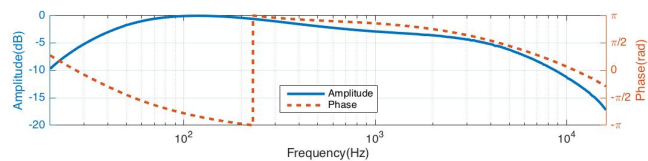


FIG. 3. (color online) Transfer function of the organ preamplifier, measured with a test signal consisting of a sine sweep between 2Hz and 20 kHz with an amplitude of 0dBu.

In 2016, the same company announced the “XK-5” model which features a traditional electronic keyboard keybed with a total of three mechanical contacts per key, each triggering three contacts in the synthesis engine.⁵ The ongoing effort by Hammond-Suzuki and other companies to reproduce the details of the control and the sound of the note onset to the highest degree of detail indirectly shows their relevance to the musicians.

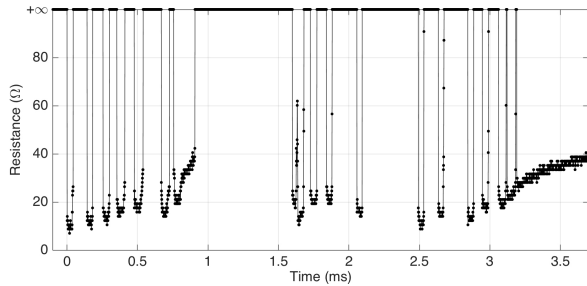


FIG. 4. Detail of the measured resistance during the onset bouncing of a key contact for a struck touch, sampled at 1MHz with an Agilent MSO-X-3054A oscilloscope. Each dot represents one sample.

1. Effect of contact bounce on the audio signal

In order to get an indication of the effect of the contact bounce on the audio signal produced by the instrument, we took coupled recordings of the audio signal at the input of the preamplifier and at its output (the line output of the organ) during a key onset, obtaining the waveforms in Fig. 2. The transients and high-frequency oscillations in the initial part of the signal are due to the bouncing of the contact associated with each active drawbar. The signal only reaches full amplitude a few milliseconds after the contact settles in the closed state. As the signal passes through the preamplifier, whose frequency response is shown in Fig. 3, the high-frequency components are attenuated and the transients are smoothed.

In Fig. 2a, a single drawbar is active, therefore all the transients are due to a single contact. By inspecting the waveform at the preamplifier input, we were able to infer and manually annotate the open/closed state of the contact, shown at the bottom of Fig. 2a. In Fig. 2b multiple drawbars are active, producing a more complex tone. As the contact associated with each drawbar closes, the corresponding frequency is added to the output signal after a brief transient noise caused by the bouncing of the contact.

C. Implications

The Hammond organ features a multi-contact keyboard and shows no relation between the velocity of the key-stroke and the loudness of the produced sound, yet some clear consequences of the multi-contact array allow the extended techniques mentioned above. Other, less-obvious dependencies may reside in the subtle control available in the shape of the key profile during a note onset, and in the way it affects the key-click. We therefore investigate if and how the velocity and the type of touch used can affect the sound of a note and how this effect is perceived by a listener.

IV. STUDY 1: DYNAMIC MECHANICAL BEHAVIOUR

During a note onset, up to nine tones from the generator are connected to the output circuit through the contacts at the back of the key. While the key is at rest, all the contacts are open. When a contact first touches the corresponding busbar, it will usually bounce a few times before it settles in the “closed” position (see Fig. 4), affecting the signal as explained in Section III.B.1. The characteristic transient in the audio signal of each note onset on the Hammond organ, the key-click, ultimately results from the overlapping of the effect of these bounces across all the contacts. One of the consequences of this is that the note’s onset transient will begin when the first contact starts bouncing and will stop once all the contacts settle in the “closed” state and the steady state part of the note begins.

In this experiment we recorded the continuous position of the key and the electrical state of each of the nine contacts activated by that key, in order to understand the relation between the gesture and the characteristics of the contact bounce. The way the instrument is designed prevents the possibility to capture the sound output at the same time as the contact state is being monitored.

A. Experimental setup

1. Key angle

The key shaft on the Hammond keyboard assembly is U-shaped and its opening is facing upwards. To measure continuous key position, an optical reflectance infrared sensor was used (Omron EE-SY1200). The sensor was placed at the top of the key shaft, pointing down towards the shaft. To avoid reflections from the internal sides of the shaft, a thin piece of white paper was glued on top of the shaft opening, so to form a uniform, reflective, flat surface to allow for more accurate measurements.

The signal from the optical sensor was buffered, amplified and scaled to a suitable voltage range with a derivation of the circuit in McPherson (2013). The bandwidth of the sensor and the analog preamplifier was measured with a test signal to be approximately 16kHz.

Optical reflectance sensors typically exhibit an inherent non-linearity when used to measure distances (Pardue and McPherson, 2013). This is accentuated in this application by the fact that the surface does not move perpendicularly to the IR beam and therefore the angle between the beam and the reflective surface changes as the key is moved. We compensated for the non-linearity through a dedicated calibration procedure.

