

Perception of touch quality in piano tones^{a)}

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Both timbre and dynamics of isolated piano tones are determined exclusively by the speed with which the hammer hits the strings. This physical view has been challenged by pianists who emphasize the importance of the way the keyboard is touched. This article presents empirical evidence from two perception experiments showing that touch-dependent sound components make sounds with identical hammer velocities but produced with different touch forms clearly distinguishable. The first experiment focused on finger-key sounds: musicians could identify pressed and struck touches. When the finger-key sounds were removed from the sounds, the effect vanished, suggesting that these sounds were the primary identification cue. The second experiment looked at key-frame sounds that occur when the key reaches key-bottom. Key-bottom impact was identified from key motion measured by a computer-controlled piano. Musicians were able to discriminate between piano tones that contain a key-bottom sound from those that do not. However, this effect might be attributable to sounds associated with the mechanical components of the piano action. In addition to the demonstrated acoustical effects of different touch forms, visual and tactile modalities may play important roles during piano performance that influence the production and perception of musical expression on the piano. © 2014 Acoustical Society of America.

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I. INTRODUCTION

For more than a century, physicists and musicians argued over whether it is only the final hammer velocity that determines the sound of an isolated piano tone, or if a pianist can influence piano timbre by varying the way the keys are touched, independently of hammer velocity (Bryan 1913, see overview by Goebel *et al.* 2005). Pianists study intensively for decades (Ericsson and Lehmann, 1996) to establish a refined technique of touching the keys in a way that the emerging sound satisfies their ambitious artistic demands (Gerig, 1974). They develop and practice a large inventory of different key press actions in order to achieve fine timbral nuances and convey their interpretation of the music to the audience (Neuhaus, 1973). Therefore, it might be hard for them to believe that piano dynamics and timbre can be defined by a single physical parameter (Bryan, 1913). Physicists, on the other hand, argue that the pianist loses control over the hammer after the jack has been escaped by

the let-off button (Hart *et al.*, 1934). Therefore, it is only the endmost velocity of the hammer that determines the intensity and thus the timbre of a piano tone (“single variable hypothesis,” Bryan, 1913). This hypothesis has been described by Ortmann (1925, p. 171) in this way: “The quality of a sound on the piano depends upon its intensity, any one degree of intensity produces but one quality, and no two degrees of intensity can produce exactly the same quality.” This opinion was widespread in the early 20th century (Ortmann, 1929; White, 1930; Hart *et al.*, 1934; Seashore, 1937) and has been supported by the construction of reproducing pianos, both pneumatic and electric, the mechanisms of which aim to reproduce measured hammer velocities at exact time points (Goebel and Bresin, 2003) and re-generate convincingly expressive performances.

Different ways of touching the keys were investigated almost a century ago. Ortmann (1925) investigated the kinematic properties of keys that were played with different touch forms. Using a piece of smoked glass mounted to the side of a piano key on which a vibrating tuning fork leaves sinusoidal traces (variations of key velocity being reflected in variations of the wavelength of the recorded fork signals), he visualized the specific acceleration patterns of the key strokes. Ortmann (1925) differentiated between a “percussive” and a “non-percussive” touch. The former is characterized by a finger hitting the key surface with a

^{a)}Portions of this work have been presented at the *International Symposium on Musical Acoustics 2004*, Nara, Japan (Goebel *et al.*, 2004) and at the *10th International Conference on Music Perception and Cognition 2008*, Sapporo, Japan (Goebel and Fujinaga, 2008).

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certain velocity and, thus, accelerating the key very suddenly. With the latter touch, the finger rests on the key surface and presses down the key with a gradually accelerating pattern. Similar antagonisms have been used in research since then: “staccato” versus “legato touch” (Askenfelt, 1994; Koornhof and van der Walt, 1994; Goebel and Bresin, 2003), “hard” versus “soft touch” (Suzuki, 2007), and “struck” versus “pressed touch” (Goebel *et al.*, 2004, 2005; Kinoshita *et al.*, 2007; Goebel and Palmer, 2008; Furuya *et al.*, 2010). The present paper will adhere to the struck-pressed terminology.

Finger, hand, and arm movement differences associated with different touch forms were studied using three-dimensional motion capture equipment. Goebel and Palmer (2008) identified the type of touch in the acceleration trajectories of pianists’ fingertip markers by identifying a kinematic landmark that occurs at finger-key contact (acceleration peak). They showed with a dozen skilled pianists that in isochronous scale-like passages, touch clearly changed with playing tempo: when performing at moderate rates (two tones per second), about half of the keystrokes were “pressed” (i.e., showing no or only small finger-key acceleration peaks), while at fast tempi (seven tones per second and faster), almost all tones were played in a struck touch quality (Goebel and Palmer, 2008, 2009). The same touch antagonism in isolated tones showed similar differences not only at the fingertip level, but also in upper-limb movement kinetics and kinematics (Furuya *et al.*, 2010). In a more recent paper on a novel optical interface for touch-sensitive keyboard performance, McPherson and Kim (2011) defined as a measure of loudness two touch features to be measured from key position apart from key velocity: touch “percussiveness” (size of initial key velocity spike) and touch “rigidity” (second key velocity spike relative to first one). Percussiveness corresponds well to the above described antagonism; rigidity reflects properties of the kinematic chain of the player’s limb and is derived from the velocity profile measured at the key.

The piano tone may contain several knock or impact sounds arising from different sources intrinsic to the pianist’s interaction with the piano action. The most prominent impact sound emerges when the hammer hits the strings (hammer-string noise, “attack thumb,” Askenfelt 1994). This component characterizes the specific sound of the piano (Chaigne and Askenfelt, 1994; Birkett, 2013), is most prominently audible in the treble strings, and cannot be changed with type of touch independently of hammer velocity (Askenfelt, 1994). The hammer impact noises of the grand piano do not radiate equally strongly in all directions (Bork *et al.*, 1995). As three dimensional radiation measurements with a 2-m Bösendorfer grand piano revealed, higher noise levels were found toward the pianist and in the opposite direction, to the left (viewed from the sitting pianist), and vertically toward the ceiling (Meyer, 2009). Of those sound components that may be varied by the type of touch, Báron and Holló (1935) distinguished between the “finger sounds” (“Fingergeräusch”) arising from interaction of finger and key surface (finger-key sounds; Goebel *et al.*, 2005), the “bottom sounds” (“Bodengeräusch”), arising from the

impact of the bottom side of the key with the keyframe, and the “upper sounds” (“obere Geräusche”), occurring when the released key returns to its initial position. Báron and Holló (1935, p. 31) define a “pure piano tone” when those impact sounds are minimized by the player. These recommendations are in line with suggestions by renowned piano educators (e.g., Gát, 1965; Neuhaus, 1973).

These various impact sounds have been discussed by several authors (Cochran, 1931; Báron, 1958; Podlesak and Lee, 1988; Askenfelt, 1994; Koornhof and van der Walt, 1994). When a key was hit from a certain distance above, a characteristic finger-key noise was found to occur 20–30 ms before the actual tone (“touch precursor,” Askenfelt, 1994, “early noise” Koornhof and van der Walt, 1994). This noise was clearly visible in audio wave form plots. Although these authors reported that listeners could easily distinguish between tones that were played from above and those played from the keys, no systematic listening test was reported (Koornhof and van der Walt, 1994). The first experiment of the present study investigates the role of these finger-key sounds in the detection of touch quality in isolated piano tones.

