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Influence of playing on the tonal characteristics of a concert piano - an observational study

Niko PLATH[(1)]

[(1)]Institute for Systematic Musicology, University of Hamburg, Germany *

Abstract

Well-maintained pianos are said to "mature" and to "change for the better" over the first years. When auditioning concert pianos for purchase, technicians do often not choose the best sounding instrument but the one with the greatest potential for future development. The present work addresses the following questions: Are structural changes measurable on a piano after one year of operation in a concert house? Are these changes perceivable by listeners? Measurements are performed on two occasions: First, on a brand new instrument prepared for sale. Second, on the same piano after having been played for one year in a concert hall. Single notes are recorded with dummy-head-microphones in player position in an anechoic chamber. An extended ABX listening test engaging 100 players, tuners, and builders, addresses the questions whether a variation in tonal quality is audible and if so, what sound properties could lead to a perceived difference. Semantic sub-grouping allows for indication on the vocabulary listeners of varying expertise use to verbalize their sensation. The statements give hints on what could have changed over the year and are used as a basis for the analysis of corresponding physical properties and psychoacoustic parameters related to the described sensations.

Keywords: Piano, Playing, ABX

1 INTRODUCTION

Instrument builders, tuners, as well as players often are certain, that new musical instruments have to be 'played in' and that older instruments can even change for worse if not played. Furthermore, it is known that wood degenerates over time, often accelerated by certain periodic climate conditions, which can affect the tonal characteristics of an instrument. The investigation at hand was prompted by indications that when auditioning brand new pianos for purchase, technicians try to 'hear the potential for future development behind the voicing' instead of just choosing the best sounding instrument. Well-maintained concert pianos are said to have their peak after five years and then gradually decrease in quality. The present work tries to establish a better understanding of what could lead to a change in tonal quality for a concert piano within a relatively short time frame of one year.

2 THEORY: INFLUENTIAL FACTORS

Possible influential factors for a change in tonal characteristics are listed and discussed for musical instruments and, in particular, for pianos in concert business. The issue is approached with regard to three main influences:

Aging: When addressing the long-term development of musical instruments, most published works focus on the time-conditioned degeneration of wood, eventually accelerated by periodic humidity alterations. For a piano, this might be relevant for material properties and geometry of the wooden soundboard with bridge and ribs. In connection with aging, the influence of climate conditions on wooden instrument parts has to be taken into account. In regard to other instrument parts, aging could show up as material fatigue of strings or mechanical parts in the action. Aging might be a crucial factor for the preservation of an instrument, particularly when dealing with historical instruments within the museum context. However, since this work attempts to address the possible changes in tonal quality for only the first year of a concert instrument under intensive supervision, other aspects gain in importance:

Playing: The vibrational properties of wood change when it is subject to vibrations for extended periods of

*niko.plath@uni-hamburg.de

time. Thereby, regular playing could cause an audible change in vibrational characteristics of piano soundboards [27]. For other instrument parts the influence of playing could show up as wear-out of mechanical connections in the action or as localized plastic deformations of hammer felt.

Maintenance: A grand piano at a concert hall is intensively monitored by a technician. It is tuned several times a week and prior to a concert, substantial adjustments to keys, action, and hammers might be made in consultation with the player to achieve a certain requested playing feel and tonal character. Since the purpose of maintenance work is to adjust the tonal characteristics, an impact in the context of this work can certainly be expected.

This section follows the tone production through the piano and describes the respective factors which presumably contribute to a difference in tonal quality of a piano. The suspected proportion of impact by each factor is estimated. The extent and interrelation of identified influential factors leads to considerations regarding the type of study design. Presented information about maintenance work on grand pianos is in part based on conversations and informal interviews with piano technicians. Furthermore, Reblitz [22] gives a comprehensive overview of service work on pianos.

2.1 Keys and Action

An important part of maintenance work on the piano is adjusting the interrelation of keys, action, and pedals, so-called *regulating*. The keys are adjusted to have certain weights needed to descend when depressed, called *down weight* and to rise back up, called *up weight*. The average down weight is approx. 50-55 grams, but professional players often have their own preference of a lighter or heavier playing feel. A possible way to change the touch weight of a key is to add or to remove lead weights from the key body. Due to a changed inertia, a different touch weight leads to a different acceleration of the key per input force and thereby will produce a different spectral distribution. Since the recorded examples are compared according to a similar key bed force, the implemented maintenance work on the keys is expected to have an impact on a potentially perceivable difference in tonal quality of the piano. For the instrument under observation the touch weight has been decreased for several keys by counterboring lead weights behind the balance rail axis. Comparable to the keys, maintenance work on the action mechanism could lead to an altered resulting acceleration of the hammer per input force. Again, this would modify the resulting spectral composition, as the string would face a hammer with different elastic properties. Thereby, maintenance on the action can be expected to have impact on the tonal quality of the piano.