2. Contacts

In order to avoid the interaction of the circuit under test with the impedances of the generator’s pickups and of the output transformers, both poles of each of the nine contacts were isolated from the rest of the Hammond organ and were connected to the test circuits described

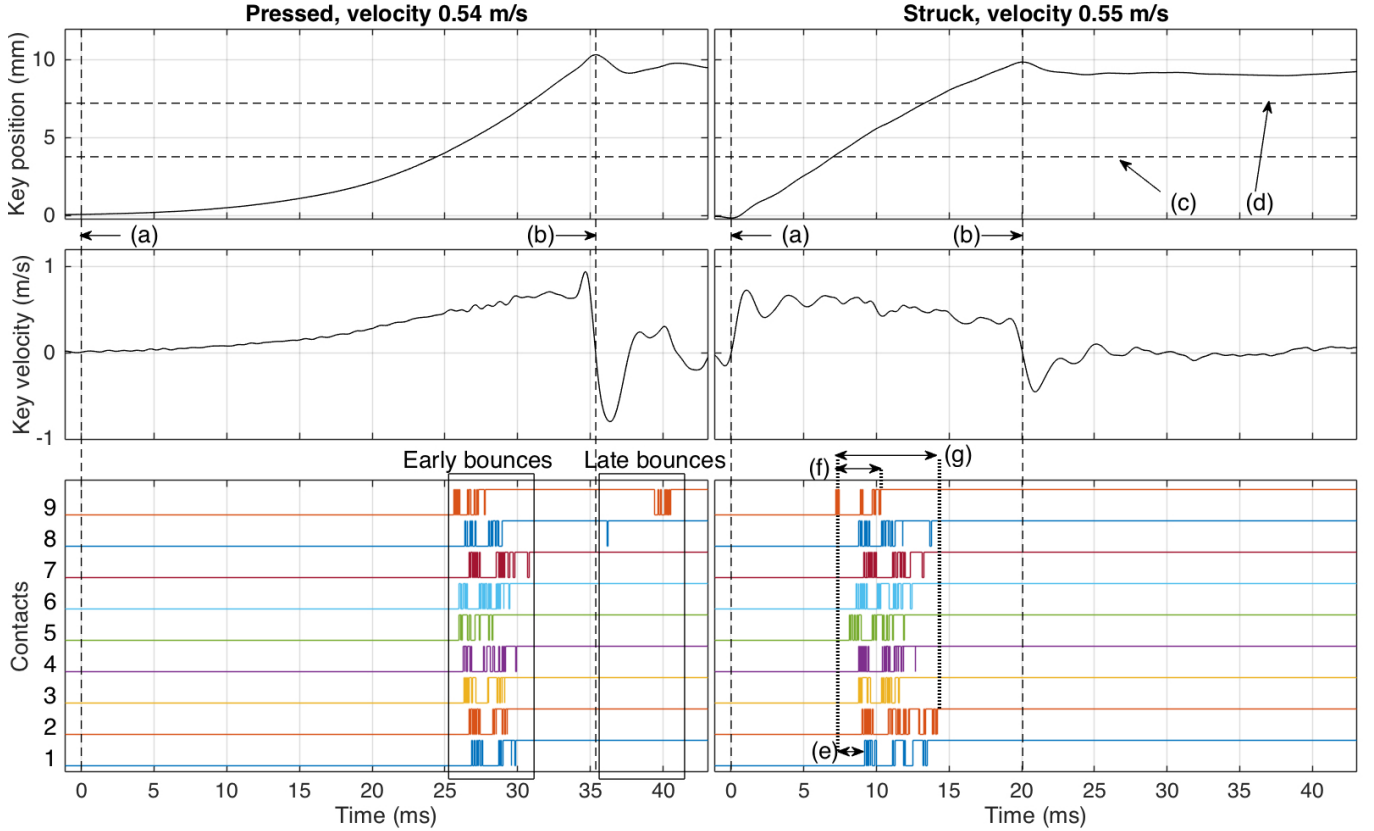


FIG. 5. (color online) Details of the key profile and the contact state for two touches with similar onset velocities and different types of touch. In the lower plot, each of the nine contacts is represented with a line. When the line is low the contact is open, when the line is high the contact is closed. (a) onset start, (b) onset end, (c) and (d) fixed points for computing discrete onset velocity, (e) contact closing offset (time range), (f) contact bounce duration for contact 9 (time range), (g) overall bounce duration (time range).

below. The wires carrying the tones to the key were disconnected at the tone generator end, while the wires from the busbars were disconnected before the matching transformer.

A preliminary test consisted in measuring the resistance of the switch using a circuit with a passive voltage divider sampled with a digital oscilloscope at a sampling rate of 1MHz. The behaviour of a switch during a typical key onset is reported in Fig. 4. This showed that the contact bounces multiple times and that the duration of each of these bounces is of the order of tens of microseconds. Each bounce brings the measured resistance from $+\infty$ (open circuit) to a small resistance value of about 10Ω (closed circuit), with very few intermediate resistance values. The “closed circuit” resistance (greater than zero) is determined by the resistance of the resistive wire connecting the tone generators to each contact.

The resistance values suggest that the dominant audible effect here is likely to be the wide range open-close discontinuity rather than the finer details of the actual resistance value when it is low. As such, we assumed that thresholding the resistance value so to only distinguish between “open” and “closed” states would not cause a significant loss of information. For each switch, a pull-up resistor circuit was used, connected to a comparator to

generate a digital signal which represents the open/closed state of the contact, with a threshold of 120Ω .

3. Data acquisition

A Bela single-board computer was used to acquire the signals described above (McPherson and Zappi, 2015). The output of the preamplifier of the optical sensor was connected to a 16-bit analog input, while the digital signals from the switches were connected to the digital inputs of the board. The Bela board sampled all the inputs at 44.1kHz and logged them to its internal memory.

4. Key presses

To generate the data for this study we chose to repeatedly press the key with a finger, as alternative options such as the robotic finger or the pendulum come with drawbacks that would have not been suitable for this task (see Section III.A).

In total, we collected data for about 800 key presses for each of 8 keys (E_3 , Ab_3 , C_4 (= middle C), F_4 , Ab_4 , C_5 , E_5 , F_5) on the upper manual of the organ. The

performer used pressed and struck touches and tried to produce with the widest possible range of velocities.