The “bottom sounds” arising from key-keyframe impacts have not been addressed systematically, as they occur almost simultaneously with the hammer-string contact and, thus, the piano tone (Askenfelt and Jansson, 1990; Goebel *et al.*, 2005). Due to this temporal proximity, it is likely that the key-bottom sound is masked by the piano tone. Theoretically, the key does not have to touch the keyframe in order to produce a tone. A quick and sudden acceleration of the key could carry an impulse to the hammer strong enough to make it hit the strings.

Suzuki (2007) compared sounds played with hard and soft touches, selecting tone pairs with equal dynamics with the help of a peak sound level meter. His definition of touch quality is based on performance instruction regarding joint stiffness: “The ‘hard’ touch is defined here as pressing the key while keeping the shoulder, elbow, wrist and finger as firm (tight) as possible. The ‘soft’ touch is defined as its opposite.” (Suzuki, 2007, p. 2). However, initial finger distance to the key surface is left undefined (apparently always at zero). Even though sound level differences fell within ± 0.3 dB, he found that at least 10% of the non-musicians could correctly discriminate between these touch qualities. As the kinematics of the piano action were not monitored during stimuli production, these results are not comparable to the present findings (Suzuki, 2007). The second experiment of this article addresses these key-bottom sounds and asks musically trained participants to distinguish between piano tones that contain or do not contain those bottom sounds, according to key acceleration information derived from measurements of a computer-monitored grand piano continuously recording key position.

II. AIMS

In this paper, we aim to provide empirical evidence that the touch quality of isolated piano tones is perceived and identified by musically trained participants. In the first

experiment, we focus on the finger-key sounds that occur prior to the piano sound by the sudden interaction of the finger and the key surface. Participants had to identify the type of touch that produced a given tone. The second experiment manipulates the key-bottom sounds that occur when the key is stopped by the keyframe felt. Participants had to distinguish piano tones produced by identical hammer velocities that contained or did not contain key-bottom sounds.

III. EXPERIMENT 1: FINGER-KEY SOUNDS

The first experiment focuses on finger-key sounds in piano tones. The aim is to examine whether musically trained participants are able to identify the type of touch quality with which a particular tone was produced in a controlled experimental situation. The finger-key sounds occur typically between 20 ms (very loud) and 200 ms or more (pianissimo) before the piano tone (Goebel *et al.*, 2005), so they are clearly separated from it and may only at very loud tones merge with the piano tone by temporal masking (Zwicker and Fastl, 1999). In order to pin down potential identification cues, finger-key sounds were removed in a subset of stimuli and identification rates compared to those with original stimuli.

A. Method

1. Stimuli

The piano tones were samples recorded on a 173-cm Yamaha grand piano (a subsample of recordings used in Goebel *et al.*, 2005). The middle C (C4, approximately 261.6 Hz) was played by two pianists (WG, RB) with two different types of touch: one with the finger initially resting on the key surface and pressing it down (*pressed*), and one hitting the key from a certain distance above (touching it already with a certain speed, *struck*). The two pianists played the piano for 29 and 34 yr and studied piano at a post-secondary level for 12 and 8 yr, respectively.

Two accelerometers were used to measure the kinematics of the piano action: One accelerometer mounted at the front end of the hammer shank monitored the hammer movement and another one mounted at the front side of the key measured key movement. The microphone was placed close to the strings (about 10-cm distance), and the digital recordings were sampled mono at 16 kHz with 16-bit word length (for setup details, see Goebel *et al.*, 2005). After the recordings, the individual samples were automatically cropped such that each sample started 250 ms before hammer-string contact (defined through an acceleration peak in the hammer acceleration trajectories) and the piano tone sounded for 750 ms, so all possible noises emerging from hitting the keys were included in the stimuli. Each stimulus was faded in (10 ms) and faded out (10 ms).

From those recorded samples, we selected 25 tone quadruples for each of the two pianists and the two touch conditions that had approximately identical hammer velocities that spread evenly across the dynamic range. The hammer velocities ranged from 0.37 to 4.07 m/s corresponding to very soft to loud dynamics. The standard deviation for each of the 25 hammer-velocity quadruples ranged between 0.005

and 0.237 m/s with a mean standard deviation of 0.065 m/s, thus showing similar hammer velocities for each stimulus quadruple. The entire stimulus material can be accessed at <http://iwk.mdw.ac.at/goebl/pianosound/>.

To demonstrate the types of touch, we show two typical piano tones in Fig. 1. Their hammer velocities are almost equal, but they were played with two types of touch. The pressed tone (Fig. 1, top) exhibits a gradual increase of key velocity, whereas the struck tone (Fig. 1, bottom) shows a very sudden initial peak. Parallel to this first key impulse, there is a clearly visible (and audible) knock in the audio wave form which we term the finger-key sound (FK sound). To further demonstrate how similar the stimuli are, we show the spectrograms of two tones with almost identical hammer velocities, but performed with different touch qualities in Fig. 2. The tone onsets are precisely aligned by the sudden peaks in hammer acceleration at hammer-string contact. The bottom panel shows the difference spectrogram $P_{\text{diff}} = 10 * \{\log_{10}[\text{abs}(P_{\text{struck}})] - \log_{10}[\text{abs}(P_{\text{pressed}})]\}$, where P is the power spectral density of each segment. The difference spectrogram exemplifies the FK sound to be the characteristic difference between these two sounds.

To test whether FK sounds are the cues used by participants to identify the type of touch that produced a given

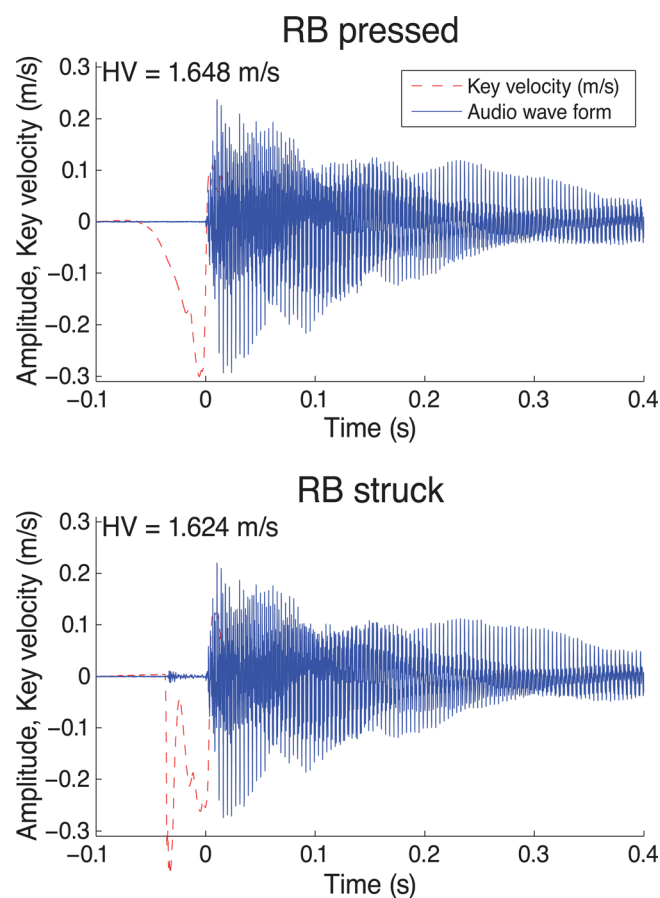


FIG. 1. (Color online) Audio wave form and key velocity trajectory (dashed line) of two piano tones with almost identical hammer velocity. The tone in the upper panel was played with the finger initially resting on the key surface, the other struck from a certain distance above. A negative key velocity denotes a velocity directing toward key-bottom. Time (s) is plotted relative to hammer-string contact.