2.2 Hammers

Brand new hammers (but also old worn hammers) are often considered to be too hard and the produced tone is too bright and harsh. If they were too soft, the tone would be too dull. The technician can influence hammer properties in several ways: One way is to needle the felt in certain areas, which separates felt fibers and thereby soften a hammer region. To harden a hammer, acetone or nitrocellulose lacquer can be applied to the felt. The lacquer soaks into the felt and hardens a certain region.

The piano under observation has had several so-called *hammer voicings* within the year. Since the only purpose of these adjustments is to change the tonal behavior of a note, it clearly can have impact on a perceived difference.

Since the instrument is revised several times a week during the year, an impact by material aging or mechanical wear-out is not expected for keys, action, and hammers.

2.3 Strings

Under beneficial conditions piano strings degenerate within a period of decades. Under heavy workload e.g. at a conservatory, the average lifespan decreases to 8-10 years with possible tears and breaks after approx. 5-6 years. Old strings are said to gain a clinking sound which may originate from the string itself, but is often also associated with loose bridge pins.

A possible explanation for the degeneration of steel strings is strengthening by plastic deformation (work-hardening). The increase in string stiffness could have the unwanted effect of increasing the inharmonicity of the string. However at least for wound strings, Houtsma [11] shows that the long-term increase of string inharmonicity can be explained by changes in mass distribution due to repeated stretching. Within one year the effect of the strings on the tonal quality of the piano is expected to be negligible.

2.4 Soundboard

A possible change of wood properties could be caused by two, often inter-working, factors: a) the aging of wood under certain climate conditions, and b) changes of material properties due to regular playing.

The effects of aging of wooden instrument parts on the vibrational behavior are studied mainly for violins, an overview is given by Bucur [5]. In particular, the gradual loss of hemicellulose is found to decrease the density but not to affect the Young's modulus. This raises the sound radiation coefficient E/ρ. For instruments in static high relative humidity the greatest change of vibrational properties is found in radial direction, increasing the degree of anisotropy [4]. The time-dependent deformation under constant load (so-called *creep*) is enhanced by periodic humidity alterations and leads to changes in the radiated spectrum [2]. Furthermore, vibrations accelerate the creep [24].

As known from conversations with the responsible technician, the piano soundboard curvature decreases and increases with a periodicity of one year. In autumn and winter the concert hall is artificially heated which decreases the relative humidity down to 20% at the extreme. As a result the moisture content in the soundboard wood decreases. The wood shrinks and the soundboard 'sinks in'. This has far-reaching consequences: With the soundboard also the bridge sinks in, which changes the angles between strings and bridge. With the angles also the static bridge pressure decreases with all implications on the pre-stressed vibrational behavior of the soundboard [16]. With the bridge also the strings sink in which changes the spatial alignment between strings and hammers. Thereby, as a compensation for changing climate conditions, the technician has to readjust the regulation.

When the heating is disabled in spring and summer, moisture content in the soundboard wood increases and the soundboard rises up again. The static bridge pressure and thereby the pre-stress conditions increase, the strings misalign with the hammers and the action has to be readjusted again. In that respect, technicians speak of 'artificial aging through air conditioning'.

Hunt and Balsan find that playing at generally high humidities leads to increased stiffness and decreased loss coefficient. As a consequence, 'old fiddles (are said to) sound sweeter' than new ones [12]. Hutchins [13] finds that long term playing (5-8 years) of violin family instruments leads to increased amplitudes of body cavity air modes. Bissinger [3] reports a general decrease of modal frequencies for a violin after approx. 250 hours of professional playing. Clemens et al. [8] find no evidence for changes of the vibrational behavior of guitars due to artificial vibration treatment.

Structural modifications on the soundboard are not part of regular maintenance work. In very rare cases, the static bridge pressure might be modified as a one-time adjustment by changing the angle between strings and bridge but this is by no means part of the daily work in a concert hall.

2.5 Disturbances determined by the Experimental Design

Prior to the measurements a technician (the same person in both states) has been asked to tune the instrument with the only instruction to give the piano a regular concert tuning with the same chamber tone. The technician could have influenced the tonal quality of the piano just by tuning in two ways:

1. Pianos are tuned with stretched octaves to compensate for the inharmonic overtone spectrum (*Railsback stretch*) [21]. The degree of tuned octave stretch relies on the judgment of the technician. Following Martin [17], deviations from the Railsback curve could be the tuners handling of soundboard resonances. In this regard different octave stretches could be the technicians response to a change in the vibrational behavior of the piano. In the same course, different octave stretches could lead to perceivable pitch differences between *State 1* and