B. Results and discussion

1. Key profile

Details of key onsets obtained with a pressed and a struck touch are shown in Fig. 5; the velocity and key position profiles of these two plots are representative of the respective types of touch. The pressed touch (left) starts from a null velocity which increases steadily, reaching maximum velocity just before key bottom. The struck onset (right) shows a spike in the velocity at the beginning of the onset, due to the inertia of the finger and arm which are already moving as they engage the key. The velocity of the key increases quickly to the peak value and the impact also triggers a resonant behaviour in the finger-key system. The velocity then slightly decreases during the remainder of the key press.

We expect that the portion of the key travel that has a wider influence on the behaviour of the key contacts is the one during which the key contacts close. Therefore, in order to compute a discrete onset velocity value for each onset, we chose to compute the average velocity between those two points d_0 and d_1 in the key throw within which 95% of the contacts close across the whole dataset of presses for that key. The discrete onset velocity metrics displayed at the top of Fig. 5 and used in Fig. 7 are therefore computed as the average velocity of the key between d_0 and d_1 :

$$v = \frac{d_1 - d_0}{t_1 - t_0} \quad (1)$$

where t_0 and t_1 are the times corresponding to key positions d_0 and d_1 respectively. For key F_5 , these points are: $d_0 = 3.7\text{mm}$ and $d_1 = 7.18\text{mm}$, and are represented in Fig. 5 by lines (c) and (d) respectively.

Discussion The different way in which acceleration is distributed in the two types of touch leads the two key presses in Fig. 5 to have a similar value of discrete onset velocity but a different duration. The duration of each key onset, measured as the time from when the key is at rest to key-bottom, is 35ms for the pressed one and 20ms for the struck one. The key-travel at the front of a white key is 11mm, therefore the above would lead to average velocity values of 0.31m/s and 0.55m/s respectively. When measuring velocity using Eq. (1), two very similar values of 0.54m/s and 0.55m/s , respectively, are found. However, if we were to compute a discrete velocity measurement based on the final velocity (the velocity 2ms before key bottom), we would obtain 0.93m/s and 0.45m/s respectively.

Comparing the continuous velocity profiles in Fig. 5 with those of a piano action, such as those in Goebel *et al.* (2005, figure 1) and McPherson and Kim (2011, figure 4), the most significant difference is that the rebounds of the finger on the key for a struck touch, visible as dips in the

early part of the velocity curve, are less deep in the case of the organ. This is due to the spring-loaded action of the organ responds more quickly to changes in finger pressure than the weighted action of the piano, following the finger more closely in its rebounds.

2. Contact closing distance

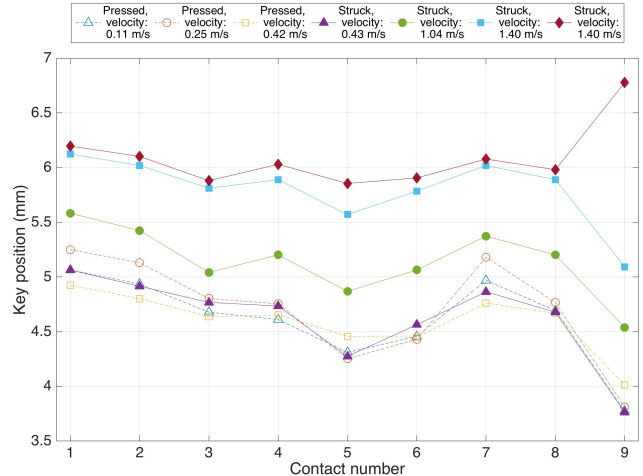


FIG. 6. (color online) Closing distance for each contact for different key presses on a F_5 key.

The instant when the spring contact first touches the busbar determines the beginning of a transient for the generator tone carried by that contact. For any given key, this does not happen at the same point in the key travel across all contacts.

Fig. 6 shows the point of the key travel at which each contact of an F_5 note first touches the busbar, for different key presses. In most cases, all the contacts start making contact with the busbar within the space of about 1.5mm from the earliest to the latest. The order in which they make contact and the spacing between them remains similar for different velocities, but there is an overall offset which is affected primarily by the velocity of the key press, with higher velocities causing the contacts to close at a later point in the key travel. Lower velocity key presses generate similar closing patterns among contacts, translated along the vertical axis as a function of velocity. For higher values of the velocity, outer contacts (1,2,8,9) occasionally break free from the pattern and close later than expected. The two struck key presses with a velocity of 1.4m/s in Fig. 6 are an example of this behaviour: they share a mostly similar contact-closing pattern, but contact 9 closes much later in one than in the other.

Discussion We find that contacts do not all close at the same point in the key travel, rather they close within a range of a couple of millimeters. This very characteristic is the one that allows the extended techniques mentioned in Section III.B: if all the contacts were closing at the

same point in the key travel, then progressive or partial key presses would not be possible. As the closing pattern changes on a key-by-key basis, partial key presses cannot be used as an alternative to drawbar registration to programmatically select which harmonics should play.

We do not have an explanation for the translation in the closing pattern depending on velocity, but we do not expect it to have an impact on the resulting sound or interaction.

3. Timing properties of the onset transient

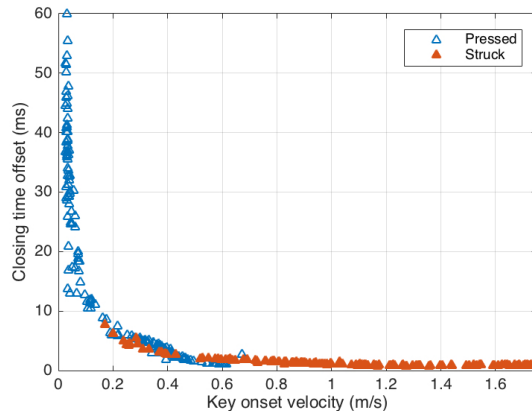
We define the **closing time offset** as the time between the beginning of the first contact onset and the beginning of the last contact onset. It is the time that it takes for all the contacts to start producing sound. The **contact bounce duration** is the time interval during which a given contact is bouncing before it settles to the closed state. This is the duration of the onset transient for the audio signal carried by that contact. The **overall bounce duration** is the time during which at least one of the contacts of the key is bouncing, from when the earliest contact starts bouncing to when the last contact stops bouncing. This is the overall duration of the onset transient for the note. In Fig. 7 these metrics are plotted against the average velocity of the onset.