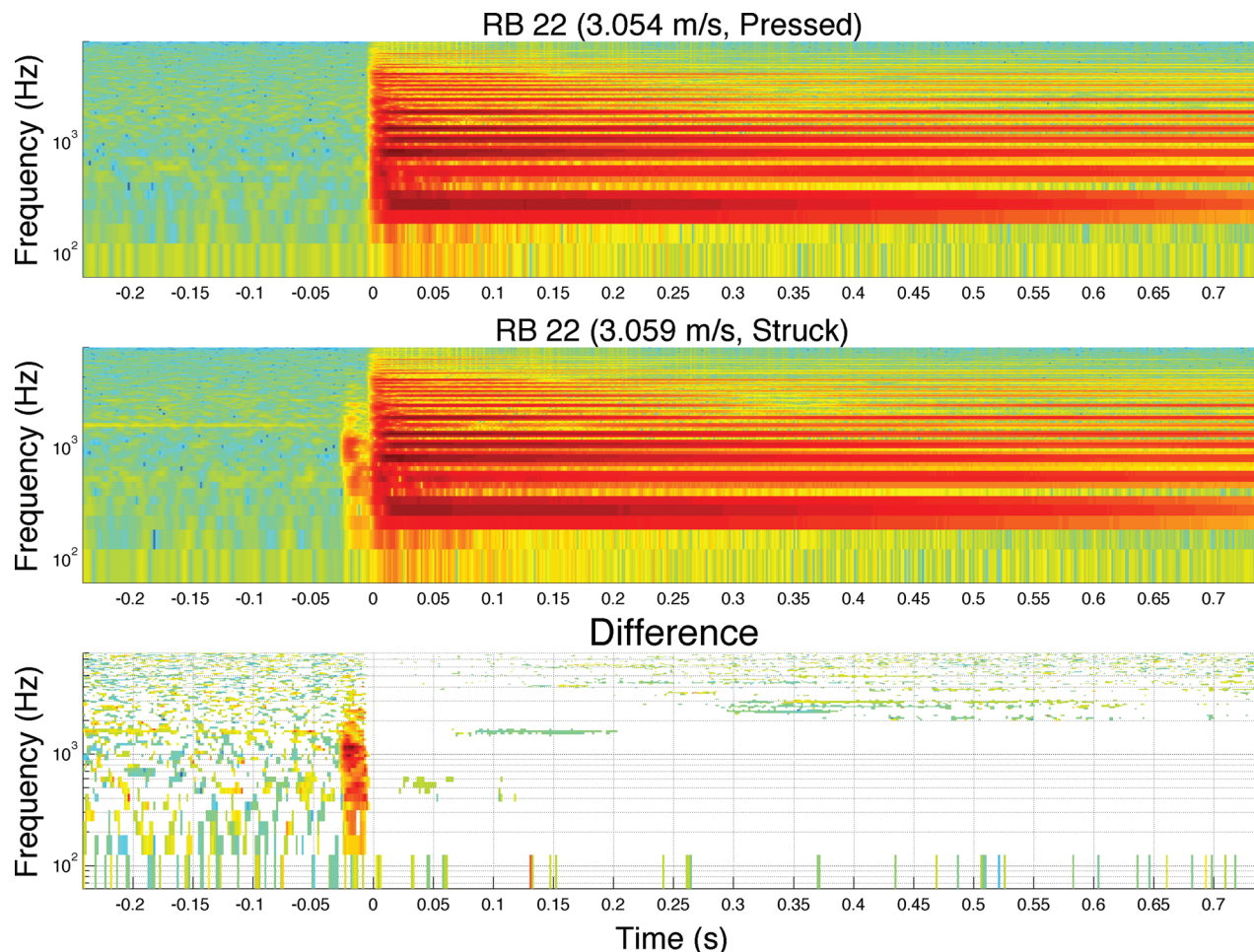


FIG. 2. Spectrograms of two tones played by RB with almost identical hammer velocities, played with a pressed touch (top) and a struck touch (middle panel). The bottom panel shows the difference between the two upper spectrograms. The spectrograms consist of sFFT windows with 256 samples with 90% overlap at an audio sampling rate of 16 000 samples per s. Spectral difference values smaller than 3 dB are left white.

stimulus sample, we removed the FK sounds in a subset of stimuli by replacing the first 240 ms of each sample by silence and fading in during the subsequent 10 ms.

2. Experimental design

A within-subjects design was used in which all participants heard all stimuli. The stimuli in block 1 included the entire stimuli. A fully crossed design was used with 2 pianists \times 2 touch conditions \times 25 hammer velocities = 100 stimuli per participant. The finger-key sounds in block 2 stimuli were removed as described above. These consisted of 2 pianists \times 2 touch conditions \times 12 hammer velocities = 48 stimuli. The 12 selected hammer velocities in block 2 corresponded to every other dynamical levels between 3 and 25 of block 1.

3. Participants

The 22 participants (8 female, 14 male) were between 23 and 46 yr old, with a mean of 31.2 yr. All were active musicians or musically well trained; 13 of them reported piano as their main instrument, while the others played violin, guitar, violoncello, or clarinet. They had been playing their instruments between 8 and 36 yr (mean = 21.7); 18 of them had studied their instrument at a post-secondary level

for an average period of 8.8 yr (2 – 18 yr). They gave written consent for their participation and received a nominal fee.

4. Procedure

The stimuli were presented to the participants via headphones (AKG K271). A graphical user interface, implemented in a Matlab environment, provided play buttons for all stimuli in a block simultaneously and arranged in random order on the screen. In a two-alternative forced choice paradigm, participants were instructed to identify whether each piano tone was originally produced by a pressed or struck touch. Participants could listen to each stimulus as many times as they wanted and in any order they liked until they were sure about all their judgments. In the first block, they listened to all 100 tones. Then, after a short break, they listened to the 48 tones of the second block in which the first 250 ms before hammer-string contact had been replaced by silence, so that all attack noises prior to the sound were removed. The rating task was the same as in block 1.

5. Data analysis

Participants' responses were collected by the graphical user interface and stored in text files for subsequent analysis

in an R statistical computing environment. The acoustic analyses of the tones were carried out in Matlab.

B. Results

Overall, the 22 participants could identify the type of touch that produced the stimuli significantly better than chance when FK sounds were present in the stimulus samples [block 1: 63.59% correct, $\chi^2(1) = 162.55$, $p < 0.001$], but performed no better than chance when FK sounds were removed [block 2: 51.04% correct, $\chi^2(1) = 0.46$, $p = 0.50$].

Participants identified pressed tones better than struck tones with FK sounds present [block 1: 68.18% versus 59.00% correct, respectively, $\chi^2(1) = 19.63$, $p < 0.001$], identified pressed tones well, but erroneously rated struck tones as pressed tones when FK sounds were removed [block 2: 57.20% versus 40.72%, respectively, $\chi^2(1) = 28.03$, $p < 0.001$]. Moreover, they could identify sounds produced by pianist RB better than those produced by pianist WG [66.64% versus 60.55% correct, respectively, $\chi^2(1) = 8.55$, $p < 0.01$ in block 1], but this effect vanished in block 2 [49.62% versus 48.30% correct, respectively, $\chi^2(1) = 0.14$, $p = 0.71$]. While in block 1, participants rated 54.6% of all stimuli as pressed touches, they did so for 58.2% of the stimuli in block 2, suggesting that the removal of FK sounds led participants more toward identifying a pressed touch.