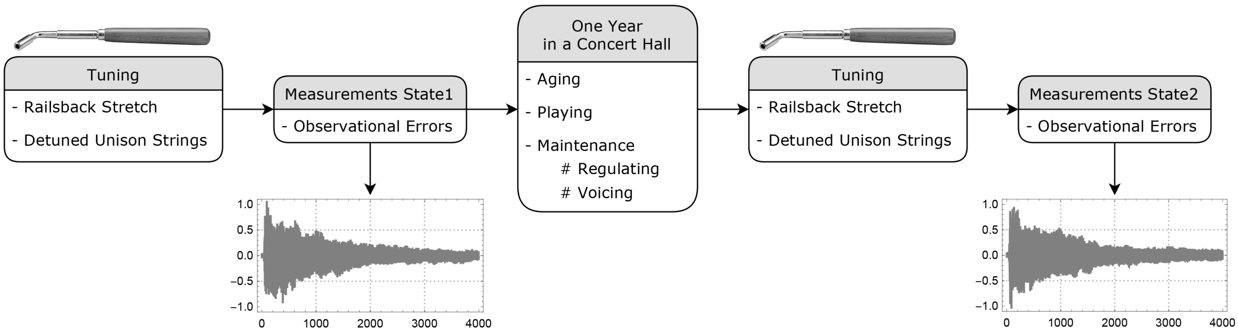

Figure 1. Influential factors and disturbances for the experimental design.

State 2 for the bass and treble range.

2. Technicians usually detune the unison strings by 1-2 cents to give the decay of the tone a complex varying structure [14]. A different degree of detuning of the unison strings for *State 1* and *State 2* could lead to a perceivable difference in the temporal development of the tones harmonic composition.

Thus, the technician who tuned the piano prior to the measurements could have strongly influenced the resulting sound. Both aspects of tuning could have crucial impact on the test because if the piano tones could be discriminated based on effects of a different tuning in the worst case listeners would only discriminate the impact of tuning the instrument and not the impact of aging, playing, and maintenance.

2.6 Study Design Considerations

The decision for a study design depends on the research question in work and is always a trade-off between two contrastive approaches with their respective advantages and drawbacks: On one side an artificial but highly controlled investigation in the laboratory where in an ideal case one independent variable is manipulated and its effect on one or more dependent variable(s) is measured. If well realized, an *experiment* can provide definitive evidence by causal relationships between individual independent- and dependent factors. Nevertheless, these abstracted studies often simplify the problem and thereby lack real relevance to the actual environment.

On the opposite side is the observation of an instrument 'in the field'. The investigation is much closer to real use and practice but control of the influential factors is limited or, in extreme cases, impossible. Randomized assignment to a control group by the researcher is not possible or a control group does not even exist. Although *observational studies* cannot provide definitive evidence by causal relationships due to the possible presence of confounding, they can show correlations between factors. Interpreted with care, these can provide valuable information about real life use and practice [23].

Maintenance work by the piano technician is an inseparable part of 'playing' in concert business. It is unlikely that an instrument would be chosen for concert use if it wasn't finely adjusted. Furthermore, many professional players demand substantial adjustments to be made on the instrument they choose for concert.[1] As described in the previous section, there are numerous influential factors for the tonal characteristics (summarized in Figure 1) which potentially are highly correlated. Moreover, most certainly there are confounding factors, e.g. the periodic curvature change of the soundboard as an independent variable affects dependent variables (psychoacoustic parameters derived from the recordings) but also affects other influential factors like the timing in the action mechanism. Furthermore, for financial as well as logistic reasons it is not possible to have a 'control group' in form of a brand new grand piano with a value of more than 100.000 euro placed into the same concert hall and not be touched or played. And it is not possible to externally control the independent variables, e.g. the

[1] Extensively documented in the awarded documentary film 'Pianomania' from 2009, which covers the work of tuner and technician Stefan Knüpfer from Vienna preparing pianos for concerts: http://www.wildartfilm.com/new/index.php?lang=en&Itemid=136, accessed in June 2019.

author could not instruct the technician to adjust parts with a certain frequency. Thus, the examination can not be conducted under 'controlled' conditions, since the influence of the technician can neither be quantified nor eliminated.

The influence of playing a piano in concert business on it's tonal characteristics can therefore not be reduced to an artificial experiment where it is 'just played'. An examination can only be done with all its disturbances in the field as an observational study.