The closing time offset in Fig. 7a exhibits a relation of inverse proportionality with the onset velocity, which is coherent with its definition: the higher the velocity, the shorter it takes for all the contacts to start closing. The duration of the individual contact bounces varies widely with the key velocity. The overall bounce duration, displayed in Fig. 7c encompasses the time interval across all contacts during which at least one contact is bouncing.

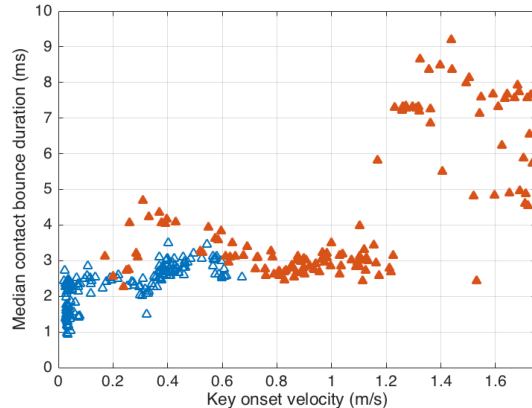
Most of the pressed onsets with higher velocity (between about 0.3m/s and 0.67m/s) exhibit a significantly longer overall bounce duration than struck onsets in the same velocity range. Only struck onsets with much higher velocity will reach similar values of overall bounce duration.

The median value of the bounce duration across all contacts for each key onset is displayed in Fig. 7b. In the range of velocities where there are both pressed and struck touches, struck touches show higher contact bounce duration than pressed ones. Only very small values of key onset velocity result in significantly smaller median contact bounce duration. Occasionally for these low velocity presses one or more contacts would exhibit no bounce at all.

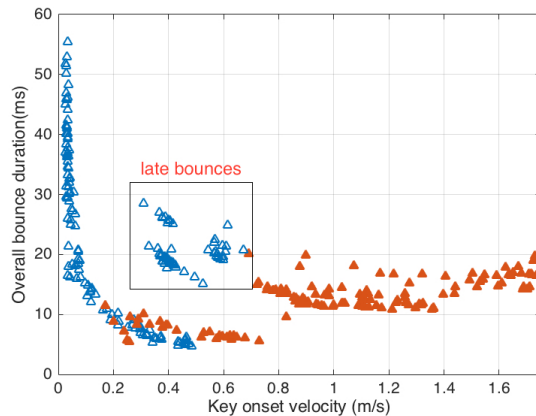
Discussion While recording the key strokes shown in Fig. 7, the player tried to cover the entire onset velocity range for both pressed and struck touches. However, only in the region between 0.17m/s and 0.67m/s did they manage to produce both pressed and struck touches. Velocity values below this range were only achieved through pressed touches and values above only through struck touches, suggesting that struck touches allow the production of higher velocity values, confirming similar findings



(a) Closing time offset



(b) Median value of contact bounce duration



(c) Overall bounce duration

FIG. 7. (color online) Onset metrics for 370 distinct keys presses on a F_5 key.

on the piano keyboard in (Goebel *et al.*, 2005).

The fixed points we chose to compute the discrete onset velocity value were chosen as those within which the contacts are more likely to close (see Section IV.B.1). Given the non-uniform distribution of the acceleration and the differences between pressed and struck key profiles, choosing different points would change the shape of the plots in Fig. 7, mainly affecting the overlap on the velocity axis between pressed and struck key presses.

Upon close inspection of the behaviour over time of

bounces of individual contacts, we observed that an onset bouncing is characterised by a first part, which we call “early bounces”, usually less than 5ms long, during which the contact quickly alternates between the open and closed position. After the early bounces, the contact is pushed against the busbars and stays closed. For some of the key presses, “late bounces” can be observed 3ms or more after the end of the early bounces. The presence of late bounces on one or more contacts may increase the overall bounce duration. In Fig. 5 we labelled early bounces and late bounces in the time-domain representation of contact bounces, while in Fig. 7c) we highlighted those touches for which the overall contact bounce duration is affected by late bounces.

We find that late bounces are correlated with the rebound of the key after key bottom, which causes some of the contacts to be temporarily released from the busbar and left free to bounce again. Late bounces are usually less dense than early bounces but could last longer, depending on the final key velocity. Moreover, late bounces are more likely to occur on those contacts that are at the outer ends of the contact pusher (contacts 1,2,8,9). The rebound of the key is ultimately affected by the key velocity at the moment when the key hits the keybed (the final key velocity), but a high final key velocity does not deterministically produce late bounces. Rather, what we observe is that the *likelihood* of late bounces is higher for presses with higher final key velocity. This can be explained by the fact that the key rebounding on the keybed and the contact pusher form a dual-pole resonant system and therefore the phases of the two oscillations will determine whether the contacts are released from the busbar and produce late bounces.

As observed earlier, pressed touches have a steadily increasing key velocity, while the velocity of struck touches starts with a spike and then slowly decreases. Therefore, for two key presses with the same value of key velocity onset, as measured by us between two fixed points, the final key velocity will be higher for a pressed touch than for a struck touch, and the former will be more likely to exhibit late bounces.

Key presses with similar values of overall bounce duration may exhibit widely different contact behaviours, according to the distribution of velocity along the key throw. For instance, the dominant factor on a onset with high overall bounce duration may be a long contact closing time offset due to a slow velocity, or - alternatively - a single contact exhibiting late bounces, due to a high final velocity.