We also assessed a possible learning effect within a block. The stimuli were presented block-wise all at once in random order. However, even though the participants could choose the order of the stimuli, could repeat any stimulus multiple times, and could revise their ratings until they were content with their judgments, most of them rated the stimuli roughly in ascending order (as revealed by the log files of the user interface). We therefore tested whether raters improved from the first half of the stimuli to the second, but could only find a small significant effect for block 1 [61.5% and 65.7% correct ratings, respectively, $\chi^2(1) = 4.15$, $p = 0.042$], but not for block 2 [$\chi^2(1) = 1.23$, $p = 0.268$].

Multiple logistic regression models were fitted on the correct (C) ratings by producing pianist (P) and type of touch (T) ($C = \alpha + \beta_1 P + \beta_2 T + \beta_3 P \times T$), separately per block. They revealed a significant interaction between pianist and touch for block 1, but not for block 2, where only the effect of touch was significant (while the coefficients for pianist and for the interaction pianist and touch came out non-significant). This interaction for the two blocks is shown in Fig. 3.

The participants described the listening test as demanding. They needed between 5 and 46 min (with a mean of 20 min) to accomplish block 1 and between 2 and 14 min for block 2 (mean = 7). Of the 22 participants, only 11 could identify the type of touch better than chance in block 1, while the other 11 rated at chance in that block. (In block 2, all participants rated at chance.) Pianists did not perform better than other musicians: eight of the 11 who identified above chance were pianists, but only five of the other 11 participants [$\chi^2(1) = 1.17$, $p = 0.28$]. The three best identifiers had between 81% and 85% of all stimuli correct, but for WG's struck tones they all rated at chance.

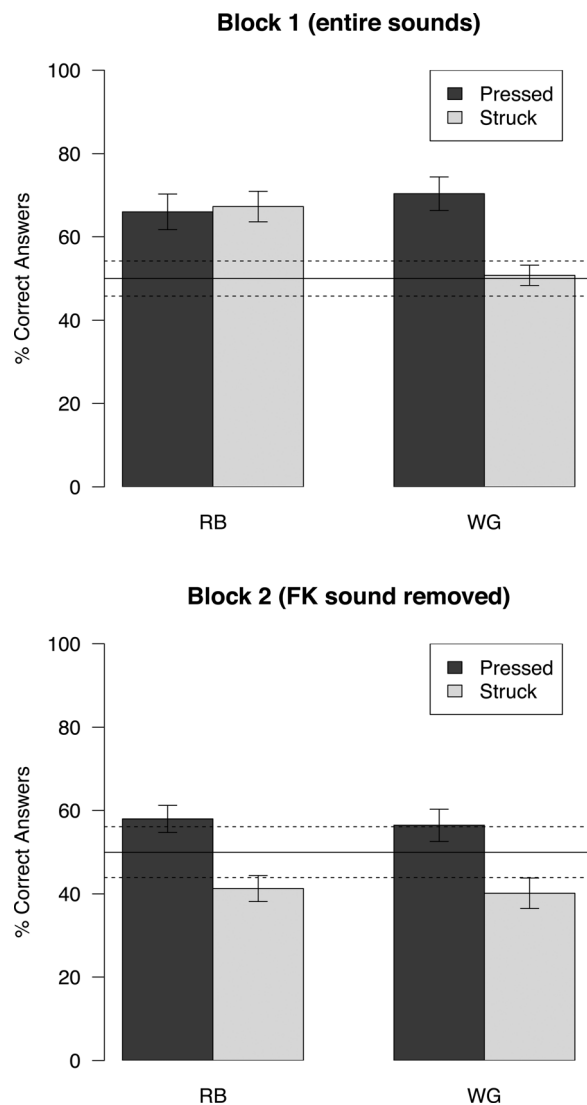


FIG. 3. Percent correct touch identifications of 22 participants separately for type of touch (pressed, struck) and pianist (RB, WG) that created the stimuli. Error bars denote standard errors across participants. In block 1, the stimuli contained all sound aspects (top panel), while the finger-key sounds were removed in block 2 (bottom panel). Identifications at chance level fall within horizontal dashed lines ($p > 0.05$).

To further understand the difference between the two producing pianists particularly at struck touches, we quantified the peak sound pressure level of the finger-key sound in the stimuli (by taking the peak of the 100-Hz low-pass-filtered signal excerpt before the tone onset of each stimulus). The sound pressure level (SPL) readings were calibrated using a ONO SOKKI SPL meter. These FK peak sound pressure levels exhibit clearly higher peak levels for RB than for WG at struck touches (63.5 versus 56.22 dB, respectively), while showing no significant difference at pressed touches (47.73 and 47.26 dB, respectively). A two-way analysis of variance (ANOVA) on FK peak SPL by pianist and type of touch showed significant effects of touch [$F(1, 96) = 66.37$, $p < 0.001$] and pianist [$F(1, 96) = 6.48$, $p < 0.05$], and a significant interaction of pianist and touch [$F(1, 96) = 5.00$, $p < 0.05$]. A Tukey's HSD *post hoc* test confirmed the 7.28-dB difference between the two pianists at struck touches to be significantly different.

The FK peak levels were added to the multiple regression models described above, thus resulting in $C = \alpha + \beta_1 \cdot P + \beta_2 T + \beta_3 FK + \beta_4 P \times D + \beta_5 P \times FK + \beta_6 T \times FK + \beta_7 P \times T \times FK$, separately for each block. The model fitted on block-1 data showed the same effects as the simpler model above and additionally a highly significant interaction between FK and touch ($\beta_6 = +0.14$, $p < 0.001$) as well as a significant three-way interaction of pianist, touch, and FK ($\beta_7 = +0.14$, $p < 0.05$). The extended model on block-2 data revealed additionally only a significant interaction of touch and FK ($p < 0.05$), but no significant three-way interaction. This analysis suggests that the individual magnitude of FK sounds in the stimuli influences the identification rates in this listening test such that the higher FK sound levels in RB's stimuli helped participants to correctly identify struck touches.

Moreover, point-biserial correlations between the FK sound levels and rating (struck versus pressed, irrespective of whether it was correct or not) for individual participants show significant coefficients for 19 of 22 participants in block 1, suggesting that the louder the FK sound, the more the rating tended toward a struck identification (with a general tendency for the at-chance-raters to have smaller coefficients than the successful raters). For block 2, only three of 22 these coefficients showed up significant.

Furthermore, the correct responses depended clearly on the stimuli's dynamics, but in opposite ways for the type of touch: pressed tones tended to be more correctly identified in soft dynamics, while struck tones more correctly at loud dynamics. Particularly struck touches at very soft dynamics were taken erroneously for pressed touches (see Fig. 4, top row of panels). When the FK sounds were removed (block 2), the linear trend in the pressed sounds remained quite the same, while at struck tones the slope of the regression line

decreased considerably, suggesting that the lack of FK sound did not help to identify the struck tones anymore, leading to ratings at chance level (see Fig. 4, bottom panels).

C. Discussion

This experiment showed that FK sound was the primary identification cue for the musically trained listeners: touch identification was better than chance when stimuli included FK sounds, but dropped to chance level when FK sounds were removed. The louder a FK sound was, the more participants tended to identify it as struck, suggesting that participants made assumptions based on loudness that influence touch identification. The significantly higher FK levels in RB's struck tones led to higher identification rates than for WG's struck tones.

We can only speculate about the reason for the differences in FK sounds by the two pianists as we have not recorded the finger motion during tone production. Inspecting the anatomy of the fingertips, however, a possible difference might be the relation of soft tissues of the fingertips and the location of the finger nails. Assuming the fingertip phalanx to strike the key with an orientation slightly less than perpendicular to the key surface, RB's finger nails might contribute to the sound during the FK impact, after the soft tissues are compressed, while WG's nails might not (as they begin further back from the soft tissues). However, these anatomical difference could be compensated by a different playing angle of the fingertips.

