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# Perception of Harpsichord Plectra Voicing

Arthur Paté[1,2], Arthur Givois[1,2], Sandie Le Conte[2], Jean-Loïc Le Carrou[1], Michèle Castellengo[1], Stéphane Vaiedelich[2]

[1] Sorbonne Universités, UPMC Univ Paris 06, CNRS, LAM/Institut d'Alembert, 75252 Paris Cedex 05, France. pate.arthur.lam@gmail.com

[2] CRC, USR 3224-ECR Musée de la Musique, Cité de la Musique, Philharmonie de Paris, 221 avenue Jean Jaurès, 75019 Paris, France

**Summary**

The way harpsichord strings are plucked depends on the mechanical and geometrical properties of the plectrum, which influence is expected on the sound (initial conditions of string vibration) and touch (mechanical reaction of the key). In harpsichord making and setup, the "voicing process" consists in selecting and shaping the plectra in order to provide the instrument with interesting sound features and homogeneity of sound and touch over the whole tessitura. This article presents a perceptual test investigating how different voicings are perceived. Experienced harpsichord players took part in a free playing and verbalisation task and evaluated two different sets of plectra. The verbal data was analysed with methods inherited from the field of psycholinguistics. A perceptual characterisation of each set of plectra was obtained, based on evaluations of loudness of the sound, hardness of the plectra, strength of the voicing, length/resonance, dynamics, equality and evolution of sound and touch over the tessitura. This perceptual characterisation was compared to physical measurements (minimum triggering force on the key, equivalent sound level) made during or after the tests. The main difference between the two voicings was the loudness of the sound (in agreement with the equivalent sound level) and the hardness of the plectra (in agreement with the minimum triggering force). More in general, this study validates the adequacy and relevance of the free playing and verbalisation method applied to musical instruments involving multimodal perception.

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## 1. Introduction

The sound of the harpsichord is the result of complex mechanical phenomena. At the beginning the finger of the musician presses a key, making the keylever raise the jack. On the jack a plectrum is attached. The plectrum is a very small piece originally made of feather quill, and nowadays often made of a plastic called polyoxymethylene, also known as the commercial name "Delrin", a registered name by *DuPont*. During the plucking action, the plectrum first comes in contact with the string, then elevates it following the motion of the jack, bends under string restoring force and finally releases the string. The string then vibrates and couples with the soundboard at the bridge, and the soundboard radiates the sound we hear.

Coupling mechanisms [1] and soundboard vibroacoustic behaviour [2, 3] have been comprehensively studied in the literature. Also the string vibration has been widely studied, though in isolation of other parts [4, 5, 6]. The string's initial conditions are determined by the phase during which the plectrum interacts with the string. During this phase the musician controls the key depression hence the elevation and velocity of the jack, but the bending of the plectrum and consequently the string deviation from rest position are also governed by the geometrical and mechanical properties of the plectrum. Players and makers attach a great deal of importance to the "voicing process", during which the plectra are selected and shaped in order to provide the instrument with interesting sound features while preserving a homogeneity of sound and touch over the whole tessitura [7].

Two studies have dealt with the plectrum material: different "pre-transients" identified in sound recordings were associated to different plectrum materials in [8], and in [9] the wearing of plastic and quill were compared. Models of plectrum bending have been proposed in the literature [10, 11, 12, 13], showing the relationships between the jack velocity and plectrum length with the initial conditions of the vibrating string, but only a few took into account the plectrum shape [14, 15]. However, none of these studies investigated how harpsichord players perceive a change of plectrum shape. Different plectrum geometries may indeed result in different initial conditions provided to the vibrating string (therefore sound differences), and in different mechanical reactions of the key (therefore tactile feedback differences). This article aims at investigating how different voicings are perceived.