To summarise, we find three primary phenomena which could affect the character of a note onset. The contact closing offset is caused by the fact that contacts do not all make contact with the busbar at the same point in the key travel. This is directly related to the onset velocity, and is shorter for higher velocities. The duration of the early bounces is determined by the velocity of the spring contact when they hit the busbar: the higher the velocity, the longer they will bounce before settling in the closed state. Late bounces may occur if the final velocity is high enough to cause a rebound of the key.

C. Variability between keys

On the Hammond organ the key action is the same across octaves, so that, unlike in the case of the piano, there is no expected systematic variation between different registers, although there may be some variation due to manufacturing tolerance.

There is no systematic way of adjusting the vertical position of individual busbars, thus affecting the triggering point for a given contact across the keyboard. However, vertical offset of the drawbars due to manufacturing tolerances or bent drawbars can affect the triggering point for a given contact systematically across keys. Superimposed to this offset there are any additional local variations due to key felt, contact pusher and individual contacts.

For the eight keys we measured on the upper manual of the organ, contact 9 is always the first one to close in the key-throw and contact 1 is always the last one. We then measured the contact closing distance on five keys on the lower manual and found that contact 6 is always the first to close and contact 1 is always the last. These findings suggests the possibility that each manual of each instrument may have a distinctive contact closing distance pattern, with additional variations due to each key.

Results in Fig. 7 are for key F_5 on the upper manual; all of the other white keys we measured show a similar overall behaviour, matching our observations earlier in this section. As for the two black keys we tested, they do not show the phenomenon of late bounces. Comparing the observed final velocity values, we find that the upper limit is around 1m/s for pressed touches on the white keys and around 0.6m/s on the black keys. The difference in the observed final velocities for the two types of keys can be explained in terms of the different key-throw (10mm for the white keys, 6mm for the white keys): given that in pressed touches the velocity of the key tends to increase during the press (see Fig. 5), the final velocity value will tend to be smaller if the overall distance is smaller. We showed in Section IV.B.3 that the presence of late bounces is associated with high final velocity values; the lack of late bounces in the pressed touches on black keys can therefore be ascribed to the smaller final velocity values obtainable on the black keys.

The A_{b2} key also showed another singular behaviour, in that contact 1 tends to bounce for long periods for struck touches of velocity comprised between 0.5m/s and 0.9m/s. This in turn causes a higher overall bounce duration in this velocity range for this type of touch, in the 10-60ms range, while most other keys would have figures below 10ms under similar conditions.

D. Implications

We show how the continuous evolution of the key position affects the behaviour of the key contacts. The early part of the bounces is conditioned by the velocity when the contacts engage the busbar, while the late part of the bounces depends on the velocity just before the impact

with the keybed. The contact closing behaviour displays a complex velocity-dependent pattern of asynchrony and bouncing which is dependent on velocity, but the velocity measured at different points in the key travel affects different aspects of the bouncing. Therefore, a single scalar velocity measurement is not enough to represent the multidimensionality of different types of touch, which distribute the velocity differently along the key travel.

V. STUDY 2: PERCEPTION OF NOTE ONSETS

The mechanical behaviour of the keyboard contacts demonstrates that different aspects of the onset transient on the Hammond organ are affected by the velocity and the type of touch in use. However, these changes only cover a small period of several milliseconds at the beginning of each note, while the sound of the sustained part of the note is not correlated with the transient stage and will always exhibit a consistent behaviour regardless of the gesture used to produce the note, as long as the key is fully depressed. We therefore set out to determine whether these changes in the transient were audible and whether they could be reliably associated with the particular type of touch that produces them.

A listening test was designed to validate or reject the following null hypotheses with regard to notes played on the Hammond organ:

1. listeners are unable to distinguish between notes played with different types of touch and velocity
2. listeners cannot distinguish what touch was used to produce a given sound
3. the accuracy of listeners performing the two tasks above is independent of the level of familiarity with the Hammond organ

The test was designed in such a way that it was possible to undertake it locally, under the direct supervision of one of the authors, or remotely, over the internet, using a bespoke online service based on the Web Audio Evaluation Tool (Jillings *et al.*, 2016).

A. Experiment design

1. Stimuli

A dataset of over 2000 key presses was recorded from the monophonic line output of a 1967 C-3 Hammond organ. The Hammond is an electromechanical instrument and is always played through a loudspeaker or recorded via a line output, therefore we disregarded any acoustic recording of the finger and key noise.

We recorded the sound outputs generated by a total of eight different keys spanning the whole range of the keyboard, namely C_1 , Ab_1 , E_2 , C_3 , Ab_3 , E_4 , C_5 , Ab_5 . The tone produced by each key press was at least 2 seconds long, but it was faded out with a logarithmic fade of duration 0.5s, starting 1s after the beginning of the onset transient, so that the release transient was not included

Touch classes	Question
slow-pressed, fast-pressed	<i>Which of these pressed notes has a FASTER velocity?</i>
slow-struck, fast-struck	<i>Which of these pressed notes has a FASTER velocity?</i>
pressed, struck	<i>Which of these notes was played with a STRUCK touch?</i>

TABLE II. Touch classes and questions for each A/B section

in the stimulus. Using the same sensing circuit described in Section IV.A.1, a discrete average velocity value was computed for each of the recorded key press. The notes were played with all the drawbars pulled out. The signal from the line output of the organ was recorded with a sampling rate of 44.1kHz and a bit depth of 24bit using a Motu 828 Mk-III soundcard.

Four combinations of velocity ranges and touch ("touch classes") were chosen for the test (slow-pressed, fast-pressed, slow-struck, fast-struck). Stimuli were selected which had a velocity value of 0.2 ± 0.05 m/s, 0.45 ± 0.05 m/s, 0.7 ± 0.1 m/s, 1.4 ± 0.1 m/s respectively. With this method, a total of 64 unique stimuli were selected: 8 stimuli per key, 2 for each combination of slow/fast and pressed/struck.