3 EXPERIMENTAL ARRANGEMENT

Measurements are performed on a concert grand piano after manufacture has been finished and subsequent to regulating, voicing and tuning (further denoted as *State 1*). Subsequently, the instrument is employed by the manufacturer as a rental piano, leased out to a concert hall in Munich, Germany. After having been played for one year and at approx. 40 concerts, the instrument is brought back to Hamburg. The previous measurements are rerun with the exact same conditions (*State 2*). For the recordings the instrument is carried into an anechoic room and the lid is dismounted. For each state a set of 440 *forte* played single notes is recorded (88 keys $\times$ 5 takes).[2] Unfortunately, a standardized mechanical finger could not be used for the study at hand. The sensor head of an impact hammer (*Kistler 9722 A 500*) is used instead to press the keys. As a pre-processing step for the analysis the 5 $\times$ 5 pairs per key are filtered with regard to a maximum difference of key bed contact forces. Based on a pre-test, a maximum possible difference of 0.6 N is chosen for the analysis. This reduces the data base to 1 $\times$ 1 for 74 keys but ensures a highly standardized input. A calibrated artificial head (*Head HSU 3.2*) is placed in player position. A piezoelectric ICP accelerometer (*PCB 352C23*) is attached to the bridge at the corresponding string termination point in direction normal to the soundboard.

4 LISTENING TEST

The aim of the implemented listening test is to answer the following questions: 1. Is a tonal difference audible for a played grand piano before and after a year of concert business? 2. What sound properties lead to a perceivable difference? How do listeners verbalize these differences?

The latter question is approached by analyzing free text input with natural language processing methods. For the first question, the following hypothesis is stated:

- **Null hypothesis** H_0**:** No difference is noticeable for played tones of a concert grand piano before and after the first year of concert business. Results of the listening test are due to chance alone.
- **Alternative hypothesis** H_1**:** Results are due to a factor other than chance.

4.1 Design and Implementation

The ABX double-blind comparison scheme after Clark [7] is an established method to identify differences between stimuli, often used for the evaluation of audio codecs or loudspeaker quality but it also has been used frequently to evaluate research questions in piano acoustics [10, 19]. Each participant receives a randomized sample of 25 unique trials out of 74 possible comparisons. After each discrimination task the participant is asked to describe the 'property which led to a possible discrimination'. The corresponding answer for each trial is typed into a free form data entry field limited to 50 characters. Subsequent to the 25 trials, the following participant variables are inquired: Years of experience as a piano builder, ... as a piano technician, ... as a piano player, or playing a different instrument. The listening test is implemented using *BeaqleJS*, an HTML5/JavaScript framework developed by Kraft and Zölzer [15]. The test is hosted on a website and can

[2] The recordings are available for download as an open access dataset: http://doi.org/10.5281/zenodo.3274772

therefore be reached worldwide[3]. For the statistical analysis cumulative binomial probabilities are used after Burstein [6].

4.2 Results

100 participants from 12 countries completed the listening test. The number of trial completions per key varies from 25 to 50. For the following analysis three sub-groups (disjoint sets) are defined regarding their experience as non-experts, players and builders/tuners (see Table 1). With a hit ratio of 96.3% the builders/tuners sub-group has the highest result, followed by the players group with a hit ratio of 93.3%. The non-experts still have a high hit ratio of 90.3%. Statistics for the listening test are calculated according to keys as well as to participants:

Table 1. Definition and hit ratio for sub-groups (disjoint sets) with participants i, completed trials n and correct answers c.

Sub-Group	Qualification	Σi	n	c	$c/n \times 100$
Non-Experts	one or less years experience accumulated in building, tuning and playing.	8	185	167	90.3
Builders / Tuners	more than one year experience in building or tuning pianos.	22	544	524	96.3
Players	more than one year experience in playing piano or other instruments and not member of Builders/Tuners sub-group.	70	1708	1593	93.3

With an average probability p_{chance} that chance alone is operating of approx. 1e-9, H_0 has to be rejected for both confidence level $> 95\%$ ($CL_{95\%}$) and confidence level $> 99\%$ ($CL_{99\%}$) for all measured keys. In other words, participants can distinguish between the two piano tones for all keys due to one or more factor(s) other than chance. With an average probability p_{chance} that chance alone is operating of approx. 1e-7, H_0 has to be rejected under $CL_{95\%}$ conditions for all but one out of 100 participants. When utilizing the stricter $CL_{99\%}$, H_0 has to be rejected for all but 5 out of 100 participants. In other words, 99% (or 95% for $CL_{99\%}$) of the participants can distinguish between the two piano tones due to one or more factor(s) other than chance. As an intermediate result a strong ceiling effect is observable. Regarding the sub-groups the following statements can be made: H_0 has to be rejected for all participants in the builders/tuners group, in other words, no builder/tuner fails in the listening test. Two out of five participants failing the listening test under $CL_{99\%}$ conditions are non-experts with 0.5 and 1 year experience in piano playing. Three out of five participants failing the listening test under $CL_{99\%}$ conditions are players with 54, 40 and 16 years of experience in instrument playing. The participant failing the test even under $CL_{95\%}$ conditions is a non-expert.