This pianist difference may be interpreted as a FK sound benefit for RB's struck tones (see Fig. 3 top) rather than a detriment of WG's struck tones, because there was an overall rating tendency toward pressed identifications. Thus, as many struck tones were identified as pressed, particularly in the soft dynamic range, pressed tones were generally better identified and struck close to random. Overall, only half of the participants were able to use those FK sounds as an identification cue; the other half rated randomly. Interestingly, pianists were not better in our sample than other musicians, suggesting that instrument-specific music experience did not aid in this identification task. Future research could test whether this group effect comes out significant with more participants.

The general trend to assign touch by tone intensity is both obvious and interesting. Louder sounds always involve larger and faster body movements (hands, arms, etc.), while softer tones require smaller, more controlled movements. This applies not only for the piano, but also for other instruments, as e.g., string or percussion instruments. Therefore it is not surprising that some participants connect loud with struck and vice versa. Moreover, a struck touch generates typically loud and loudest tones, while a pressed touch provides more tone control and is typically applied for soft and softest tones (as reported in Goebel *et al.*, 2005).

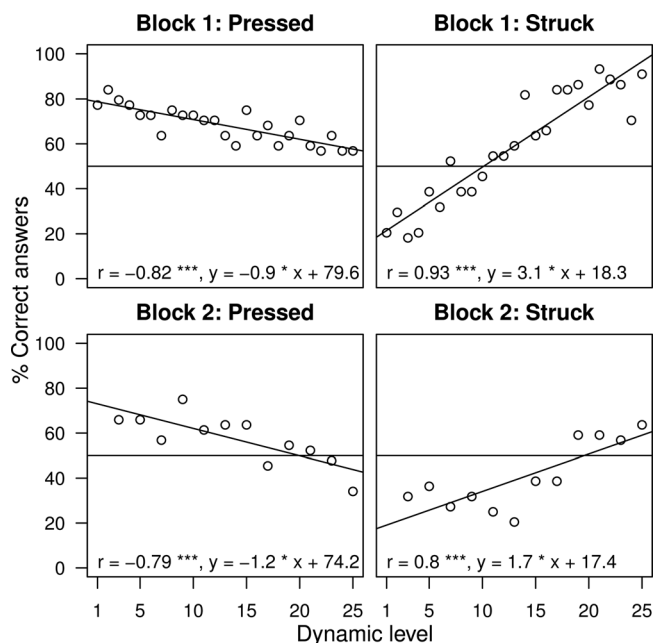


FIG. 4. Percent correct touch identifications of Experiment 1 separately for type of touch and dynamical level from soft (1) to very loud (25, top panel) or soft (3) to very loud (25, bottom panel). In block 1, the stimuli contained all sound aspects (top panel), while the finger-key sounds were removed in block 2 (bottom panel).

IV. EXPERIMENT 2: KEY-BOTTOM SOUNDS

Finger-key sounds occur before the piano tone, as the key requires time to travel down and actuate the parts of the

piano action. However, the key-bottom sounds that are generated by the impact of the key with the keyframe (“Bodengeräusche,” [Báron and Holló, 1935](#)) occur within ± 5 ms of the piano tone at most dynamic levels ([Goebel et al., 2005](#)); thus, they may be temporally and spectrally masked by it.

The key-bottom contact is defined as the moment at which the piano key reaches its mechanical lower limit. At that point, the key movement is stopped by the felt on the front-rail of the keyframe. The impact of the key at keybed produces sounds that may contribute to the overall piano sound. However, this key-keyframe impact at key-bottom is not necessary to produce a piano tone. It is possible to produce a piano tone without the key reaching the keyframe ([Brendel, 1976](#)), even though this may occur infrequently.

In this study, a representative collection of single piano tones was recorded on a computer-monitored piano that measures hammer velocities, onset timing, and continuous key position. A key-bottom contact was defined when the peak key deceleration (acceleration in the upward direction) exceeded a certain threshold and the key position was low enough to plausibly make contact with the front-rail felt. Tone pairs were selected that were identical in pitch and intensity (hammer velocity), but differed by the presence or absence of a key-bottom sound. We investigated whether the absence or presence of a key-bottom impact makes two piano tones with identical final hammer velocities distinguishable to musically experienced listeners.

A. Method

1. Equipment

The stimuli were played on and recorded by a computer-monitored 290-cm Bösendorfer imperial grand piano (“CEUS”) situated at the BRAMS laboratory in Montreal (Fig. 5). The CEUS system was introduced by Bösendorfer in late 2005 and records tone onsets, hammer



FIG. 5. (Color online) The stimuli were played and recorded on this Bösendorfer CEUS computer-monitored grand piano. The stimuli for the experiments were taken from the microphone to the right of the keyboard. The contact microphone and the microphone further back pointing toward the piano strings are not used in this experiment.

velocities, and position information for all 97 keys and three pedals. The timing of the onsets are provided in millisecond resolution and the hammer velocities in 8-bit word-length ranging from 0 (silent) to 255 (extremely loud); the position information of each of the 97 keys and the three pedals are provided every 2 ms again in 8-bit resolution (ranging from 0, default position, to 255 fully depressed). The key position data were converted into millimeters assuming -10 mm to be fully depressed (255) and 0 m to be the key at rest. We perform this simplifying conversion without calibrating individual keys through measurements to allow the reader a rough approximation of the key kinematics. The information recorded by CEUS is stored in text files with the extension “.RAW” containing all performance data in hexadecimal characters. Current versions of the CEUS system (from version 2.00, February 2011, on) store the identical data in binary form. For internal playback, CEUS creates another file format with the extension “.BOE,” in which the key trajectories are slightly modified to ensure flawless playback (personal communication with the CEUS’ hardware developer TVE Inc. Vienna, 2006 and Bösendorfer Vienna, 2013). The CEUS system normally removes key position values smaller than three, to avoid recording data of sensors sending data from keys that are not pressed. However, the CEUS system in the present experiment had a user-requested “science flag” activated that prevents trashing those small key values thus providing complete key value information (personal communication with TVE Inc., 2006).

The piano was placed at the shorter side of an almost rectangular studio at BRAMS laboratories. The keyslip and the keyblocks were removed for the duration of the recordings. Acoustic recordings were made with DPA microphones (type 4006). One was placed close to the piano keyboard (approximately 35 cm diagonally above, see Fig. 5), another close to the strings approximately 25 cm above the soundboard, and a third one 5 m back from the keyboard. Additionally, a contact microphone was glued on the keybed in front of the keys (see Fig. 5). For the experiment, only the audio recording from the microphone close to the keys were used.

2. Stimuli preparation

A skilled pianist (the first author) produced a total of 543 isolated tones on CEUS trying to create sounds with a wide range of dynamics and in different kinds of touch. One focus was to try to avoid touching the keyframe felt with the key. This requires a touch form in which a quickly flexing index finger generates a fingertip movement from the keylid toward the front-end of the keys (i.e., toward the player’s body) and simultaneously applying an impulse into the key. This special touch form was counterbalanced with keystrokes involving a prominent key-keyframe felt impact, which corresponded to a common struck touch ([Goebel et al., 2005](#)).

The recordings involved two pitches in the high register of the piano (E7 and F7 with theoretical fundamental frequencies of 2637 and 2794 Hz or MIDI note numbers of 100 and 101, respectively). This choice was made based on two reasons: first, we assumed that key-keyframe sounds are perceived more easily when the fundamental frequency of the

piano tones is spectrally far away from the frequency of the keybed resonance (Suzuki, 2007 also found most spectral differences in the highest tone he recorded); second, there are no dampers at these high pitches which made the tone offsets uniform between all played tones.