2. Structure

The test consisted of a training section followed by four test sections, one of which was an A/B/X test and three of which involved A/B tests. Before the test the subject had to go through a short survey asking about their familiarity with the Hammond organ. An optional survey at the end allowed us to gather feedback from the participants.

The A/B/X section consisted of 72 trials. For each trial, participants were asked to listen to three stimuli, all generated from the same note, labelled A, B and X. They could listen to each stimulus as many times as they liked. Stimuli A and B belonged each to one of the four touch classes and the class of A was always different from the class of B. The X stimulus was a duplicate of one of A or B. Participants had to select the stimulus that better answered the question "*Which of these sounds matches the reference X?*"

Each A/B section consisted of 24 trials. For each trial, participants had to listen to two stimuli, labelled A and B, which were generated from the same note. They could listen to each stimulus as many times as they liked. For each section, stimuli were selected which belonged to two touch classes and the participant was informed what these classes were. In each trial, then, each class would be represented by exactly one stimulus. The same question was asked for each trial throughout a section. After listening to the stimuli, the participant had to select the stimulus that better answered the question. The touch classes used and the question asked in each section are summarised in Table II.

Each set of 24 stimuli for each category consisted of 3 pairs of stimuli for each of the 8 notes. Within the 3 A/B pairs for each note, 2 of them consisted of the same pair of recordings. All the 48 unique pairs from the A/B tests were collated together and used in the A/B/X trials. Additionally, 24 of these pairs were presented twice in the 72 A/B/X trials.

The A/B/X section would always be the first section in the test, immediately after the training, followed by the three A/B sections. For each participant, the following variables were randomised: the order in which the three A/B sections were presented, the order in which the trials were presented within each section, the A/B labels assigned to each stimulus, the stimulus labelled X in each of the A/B/X trials.

3. Training

Some basic training was given prior to the test in order for the participant to understand the basics of the effect of touch on the Hammond organ.

A brief video demonstrated visually and aurally the difference in the physical action between a pressed and a struck note⁶. The aim of the video example was to help the participant get a better understanding of the physical action associated with the sound, hopefully helping them to create a stronger link between the type of key press and the associated sound.

All participants were then presented a set of training stimuli which included one example stimulus for each of the touch classes used in the remainder of the test (slow-pressed, fast-pressed, slow-struck, fast-struck) for each of 3 notes (A_{b2} , C_4 , E_5). Participants could listen to each stimulus as many times as they wanted.

The participant was forced to go through the training once at the beginning, but they were then allowed to go back to it at any later time during the test.

B. Results

A total of 50 participants completed at least one of the sections of the test and 46 of these completed all of the sections. 27 participants undertook the test locally at our research facilities, while the remaining 23 did it remotely online. The local participants were recruited among the postgraduate students at [institution omitted for review], age range = 25-39. The age data was not collected for online participants. Most (42) of the 50 participants had experience playing an instrument, and 37 of these had played their main instrument for more than 5 years, 6 of them at a professional or semi-professional level. The listening test was approved by the [institution omitted for review] Ethics of Research Committee, with approval code [omitted for review] and followed the institution’s guidelines in participant data collection. Local participants were provided with a set of Bose QT-25 headphones, while remote participants were encouraged to use headphones for the test.

	A/B/X	A/B pressed: slow/fast	A/B struck: slow/fast	A/B pressed/ struck
pessimistic	46(0)	45(2)	34(20)	23(2)
optimistic	50(0)	45(0)	32(11)	34(0)
consistency	44	41	28	29
participants	50	47	46	48

TABLE III. Results of the listening test. For each test condition, we report the number of participants for whom we can reject the null hypothesis with $p < 0.05$. Numbers in parentheses indicate how many of these had reversed the labelling.

We performed a statistical analysis on the results of the listening test. To test the first of our hypotheses, that listeners are unable to distinguish between notes played with different types of touch and velocity, we used the results of the A/B/X test. The second hypothesis, that listeners cannot distinguish what touch was used to produce a given sound, was tested under three different conditions with the A/B tests. The data from all the test conditions combined with the self-reported familiarity of the participant with the Hammond organ were used to evaluate the third hypothesis, that the performance obtained by listeners at these tasks is independent from their familiarity with the instrument.

Each A/B/X and A/B trial can be considered a Bernoulli trial, with a probability $p = 0.5$. Assuming the trials are independent, we can analyse the collection of results using null-hypothesis statistical tests under the binomial distribution (Boley and Lester, 2009). Duplicate trials are, by definition, not independent, and have to be removed before the analysis. In order to remove duplicates, we used a dual optimistic/pessimistic approach. We reduced each pair of duplicated trials (which yielded outcomes r_1 , r_2) to a single trial, of outcome r_d . In the case of the *optimistic* approach, “success” if the outcome of *at least* one of two trials was “success”, “failure” otherwise: $r_d = (r_1 \text{ OR } r_2)$. In the case of the *pessimistic* approach, the outcome of *both* trials was “success”, “failure” otherwise: $r_d = (r_1 \text{ AND } r_2)$

In this test the listener was asked to make judgements on sounds - actually a specific characteristic of the sound - that they potentially never heard before, or had never considered to such level of detail. Despite the training provided, it is reasonable to expect that some of the participants may have learned the labels wrong and/or reversed their decision criteria during the test. We therefore took into account the reversal effect (Boley and Lester, 2009) if a participant is able to label sounds belonging to a given class of touch in a consistent way, it means that they can discriminate between the classes, regardless of the fact that the labelling itself is correct or wrong.