4.3 Verbalizations

After pre-processing the free text input with tokenization, stop word removal, and stemming, the data set contains 2267 total words and 776 unique word forms. A classification of the given word forms is performed and each word is assigned to one of the domains *Timbre*, *Temporal*, *Pitch*, *Loudness*, and *Spatial*. The most dominant key words are related to *Timbre*, *Pitch*, and *Temporal* domain. Examining the data set, a second possible approach of classification becomes apparent: A similar auditory event may be described in terms of three types of foreknowledge, hereafter denoted as *descriptive*, *technical*, and *causal* (compare Table 2). On the

[3] http://musicalinstruments.digital/listeningtest/, accessed in May 2019.

Table 2. Classification of the 50 most frequent words into perceptual domains (average usage percentage in brackets) and levels of foreknowledge.

	Timbre (36%)	Pitch (16%)	Temporal (11%)	Spatial (3%)	Loudness (1%)
causal	*strings, unisons, hammer, needling*				
technical	*partials, beating harmonics, intonation, obertonreicher, resonanz, chorrein*	*pitch, tuning frequency detuned*	*attack, onset sustain, puls decay, nachhall*	*panning stereo, envelope*	*volume loudness*
descriptive	*cleaner, brillanter harder, rounder clearer, metallischer stronger, darker sharper, brighter dumpfer, softer*	*higher lower*	*longer, shorter faster, duration shifting*	*direkter farther*	*louder leiser*

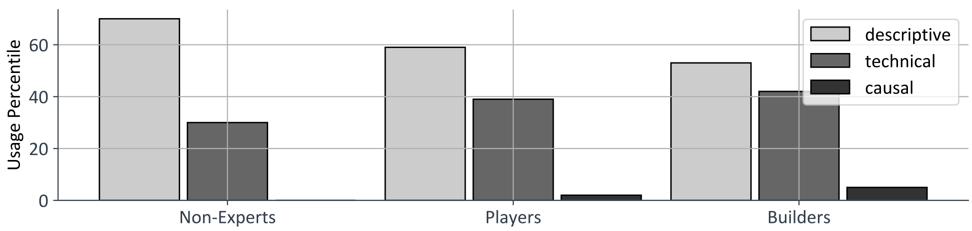

Figure 2. Percentage of used words per sub-group and category.

descriptive level one would verbalize a sensation in terms of descriptive, often metaphoric adjectives, e.g. as *'rough'* or *'dirty'*. On the *technical* level the used terms would presume a certain educational background, e.g. one would write about *'temporal development of higher partials'*, where the term 'partial' would imply a certain music-theoretical or scientific education. On the *causal* level, participants would not describe the acoustical sensation but the instrument component they hold accountable for the sensation. E.g. they would only write *'unison strings'*. The described categories moreover can be understood as representations of different concepts of knowledge: The *technical* vocabulary requires a form of education where technical terms are taught, often related to science and engineering. In contrast, the *causal* vocabulary does not require any theoretical knowledge but a high degree of empirical knowledge which can be informal, and hardly verbalisable but needs years (or sometimes generations) to establish [20].

Figure 2 shows the proportional usage of defined categories for non-experts, players and builders, which can be summarized as follows: *descriptive* vocabulary is most frequently used by non-experts (70%), but even builders and technicians use it to a high degree (53%). The proportion of *technical* vocabulary increases from non-experts over players to builders and tuners. Non-experts do not use *causal* vocabulary at all. Builders have the highest, yet only a 5% proportion of used *Causal* vocabulary.

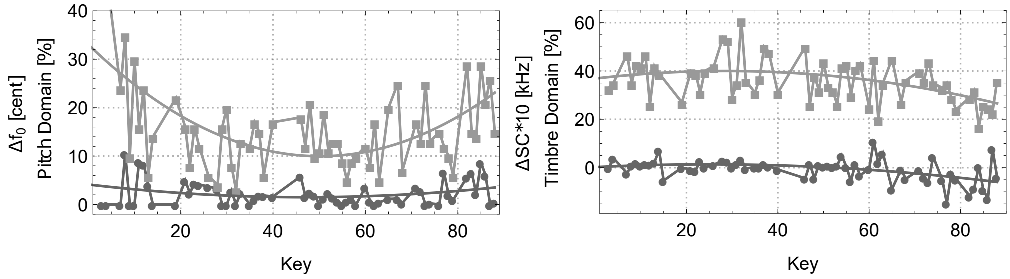

Figure 3. left: f_0 difference between *State 1* and *State 2* in cent (dark circles) vs. usage percentile of *Pitch* domain verbalizations (bright squares).
right: Spectral centroid development $\Delta SC \times 10$ between *State 1* and *State 2* (dark circles) vs. usage percentile of *Timbre* domain verbalizations (bright squares).