The CEUS data of all recorded tones were analyzed in Matlab with scripts programmed by the first author for this purpose. The CEUS data and the audio recordings were aligned *post hoc* by matching the detected onsets in the audio signal with the recorded note-on values in the CEUS file (.RAW). The first and last onset of a recorded file (60 – 80 tones each) were detected and aligned to the CEUS onsets. These measurements showed that the clocks of the recording system and the CEUS were slightly different (the CEUS clock was faster by an average factor of 66.361×10^{-6} (thus 0.01% faster); this difference was accounted for in further analyses.

The key trajectories were converted into a functional form using Functional Data Analysis (Ramsay and Silverman, 2002). Order-6 b-splines were fitted into the key position data and the first two derivatives (velocity, acceleration) with a roughness penalty of $\lambda = 10^{-18}$ and knots on each data point (thus every 2 ms). To account for abrupt decelerations at key-bottom contact, additional knots were placed at key-bottom contacts of the keys which were detected by identifying the minimum key position within a small time window close to a note onset. From these functions, position, velocity, and acceleration curves were re-sampled at 1000 samples per s (see Goebel and Palmer, 2008). The key position trajectories and the two derivatives

key velocity and acceleration data of one stimulus pair are shown in Fig. 6. Red vertical lines indicate note onsets by the CEUS system (HS), green lines key-bottom contacts (KB), and blue lines the begin of key press (FK).

The key position trajectories of each tone were categorized as to whether a key touched the keyframe felt or not. We defined a tone not to have a key-bottom sound when the key deceleration did not exceed 25 m/s^2 ; conversely, a tone with higher key decelerations and with a minimum position of lower than -7.84 mm was classified as having a key-bottom contact.

From the over 500 tones, we chose pairs of tones (each with and without key-bottom contact) of equal hammer velocity for both involved pitches that also matched approximately three different dynamics (soft, medium, loud). Thus, we selected a total of 12 tone pairs with two pitches, three loudness categories (ranging from 104 to 122 on a scale between 0, silent and 255, maximally loud), and with and without key-bottom sound, respectively. The detailed values of the selected stimuli are given in Table I.

Each sounded tone was faded in over 10 ms prior to its measured physical tone onset to eliminate finger-key sounds and sounded for 600 ms, before it was faded out again within 10 ms (as in block 2 of experiment 1). A constant gap of 50 ms of silence was introduced between the tone pairs.

3. Experimental design

Each participant had to rate all 96 tone pairs resulting from a fully crossed design of two tones (E7, F7) \times 3

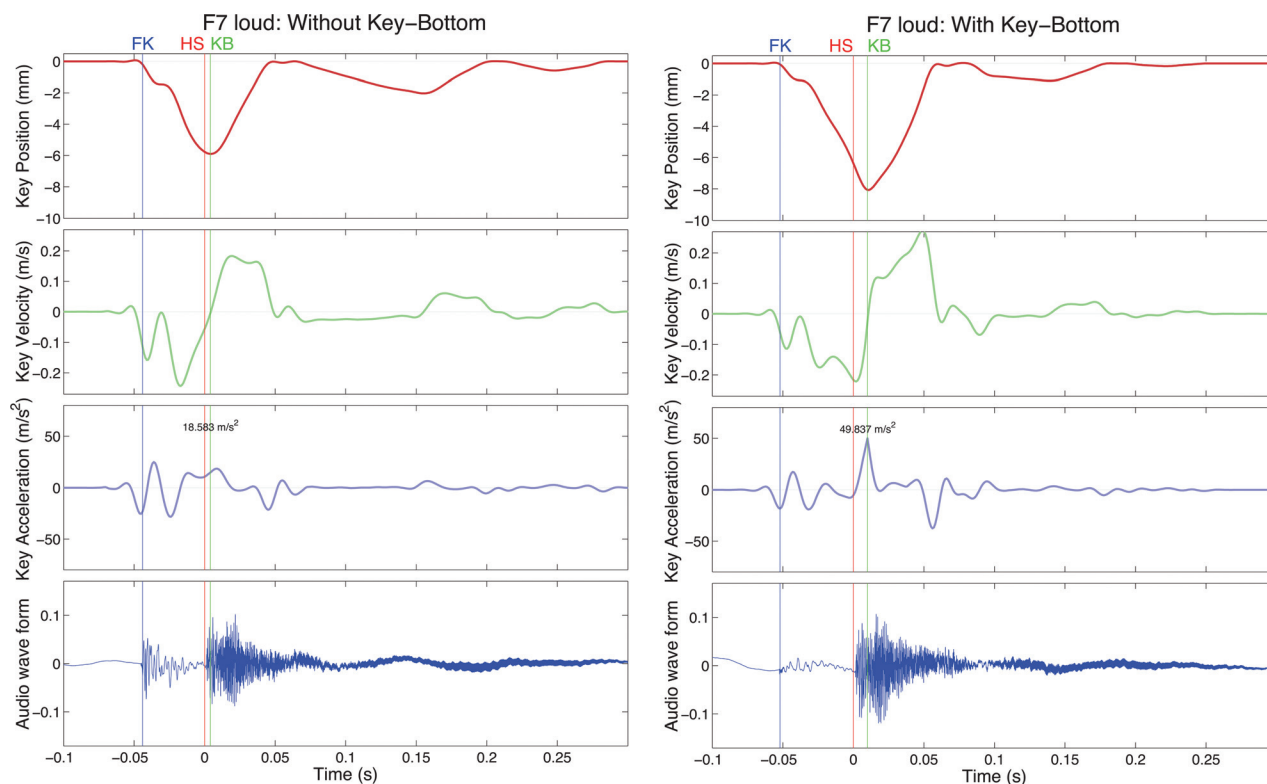


FIG. 6. Key position, key velocity, key acceleration, and the audio wave forms of stimulus pair F7 loud (see Table I): left panels played without key-bottom sound (KB), right panels played with KB. Three time instants are marked by vertical lines: finger-key contact (FK), hammer-string contact (HS), and key-bottom minimum (KB). Time is plotted relative to HS.

TABLE I. The stimuli pairs (with or without key-bottom impact, KB) selected for the listening experiment including two pitches (E7, F7), three dynamical levels (soft, medium, loud), provided by CEUS: the hammer velocity (HV, 0–255) and minimum key press (mnKey, in mm) as well as the maximum key acceleration at key-bottom (mxAcc in m/s^2).

	Pitch	Dynamics	Without KB			With KB		
			HV	mnKey (mm)	mxAcc (m/s^2)	HV	mnKey (mm)	mxAcc (m/s^2)
1	E7	soft	105	−7.65	9.64	105	−8.16	38.40
2	F7	soft	104	−6.00	15.45	104	−7.92	36.66
3	E7	medium	111	−6.04	17.41	111	−8.00	32.71
4	F7	medium	119	−6.55	15.76	119	−7.92	41.01
5	E7	loud	120	−7.96	24.35	120	−8.43	58.41
6	F7	loud	122	−5.88	18.58	122	−8.12	49.84

dynamics (soft, medium, loud) \times 2 orders (key-bottom sound present or not in first tone) \times 2 identity (same, different) \times 2 repetitions \times 2 blocks. Thus, each tone pair was rated four times by each participant allowing us to assess within-rater consistency.

4. Participants

Nineteen musically trained participants (3 female, 16 male) rated the 96 tone pairs with regard to their identity (same or different) in a 2AFC paradigm. On average, they were 27.5 yr old (23 – 33 yr), had an average of 9.1 yr of music lessons (from 1 – 20 yr) and 5 yr of piano lessons (0 – 17 yr). All but one were enrolled in post-secondary music courses at McGill University, a majority of them at the music technology program. Most of them (nine) were self-reported semiprofessional musicians, eight were amateur or serious amateur musicians, one was music-loving, and one was a professional musician.