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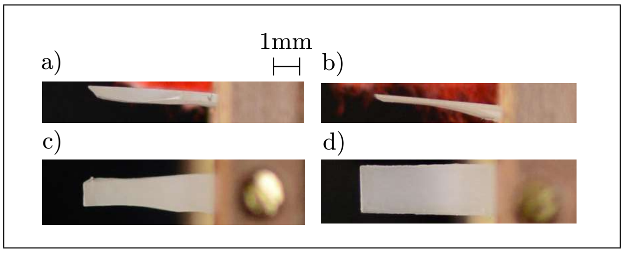


Figure 1. Photographs of the plectrum corresponding to key number 46 (note E5), for each of the voicings of the study. a) Side view of the plectrum of V1; b) Side view of the plectrum of V2; c) Top view of the plectrum of V1; d) Top view of the plectrum of V2.

There have been perceptual studies about the piano, for example listening tests conducted with synthesised piano sounds in order to assess how the inharmonicity [16, 17] or the longitudinal string modes [18] are perceived, listening tests with a focus on "key-bottom" and "finger-key" sounds [19], and playing tests with fixed questionnaire focused on the sensation of touch [20]. In comparison with the piano, only a few studies have dealt with the perception of the harpsichord. An exploratory study about the harpsichord sound quality was conducted using the free categorisation task during listening tests [21]. In [22] listening tests were conducted in order to assess whether differences in performances by different players can be identified; in [23] listening tests were carried out in order to assess whether a "soft" and a "loud" touch can be discriminated. In [24, 25] automatic signal processing methods were used in order to characterise the interpretation of different performers.

This article presents a perceptual test aimed at investigating how different voicings are perceived by harpsichord players, addressing issues of usual methods used in perceptual studies of keyboard instruments. Indeed in the aforementioned studies, the auditory and tactile modalities were studied as independent modalities, rarely in the context of musical performance. However, in the case of harpsichord playing, and *a fortiori* when studying the voicing process, there is no reason to assume that auditory and tactile perceptions are uncoupled. Moreover, it is *a priori* expected that the plectrum geometry has an influence on the sound and touch. These reasons make it unavoidable to take the point of view of the harpsichord player her/himself, in a musical playing context (not limited to a listening task). Furthermore, in the absence (to the knowledge of the authors) of pilot studies about how harpsichord players perceive their instrument in general, it is not possible to *a priori* select and impose evaluation criteria to the subjects: it would mean risking to either miss important criteria not foreseen by the experimenters, or to focus the subjects on criteria which are not relevant to them. For all these reasons, this study takes on the theoretical framework and experimental procedure of previous studies [26, 27, 28, 29]: A free playing and verbalisation task was organised, leaving the subjects free to follow their own evaluation strategy, and allowing us to access their cognitive representations and evaluations through discourse analysis. Finally, a further originality of the present perceptual study in comparison with the literature is its focus on a lutherie parameter rather than on performance-related parameters.

Section 2 describes the experimental procedure: Experienced harpsichord players were asked to freely play and evaluate two different sets of plectra (two "voicings"). Section 3 then presents the analysis method for the verbalisations, inherited from the field of psycholinguistics. In Section 4 the verbal descriptions of each voicing are presented, and they are compared to physical descriptors in Section 5. The results are eventually discussed in Section 6.

## 2. Experimental procedure

### 2.1. Subjects

The eight subjects were professional harpsichordists. We define being a "professional harpsichordist" here as having a main activity involving harpsichord playing: concerts, masterclasses, lessons or recordings. Subjects are numbered from S1 to S8. All subjects were unpaid for their participation.

### 2.2. Harpsichord

A harpsichord made by French maker Marc Ducornet was used. It has the specifications of a small single-keyboard (56 notes, from G1 to D6, fixed register), single-stop (eight-foot) harpsichord inspired by the instruments of French makers of the 17th century. This harpsichord is usually played by docents at the Music Museum in Paris during musical and pedagogical visits. Before the realisation of the plectra (cutting, carving), the keyboard and mechanism of the harpsichord were adjusted, and two identical series of jacks were prepared (identical dimensions, pre-adjustment of the tongue and spring). For the playing tests and physical measurements, the harpsichord was tuned to a Corrette temperament, with reference A4 at 415 Hz.