5 COMPARISON WITH PSYCHOACOUSTIC AND STRUCTURAL METRICS

5.1 Timbre Domain

The spectral centroid (SC) as a well established indicator for the perception of brightness of complex tones is calculated for all keys. Figure 3 shows the SC difference between *State 1* and *State 2* vs. the percentage of used Timbre domain verbalizations. For the highest octaves SC values decrease from *State 1* to *State 2* which is in accordance with statements by the responsible technician that the treble was too harsh when the piano was delivered which he had to adjust within the following months by needling the hammer felts. Nevertheless, a comparison with the proportion of timbre related verbalizations does not reflect this development: The treble range with the highest SC difference has the lowest proportion of used timbre related words. Calculations of *Roughness* after Sethares [25] and *Sharpness* after Zwicker and Fastl [9] do not show general differences between *State 1* and *State 2*.

5.2 Pitch Domain

Fundamental frequencies (f_0) are estimated for all keys by automated peak picking in the frequency domain.[4] Figure 3 shows the f_0 difference between *State 1* and *State 2* in cent. The differences can be summarized as follows: Apart from three strong outliers, the keys on the bass bridge (key 1-20) are tuned without measurable differences. In the mid range deviations of approx 2.5 cent are observable. In the highest octave deviations of up to 10 cent are observable. These notes are also the hardest to tune properly. The greatest average detuning in the bass and treble range with the minimum in the midrange could be explained with a differently tuned octave stretch since this would be most pronounced in bass and treble range. Professional musicians are able to differentiate pitch differences of a few cents [26], therefore pitch could be a cue in the listening test at least for some keys. A comparison of the measured f_0 differences and the pitch related verbalizations shows some remarkable results (compare Figure 3): For the general trend there is good agreement between measurements and verbalizations with higher values in bass and treble range. However, when looking at the relations in detail, the highest proportion of pitch related verbalizations is given for keys with no measurable difference in f_0 values. For the lowest bass notes this could be explained with the general difficulty to determine a pitch due to the quantity of audible transversal partials, a high degree of inharmonicity, and audible longitudinal partials. But also for some higher notes, 20%-30% of the verbalizations are pitch related with corresponding measured f_0 differences of 0-1 cent. In other words, participants hear a pitch difference, where there is at least no f_0 difference. This could be explained by the fact that for complex tones participants have difficulties to ignore

[4] Note that the lowest measurable harmonic does not always have to coincide with the perceived pitch. For the lowest bass notes the soundboard is not capable to project f_0 and the first measurable frequency component is the octave. Nevertheless, due to the periodicity implied by the quasi-harmonic overtone structure the pitch of the tone is perceived at the *missing fundamental* frequency.

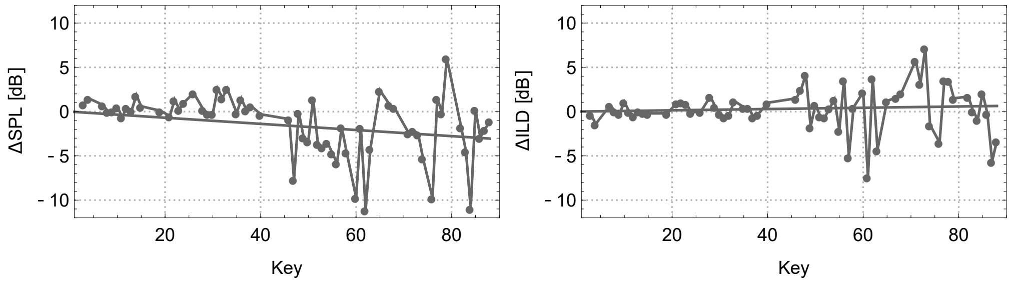

Figure 4. SPL (left) and ILD (right) development between *State 1* and *State 2*.

alterations in brightness (due to changes in the spectral distribution) when making pitch judgments (due to changes of the fundamental frequency) [18].

5.3 Temporal Domain

Notwithstanding the frequent use of words from the temporal domain (11% average per key) like e.g. *attack, onset, faster, shorter,* and *decay*, no general difference is observable, neither for the attack time, nor the decay as reverberation time RT_{60}.

5.4 Spatial and Loudness Domain

The sound pressure level (SPL) is calculated for both dummy head ear channels with reference pressure p_0 = 20 μPa. Up to the chamber tone no difference is observable for SPL or interaural level difference (ILD) (see Figure 4). For the mid- to treble range SPL values decrease within the year which can be explained with softer hammers due to several voicings. For single keys in the treble range SPL values vary up to 10 dB, ILD values vary up to 7 dB, which both should be perceivable. In the same course, with 3% and 1% usage, spatial and loudness attributes may not play an important role for discrimination when differences in more dominant domains like timbre or pitch can be used for the evaluation.