In the context of a binomial distribution, the cumulative distribution function gives the probability that a certain number of “success” outcomes from a number of Bernoulli trial is not the result of randomised answers (Boley and Lester, 2009). We used a minimum of 95% confidence level, so that when a participant has cumu-

Familiarity	A/B/X	A/B pressed: slow/fast	A/B struck: slow/fast	A/B pressed/ struck
low(14)	85.7%	85.7%	78.6%	35.7%
mid(17)	100.0%	100.0%	64.7%	58.8%
high(19)	89.5%	84.2%	63.2%	42.1%
not played(32)	90.6%	90.6%	71.9%	50.0%
played(18)	94.4%	88.9%	61.1%	38.9%

TABLE IV. Percentage of participants in each group who passed the test, according to the pessimistic evaluation. Within parentheses is the number of participants in each group.

lative binomial probability above 95% or below 5%(accounting for the reversal effect) under a given test condition, this indicates a relevant perceptual difference. Results of the test are summarised in Table III.

For each of the test conditions we also tested for self-consistency of the listeners, leveraging the duplicated trials. In order to do so, we considered each pair of duplicate trials as a single consistency trial whose outcome is “success” if the outcomes of the two trials are the same or “failure” if the outcomes of the two trials differ, thus making the consistency trial a Bernoulli trial. We then computed the cumulative distribution function for each test with a threshold of $p < 0.05$. The number of participants who passed the consistency test are in Table III. Out of the 46 participants who completed all of the four tests, only 1 was not consistent in any of the tests, 3 were consistent in one test only, 12 in two tests, 11 in three tests and 19 in all the four tests.

Participants were asked to report their familiarity with the sound of the Hammond organ and with the technical aspects of the instrument, each as a numerical rating on a scale between 1 and 5. By averaging together the numerical ratings from the two questions, we grouped participants in three groups, according to their familiarity with the instrument: “low”(average ≤ 2), “mid”(2 $<$ average ≤ 4), “high”(rating > 4). In a different analysis, we split the participants in two separate groups between those who had a significant experience in playing the instrument and those who never or almost never played it, on the basis of their answer to a dedicated question in the survey. The results, expressed as relative number of correct outcomes, for each of these groupings are in Table IV.

In all the tests, participants were allowed to listen to the samples as many times as they liked and in any order. The samples in each pair were taken from the same note and with the same drawbars setting and the same volume, therefore there is no difference in loudness levels between the two notes, which rules out possible effects of forward masking - as identified, e.g.: in MacRitchie and Nuti (2015). Chi-squared tests did not show any significant effect of the presentation order for the A/B/X test [percent correct: 86.1%, $\chi^2(2) = 1.04$], the A/B pressed test [percent correct: 91.4%, $\chi^2(2) = 0.74$] or the A/B struck test [percent correct: 74.55%, $\chi^2(2) = 0.87$]. However, the chi-squared value shows an apparent effect of

Notes	A/B/X:	A/B pressed: slow/fast	A/B struck: slow/fast	A/B pressed/ struck
C_4	189	111	115	86
$A\flat_6$	194	116	111	78
$A\flat_2$	191	130	114	92
$A\flat_4$	200	135	109	97
C_2	198	129	83	85
C_6	194	139	109	115
E_3	196	136	93	101
E_5	191	135	89	99
Trials per note:	225	141	138	144

TABLE V. Number of successful trials for individual notes in each test.

the presentation order in the A/B struck/pressed test, [percent correct: 65.4%, $\chi^2(2) = 5.42, p < 0.02$], where participants tended to select “A” when the correct response was “B” more often (229 times out of 607, 37.8%) than they would select “B” when the correct response was “A” (170 times out of 545, 31.2%).

Results in Table IV show that there is no clear difference in the results achieved by participants with different levels of familiarity with the instrument. Of the participants with a high familiarity with the instrument, only 2 took the test locally. A chi-squared analysis could not find any significant difference in the overall performance of those who attended the test locally and those who attended it remotely [$\chi^2(2) = 0.042$], so there seems to be no effect due to non-uniform testing conditions.

A breakdown of the number of correct outcomes for each note is shown in Table V. A chi-squared independence test shows no effect across notes for the A/B/X test, however it found that for each of the A/B tests there is a significant difference between the notes ($p < 0.001$).

C. Discussion

From the outcome of the A/B/X test, we conclude that for at least 46 out of 50 participants there is a perceptually relevant difference between stimuli produced with different types of touch and velocity. This outcome is, by itself, enough to reject our first null hypothesis. 40 participants went through the section in less than 25 minutes and only 3 took more than 40 minutes, but there is no way to control whether they had breaks during the session.

Most participants were also able to reliably distinguish between the slow-pressed and fast-pressed touches. This test was the one on which participants spent the least amount of time (about 2 minutes and 10 seconds on average), while the other A/B sections took about 3 minutes each. The comments of 6 participants specifically refer to this task as being the easiest one, with one participant mentioning that in the slower presses “*it was almost possible to hear harmonics coming in*”.

There were fewer successful cases in the slow-

struck/fast-struck A/B test, yet at least 32 participants could distinguish between the two. A large number of reversal effect cases was registered in this particular section, suggesting that, while participants were able to consistently distinguish between transients, they struggled to remember which class a specific type of transient belonged to.

We found in Section IV.C that key Ab_4 shows a behaviour different from all the other keys under test in that the struck touches with lower velocity (slow struck) show larger overall bounce duration than the other keys. The Ab_4 has the lowest number of correct trials in the A/B struck slow/fast test, suggesting that the unusual behaviour of the key makes the identification task harder for the listener.

The pressed/struck A/B section is the one with the lowest number of successes. This test condition is the only one that presents stimuli from all four touch classes. The test set therefore contains a more diverse set of samples, though the participant is still asked to choose between two (pressed and struck). A recurring comment, mentioned by 9 participants, is that differentiating between the three cases of fast-pressed, slow-struck and fast-struck was very difficult, which is in line with the results for this test condition.