5. Procedure

Participants sat in front of an Apple Macbook Pro (2.4 GHz Intel Core2 Duo) running Mac OSX 10.5.1, listening to the stimuli with Sennheiser HD-280 Pro headphones. The volume was initially kept constant at a medium level, but the participants were allowed to adjust the volume to their needs (which they barely did). A graphical user interface was designed for this experiment and implemented in JAVA programming language allowing the participants to navigate through the training and experimental blocks and to listen to the individual stimuli.

The participants set out with a practice block in which they received feedback as to whether their answers were correct or not to train their judgment. After a minimum of six training stimuli (maximum 24, depending on their choice), they continued with two test blocks, each containing the 48 tone pairs presented in random order. They were allowed to navigate back and forth in the stimuli within a block, and to listen to each stimulus as many times as they wished. For each tone pair, they had to answer “Do these two tones sound the same or different?” by clicking “same” or “different” radio buttons, thus employing a 2AFC paradigm. Between the blocks they were encouraged to take a break to rest. Afterwards, they filled in a musical background questionnaire. The entire experiment took an average of 14 min

(from 7 to 22 min, except for one participant who took 39 min to complete the experiment) and the participants received a nominal fee. The procedure of this experiment was approved by the McGill ethics review committee and the participants gave written informed consent prior to their participation.

6. Data analysis

The participants’ responses were automatically collected by the graphical user interface together with information about order, listening repetition, and total response time per item. The responses were labeled according to their correctness into “correct” and “incorrect” and prepared for subsequent analysis in an R statistical computing environment.

B. Results

Overall, participants detected difference and sameness within presented tone pairs significantly more accurately than chance [82.02%, $\chi^2(1) = 1495.86$, $p < 0.001$]. There was an effect of pitch [E7: 77.74%, F7: 86.29%, $\chi^2(1) = 44.65$, $p < 0.001$], but no effect of dynamics [$\chi^2(2) = 2.2$, $p = 0.33$].

All but one (participant 6) were able to perform the test significantly better than chance; four participants identified difference in tone pairs well, but sameness at chance (participants 4, 6, 7, 16) and two rated difference at chance while identifying sameness well (participants 12 and 18).

We also tested our response contingency tables for potential effects of block, repetition, identity, and order by applying separate χ^2 -tests. None of these four factors gained significance; only the variable block approached significance [$\chi^2(1) = 2.97$, $p = 0.09$] pointing to a faint learning effect with participants performing slightly better in the second block (83.11%) than in the first (80.92%).

Inter-rater agreement was determined using Krippendorff’s alpha (Krippendorff, 2004), with 19 raters for 24 ordinal items. It was $\alpha = 0.653$ across all participants, when removing participant 6 it increased to $\alpha = 0.681$, $1 \geq \alpha \geq 0$), suggesting a considerable inter-rater reliability in this perception test. To estimate the intra-subject consistency, we rated the four responses (2 repetitions \times 2 blocks) on each of the 24 stimulus pairs as either 1 when all four were rated the same (highest reliability), 0.75 when three of four were rated the same, and 0.5 when two of four were rated the same (at chance). The average consistency per

participant were between 0.74 and 0.97, with an overall average of 0.87. There was a clear correlation between this consistency measure and the overall per-person success ($r = 0.899$, $n = 19$, $p < 0.001$), suggesting that the more consistent participants gave also more correct responses.

Due to the redundancy in the experimental design and the considerable inter-rater reliability, the four repetitions were combined into one dependent variable. A two-way repeated-measures ANOVA on the combined correct ratings by dynamics and pitch as within-subject factors revealed a significant main effect of pitch [$F(1, 18) = 17.06$, $p < 0.001$] and a significant interaction between pitch and dynamics [$F(2, 36) = 23.6$, $p < 0.001$], which is shown in Fig. 7. No other main effect gained significance. The pitch differences in medium and loud dynamics were not significant according to pairwise Tukey's HSD *post hoc* tests, suggesting that the interaction can be attributed to the two tone pairs in the soft condition.

To further understand the participants' better performance at the F7 tones with soft dynamics, the spectrograms of these two tones are shown in Fig. 8 together with the difference spectrogram $P_{diff} = 10 * \{ \log_{10}[\text{abs}(P_{\text{Without}})] - \log_{10}[\text{abs}(P_{\text{With}})] \}$, where P is the power spectral density. Between 0.15 and 0.25 s there is clearly more energy in the stimulus with a key-bottom sound than in the other, suggesting that these sounds may originate from the key release (upper sounds in the terminology of [Báron and Holló, 1935](#)). These upper sounds might interfere with sounds produced by a key-bottom impact and thus take over as the distinguishing factor. This has to be confirmed in further research.

C. Discussion

The second experiment showed that musically trained listeners were able to differentiate between sounds that contained or did not contain a key-bottom sound in stimulus

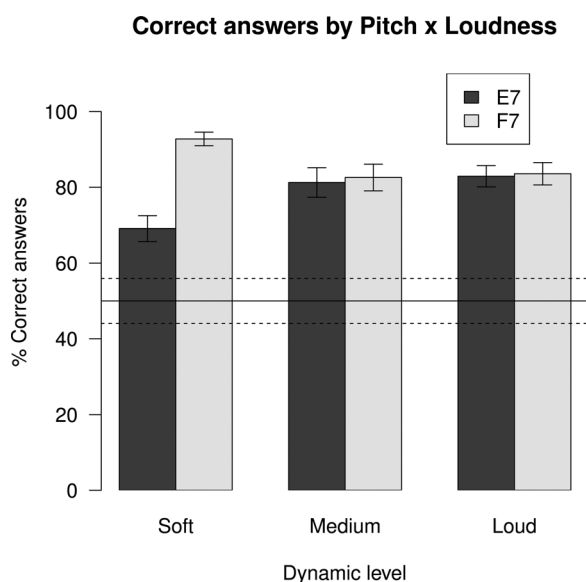


FIG. 7. Percent correct identity ratings: two-way interaction of pitch and loudness. Error bars denote standard errors across participants. Identity ratings at chance levels fall within the horizontal dashed lines ($p > 0.05$).

pairs that were carefully matched for hammer velocity, pitch, and duration. Despite the subtlety of this kind of touch sounds and the fact that they occur almost simultaneously with the far more salient onset of the actual piano tone, the results confirmed participants' robust ability to detect the differences correctly. These results show that the touch sounds contained in piano tones ([Báron and Holló, 1935](#)) contribute to the piano sound beyond hammer velocity, enough to become perceptually relevant in a controlled experimental situation. It might be that key-bottom sounds are also perceptually relevant in real-world settings, but this has to be studied in future research.

Even though the creation and selection of the experimental stimuli were carefully accomplished in this experiment, there might have been other identification cues than the one in focus. Sounds that arise from the piano action after the tone onset (such as the release sounds from the key) could have been used by the participants to guide their discrimination rating of the tone pairs. Nevertheless, this experiment is among the first to provide empirical evidence that key-bottom sounds may play a more prominent role in piano performance than previously assumed ([Suzuki, 2007](#)).