5.5 Driving Point Mobility / Soundboard Crowning

Driving point mobility measurements are performed at the bridge in direction normal to the soundboard plane for both states. The same impact hammer and accelerometer as mentioned in Section 3 are utilized. The soundboard is excited at 10 string termination points on the bridge, all strings are damped, 10 takes per input are recorded. Figure 5 shows an exemplary comparison between *state 1* and *2* for key *F4*. The mean mobility for *state 2* lies within the standard deviation of the *state 1* measurement. Therefore, no significant difference can be observed.

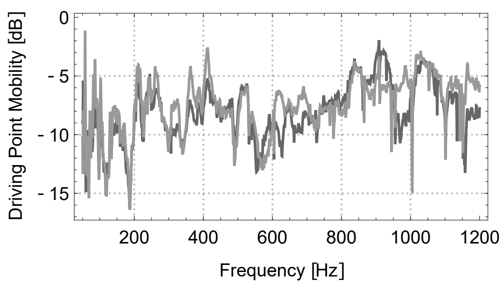

Figure 5. Driving point mobility for state *1* (dark) and *2* (bright) at key *F4*.

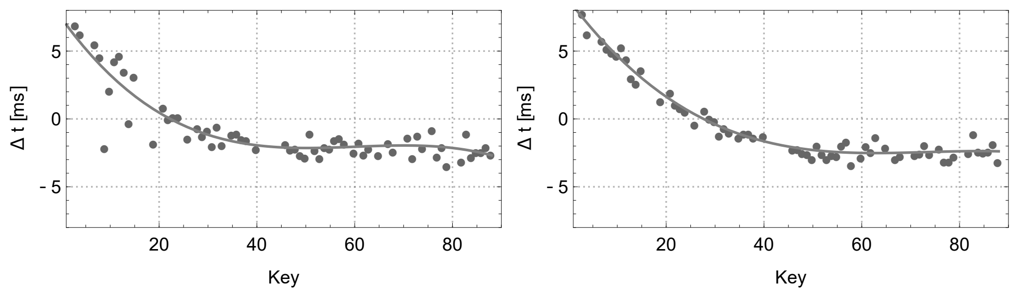

Figure 6. Time delay (Δt) between key bed contact and vibrational activation at the bridge for *State 1* (left) and *State 2* (right).

The soundboard crowning height is measured at several points on the bridge for both states with a laser rangefinder. The maximum crowning difference between states is 1 ± 0.5 mm. As described in Section 2.4, the crowning is expected to vary within a year with amplitudes of up to several millimeters. However, both measurements have been performed in the same season (winter) and therefore the soundboard should have a similar equilibrium moisture content.

5.6 Action Timing

The time delay Δt between key bed contact and vibrational activation of the piano is crucial for the sensation of how 'fast' the piano feels for the player [1]. Although this feature should not have impact for the listening test, it is a good example showing empirical proof for the work of the technician. Figure 6 shows Δt measurements for *State 1* and *State 2*. A general trend is observable with positive delays in the bass range decreasing to the mid range and a constant negative delay in the treble range. Comparison of *state 1* and *2* shows that the outliers in the bass range are leveled and the general variance decreases. This can be explained with maintenance work by the technician who diminished the outliers by regulating to yield a more consistent playing feel.

6 CONCLUSIONS

With regard to the listening test it can be noted that a difference in tonal quality is perceivable for a piano after one year in concert usage even for non-experts. Despite an observable ceiling effect for the test, builders and tuners have the highest competence to make a distinction between piano tones, which is a conclusive result, since this is one of their main professional skills. The most stated properties used to distinguish between piano tones are timbre related, followed by pitch and temporal attributes. Even experts in piano playing or building use descriptive and metaphoric vocabulary to a high degree in describing their sensations. The vocabularies of non-experts, players, and builders differ far less than assumed. In comparison a contrast becomes apparent between clear perceptibility of tonal differences on one hand, and insufficient representability with well established psychoacoustic metrics on the other hand. Although even non-experts seem to perceive small differences in tonal quality of similar piano tones, individual well established psychoacoustic parameters do not seem to be capable to reflect these differences. Due to the study design, no causal relationships can be revealed but within the time frame of one year, the technician can be expected to have much more impact on the tonal development of the piano than the effects of wood aging or playing. The presented findings give the technician to the same extent the responsibility, but also the opportunity to turn a good concert instrument into an excellent one.

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REFERENCES

[1] A. Askenfelt and E. V. Jansson. From touch to string vibrations. I: Timing in the grand piano action. *The Journal of the Acoustical Society of America*, 88(1):52–63, 1990.