In all the tests, according to both the pessimistic and the optimistic evaluation, the number of participants for whom we can conclude there is a relevant perceptual difference is well above 5%, thus suggesting that the statistically relevant result is that listeners are able to classify notes played on the Hammond organ according to the type of gesture used to generate them, thus rejecting our second null hypothesis.

While differences due to familiarity are often small, there is no clear evidence that people familiar with the Hammond organ performed better at this test, thus confirming our third null hypothesis. This finding suggests that the sonic differences due to the touch may not be trivial to tell apart for Hammond organ players, or at least not when they are decoupled from the actual gesture which produces them.

VI. CONCLUSIONS

A. Findings

In this paper we analysed the details of note onsets on the Hammond organ. The instrument does not show a relation between key velocity and the amplitude of the produced sound. Yet, the way a key is pressed affects the onset transient of the note.

A first study shows that the behaviour of the key contacts, which are ultimately responsible for generating the onset transient, is affected by the continuous key position and key velocity during the key press. The velocity measured around the points in the key travel where key contacts close affects the spread over time of the contact transients and the duration of the early part of each contact's bounces. The velocity measured immediately before key-bottom affects the probability that late

bounces appear due to the rebound of the key on the keyboard. Pressed and struck touches show two clearly distinct velocity profiles over time, which means that the above measurements are both needed and one cannot be inferred from the other without previous knowledge of the type of touch in use. Additionally, the instantaneous position of the key is also relevant, as it ultimately determines which of the key contacts are active at any point in time.

Our second study, a listening test, shows that combinations of different types of touch and velocities produce different sounds, and that these can be perceived as such by the listener. A statistically significant number of our test subjects managed to classify a set of recordings according to the touch and velocity used to produce them. This indicates that the key gesture has a perceivable effect on the onset transient of the generated sound.

These observations make the instrument not only touch-responsive, but they make it so in such a way that cannot be captured with traditional velocity-based keyboard sensing. Reducing the richness of the key gesture to a single velocity parameter causes a loss of information, losing details on the original intent of the player and making it impossible to fully describe the sonic outcome. Most digital emulations of the Hammond organ do not allow the player to control the sound generator with the continuous position of the key, as they mostly use regular MIDI keyboard controllers with a single discrete velocity measurement.

This dimensionality reduction is similar, in a certain sense, to the one that occurred on pipe organs when electro pneumatic valves were introduced to replace direct control of air flow. On organs with direct control, the player retains a certain degree of control on the shaping of the transient onsets which improves phrasing and articulation, but is lost when the key acts as an electronic switch controlling the valve (Le Caine, 1955). For both the pipe organ and the Hammond, the control at the musician's fingertips is subtle and not such that it allows to the player to vary the loudness of the produced sound. Yet, in both cases, players tend to react negatively to limitations imposed by simplifications in the response of the keyboard action enforced by the advent of a new technology.

B. Recommendations

Our findings suggest some general recommendations for creators of digital emulations of the Hammond organ, in order to replicate the amount of control available on the original instrument.

Keyboard controllers based on switches are very common; these compute a velocity parameter from the time interval between the closing of two switches placed at different points in the key throw. Most controllers have two switches per key, but keyboards with three switches per key have recently surfaced on the market. The position of the switches along the key-throw is critical, and there is a trade-off between their position and the velocity metrics that can be obtained.

A keyboard controller that provides continuous tracking of the key-position, such as the one described in (McPherson, 2013), is the only choice to capture all the subtleties of the gesture on the key. A continuous controller can provide appropriate control over very slow key presses, as the fine movements they involve cannot be tracked sensing technologies based on a two or three discrete switches.

C. Limitations and future work

In the two studies presented in this paper we focussed on individual key presses, on a single instrument, in a non-performance context. The action of tonewheel Hammond organs has not changed much over the years, so we would expect to find similar results on different instruments from different years, but a comparative study is required to ascertain this. Extensions of the listening test we performed would also investigate how different combinations of drawbars and partial key presses would impact the final result. We did not specifically perform audio analysis of the onset transient, but rather we inferred some of its characteristics and its perceptual significance from the two studies.

A further step would re-frame these experiments in the context of an actual musical performance, where the phrasing and the articulation, the presence of simultaneous sounds, the use of the expression pedals and drawbar registrations, as well as the influence of sound processing effects and loudspeaker surely play a big role in capturing the attention of the listener. Whether in real-world conditions the touch-responsiveness of the instrument still makes a difference to the listener remains an open question. On the other hand, as Le Caine (1955) reported, the playing of pipe organ players is affected at a macroscopic level by a small amount of touch-sensitivity, so it is not unreasonable to expect similar results for the Hammond.

1. The profile of the tonewheel is designed and cut in such a way that it induces a sinusoidal signal in the pickup. However, manufacturing and mechanical tolerances may lead to the generated sound including higher order harmonics (Hammond Instrument Company, 1987, sec. 2, p. 10). In order to remove the higher components, a passive filter consisting of capacitors and transformers is added to some of the tones (Hammond Instrument Company, 1987, sec. 2, pp. 11-12). The harmonic content of the tones has not been carefully studied in the literature, however (Werner and Abel, 2016) and (Pekonen *et al.*, 2011) treat them as sine waves.
2. The number of drawbars is always the same as the number of busbars and as the number of contacts per key.
3. More on squabbling at <http://www.keyboardmag.com/funk/1300/must-know-techniques-for-hammond-organ/28833> (date last viewed 23/7/17)
4. <http://hammondorganco.com/wp-content/uploads/2011/03/B3mk2.pdf>, page 62 (date last viewed 23/7/17)
5. <http://hammondorganco.com/products/portable-organs/xk-system-series/> (date last viewed 23/7/17).
6. <https://youtu.be/kcRtyvQxbgU> (date last viewed 23/7/17)

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