V. GENERAL DISCUSSION

This study delivers empirical evidence that the primary cue to discriminate between two equally loud piano tones produced with different touch qualities are the different sound components arising from the interaction of finger and key and within the parts of the action ([Báron and Holló, 1935](#); [Askenfelt, 1994](#)). The finger-key sounds, as the most prominent of those sound components, arise when the key is struck, and are absent when it is pressed down. This study provides a controlled perceptual evaluation as to whether musicians can aurally identify the type of touch that produced an isolated piano tone, independently of hammer velocity. The far more subtle key-bottom sounds were addressed in a second experiment. The stimulus selection was based on kinematic measurements and contrasted tone pairs that were different in whether they had a key-bottom impact or not. Participants detected those differences well, independently of dynamics and pitch. They performed slightly better in a tone pair that presumably contained also sounds of the releasing key (upper sounds) that may have outbalanced the key-bottom sounds as a cue.

The experiments have shown that sound components that are under direct control of the pianists—beyond mere hammer-velocity—play a role in the perception of piano sounds. Particularly in the light of sound source perception (e.g., [Giordano et al., 2013](#)), these findings are interesting. Sound source perception refers to the perceptual ability to identify properties of a sound source, rather than the ability to name the quality of the acoustical signal ([Yost et al., 2008](#); [Giordano et al., 2013](#)). The common coding approach in neuroscience research argues for a close neural action-perception link that is represented by common shared neural structures for the perception and the production of action outcomes ([Prinz, 1990](#)). The results of the present experiments can be seen in the light of both of these theories: they

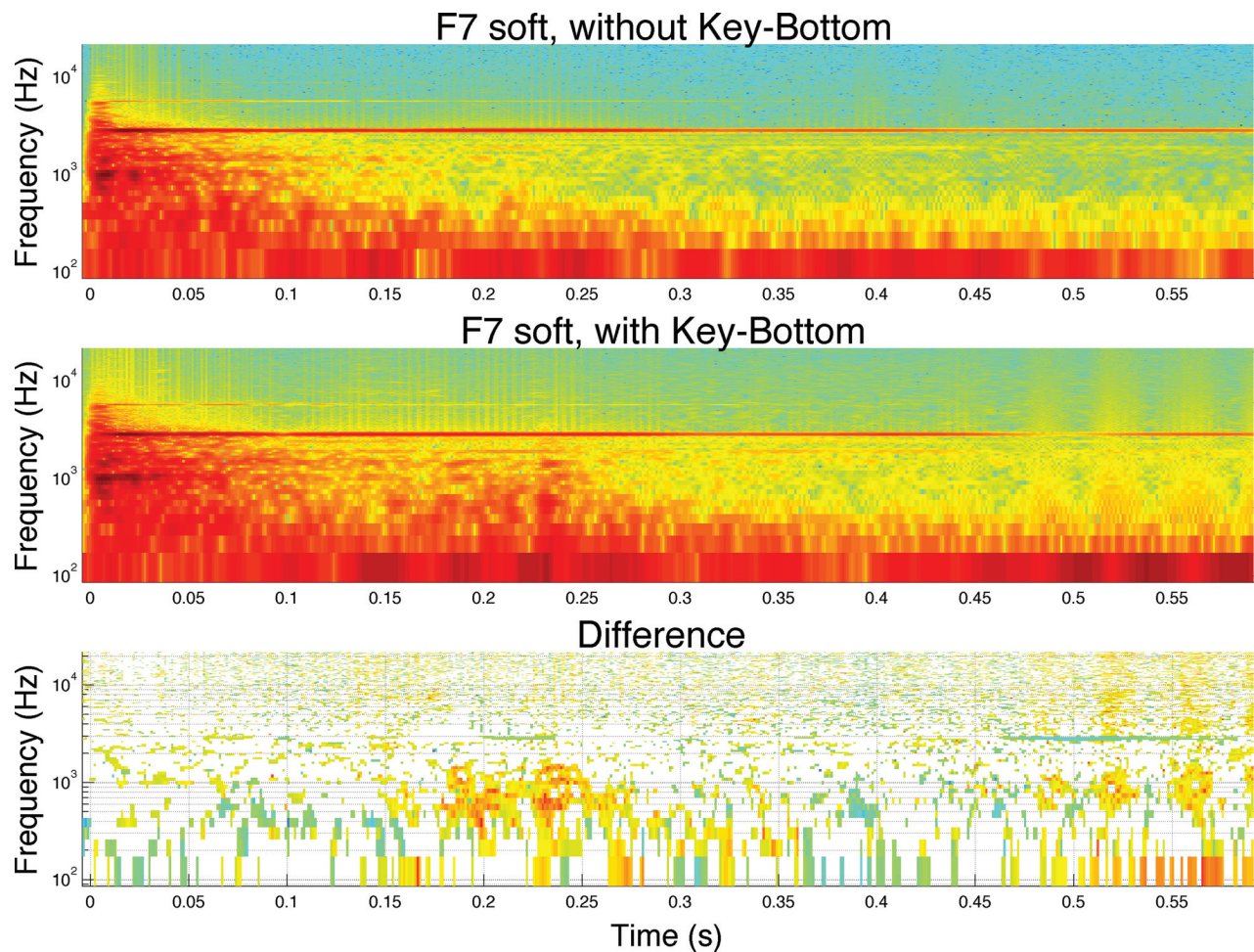


FIG. 8. Spectrograms of the tone pair F7 with soft dynamics (see Table I): top panel without key-bottom sound, middle panel with key-bottom sound. The bottom panel shows the difference of the two above spectrograms (middle minus top panel). Spectrograms consist of sFFT over 512 samples with 90% overlap at an audio sampling rate at 44 100 samples per s. Spectral difference values smaller than 3 dB are left white.

suggest that the sound parameters related to touch are perceived as part of the piano tone and help to invoke a sense of the way the particular piano tone was produced. This interpretation, however, would imply that participants who were pianists should be better than other musicians in identifying the actions that produced particular piano tones, because they are better trained in producing those piano sounds themselves. This hypothesis could not be confirmed in the present data, as piano and non-piano groups were not large enough to make a statistically meaningful comparison.

Another factor may play a crucial role in the auditory perception of touch in piano tones: the tactile experience and sensory feedback obtained through physical performance on a piano. The subjective tactile-sensory information (key resistance, inertia, sound vibrations, see also [Askenfelt and Jansson, 1992](#)) from the keyboard is (unconsciously) combined by the pianist with the acoustic percept, who supposedly cannot judge these two independently (as hypothesized by [Galembo, 2001](#); [Parncutt, 2013](#)). [Galembo \(2001\)](#) showed that conservatory professors were unable to discriminate between three grand pianos by listening only, which they previously ranked according to their quality and from which they indicated to be able to easily hear the differences in sound. However, when they played them blindly (without

visual feedback) and deaf-blindly (without visual and auditory feedback), they could keep them well apart ([Galembo, 2001](#)). [Galembo's](#) experiment demonstrates the importance of tactile-sensory feedback at judging piano sound quality. Conversely, it has been shown that auditory information may alter the perception of touch ([Lee and Spence, 2008](#); [Ro et al., 2009](#)). This sensory association of auditory and haptic-tactile modalities may be interpreted as weak synesthesia ([Parncutt, 2013](#)) that influences audio-visual ([Wöllner et al., 2010](#)) and even pure auditory perception of piano performance, as in the present experiment.

Future research should refine the selection of stimuli used in perception experiments, and should consider and manipulate the tactile modality to investigate the perceptual effects of touch quality in piano tones. As the present study focused on auditory effects in controlled experimental conditions, we can only speculate about how the present findings generalize to a real-world concert situation (including pedals, reverberation, reflections, and the listener at a certain distance away from the piano). Nevertheless, in the century-long debate between physicists and musicians on piano touch this study puts weight on the musicians' argument that touch qualities are indeed transmitted through the auditory domain.

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