[2] A. Beavitt. Humidity cycling. *Strad*, (November):916–920, 1996.

[3] G. Bissinger. Modal Analysis Comparison of New Violin Before and After 250 Hours of Playing. *Proc.13th Intern. Modal Analysis Conf.- Soc. Exp. Mechanics*, (July):822–827, 1995.

[4] I. Brémaud and J. Gril. Effect of transitional moisture change on the vibrational propoerties of violin-making wood. In *Cost FP1302 WoodMusICK annual conference "Effects of playing on early and modern musical instruments"*, 2015.

[5] V. Bucur. *Acoustics of Wood*. Springer Series in Wood Science. Springer-Verlag, Berlin, 2006.

[6] H. Burstein. Approximation Formulas for Error Risk and Sample Size in ABX Testing. *Journal of the Audio Engineering Society*, 36(11):879–883, 1988.

[7] D. Clark. High-Resolution Subjective Testing Using a Double-Blind Comparator. *Journal of the Audio Engineering Society*, 30(5):330–336, 1982.

[8] B. M. Clemens, J. Kadis, D. M. Clemens, E. Pollack, P. Clark, and J. R. Groves. Effect of Vibration Treatment on Guitar Tone: A Comparative Study. *Savart Journal*, pages 1–9, 2014.

[9] H. Fastl and E. Zwicker. *Psychoacoustics: Facts and models*. Springer, 2007.

[10] A. Galembo, A. Askenfelt, L. L. Cuddy, and F. a. Russo. Effects of relative phases on pitch and timbre in the piano bass range. *The Journal of the Acoustical Society of America*, 110(3):1649–1666, sep 2001.

[11] A. J. M. Houtsma. Inharmonicity of wound guitar strings. *The Journal of the Acoustical Society of America*, 71(S1):S9–S9, apr 1982.

[12] D. G. Hunt and E. Balsan. Why old fiddles sound sweeter. *Nature*, 379(6567):681–681, 1996.

[13] C. M. Hutchins. A Measurable Effect of Long-term Playing on Violin Family Instruments. *Catgut Acoustical Society Journal*, 3(5):38–40, 1998.

[14] R. E. Kirk. Tuning Preferences for Piano Unison Groups. *The Journal of the Acoustical Society of America*, 31(12):1644–1648, dec 1959.

[15] S. Kraft and U. Zölzer. BeaqleJS : HTML5 and JavaScript based Framework for the Subjective Evaluation of Audio Quality. *Linux Audio Conference (LAC-2014)*, (May), 2014.

[16] A. Mamou-Mani, S. Le Moyne, F. Ollivier, C. Besnainou, and J. Frelat. Prestress effects on the eigenfrequencies of the soundboards: Experimental results on a simplified string instrument. *The Journal of the Acoustical Society of America*, 131(1):872–877, jan 2012.

[17] D. W. Martin and W. D. Ward. Subjective Evaluation of Musical Scale Temperament in Pianos. *The Journal of the Acoustical Society of America*, 33(5):582–585, 1961.

[18] B. C. J. Moore and B. R. Glasberg. Frequency discrimination of complex tones with overlapping and non overlapping harmonics. *The Journal of the Acoustical Society of America*, 87(5):2163–2177, may 1990.

[19] F. Öberg and A. Askenfelt. Acoustical and perceptual influence of duplex stringing in grand pianos. *The Journal of the Acoustical Society of America*, 131(1):856–871, jan 2012.

[20] S. Petersen. *Vom "Schwachstarktastenkasten" und seinen Fabrikanten - Wissensräume im Klavierbau 1830 bis 1930*. Waxmann Verlag, 2011.

[21] O. Railsback. Scale temperament as applied to piano tuning. *The Journal of the Acoustical Society of America*, 37:2013, 1938.

[22] A. A. Reblitz. *Piano Servicing, Tuning, and Rebuilding*. Vestal Press Inc., 1993.

[23] P. R. Rosenbaum. *Design of Observational Studies*, volume 27 of *Springer Series in Statistics*. Springer New York, New York, NY, 2010.

[24] E. Segerman. Some aspects of wood structure and function. *Catgut Acoustical Society Journal*, 4(3):5–9, 2001.

[25] W. A. Sethares. Local consonance and the relationship between timbre and scale. *The Journal of the Acoustical Society of America*, 94(3):1218–1228, sep 1993.

[26] M. Tervaniemi, V. Just, S. Koelsch, A. Widmann, and E. Schröger. Pitch discrimination accuracy in musicians vs nonmusicians: an event-related potential and behavioral study. *Experimental Brain Research*, 161(1):1–10, 2005.

[27] G. Weldert. Sound Enhancement of Musical Instruments by ' Playing them in ': Fact or Fiction? *Europiano*, (9):0–7, 2017.