### 2.3. Voicings

Two professional harpsichord makers were involved in the project. Each of them was lent the harpsichord and given a series of pre-adjusted jacks and a piece of polyoxymethylene from the same plastic sheet. Each of them was then asked to "voice" the harpsichord, that is to say to produce a series of plectra that are adapted to the harpsichord of the study (Section 2.2). No further instruction was given to the harpsichord makers, so that they were free to choose their own voicing strategy. The two series of jacks fitted with the shaped plectra form the two "voicings" investigated in this study. They are given the names V1 and V2. Figure 1 presents side and top views of an example plectrum for V1 and V2.

### 2.4. The task

Subjects were asked to perform a free playing task, as previously done in [26] in the case of the electric guitar. The instructions of the task were:

> *This study is made of two parts.*
>
> *Please play on this harpsichord the way you would do if you were looking for an instrument for a personal purchase or an upcoming concert. Please freely tell us about your feelings when playing. When you are done, we will ask you to perform short musical excerpts that are going to be recorded by various sensors that we will describe to you.*
>
> *We will then have a short break and start over again the same task.*

Each subject was therefore presented to V1 and V2 successively, with a short break in between (5 to 10 minutes, the time needed for the experimenters to remove the first series of jack and install the second one). The order of presentation was balanced across subjects. The test is said to be a "blind test", because subjects were not told about any possible difference between the experimental setup of first and second phase[1].

The instructions were deliberately loose in order to let the subject focus on what really is relevant for him/her: no evaluation criterion was suggested to the musicians. The role of the experimenters (first two authors) was to keep the conversation going, asking for details, rewordings, *etc.* In order not to influence the subject, the experimenters took care to not use words if they had not been previously used by the subject.

The musical excerpts were selected by the authors with the help of harpsichord players (who did not participate in the playing task). The main selection criterion was to propose a collection of excerpts that is quite representative of the usual repertoire played on such a harpsichord. In order to make the subjects comfortable with the excerpts, they were chosen to be quite easy to perform and part of the expected repertoire of an experienced harpsichord player. The chosen excerpts were:

- "Les Idées heureuses" by François Couperin (bars 1 to 8, score in Figure A1)
- "Fantasia V" by Johannes Jakob Froberger (first 9 bars of the part with 6/4 time signature, score in Figure A2)
- "Prélude en la mineur" by Louis Couperin (first 2 lines, score in Figure A3)
- "La Piémontoise" by Louis Couperin (bars 1 to 8, score in Figure A4)

The excerpts were played in the order wanted by each player. Manually-estimated average tempo was 46±4 BPM (46±4 BPM for V1-performances, 46±4 BPM for V2-performances) for "Les Idées heureuses", 197±26 BPM (198±24 BPM vor V1, 195±30 BPM for V2) for "Fantasia", 81±13 BPM (81±14 BPM for V1, 82±13 BPM for V2) for "La Piémontoise". The voicing does not seem to have an influence on the tempo. No tempo estimation was carried out for "Prélude en la mineur" since it is an unmeasured piece of music.

The tests had an overall mean duration of 77 (±8) minutes. The order of presentation of the two voicings was balanced across subjects: odd-numbered subjects were first presented to V2 and even-numbered subjects were first presented to V1. All tests took place in the same room, selected for its acoustic neutrality, usually used for pedagogical visits at the Music Museum.

### 2.5. Experimental setup

In addition to the harpsichord and jacks described above, the experimental setup included two microphones for the evaluation sessions. While the harpsichord player freely played and talked, two microphones (*Schoeps CMC6* fitted with *Schoeps MK4* capsule, X-Y position, 21.5 cm above the G3-string, at 37 cm from the jack rail) recorded the sound radiating from the soundboard. Another microphone was used for the recording of the musician's speaking. Note that the type (cardioid) and position of the *Schoeps* microphones were chosen in collaboration with a recording engineer: they were deliberately chosen to fit artistic and not laboratory measurement expectations. This insures the ecological validity of these recordings if used as stimuli in future listening tests. Furthermore, the recorded sounds may be used for outreach activities. The measurements of equivalent sound levels in Section 5.3 were based on the recordings with this microphone setup. In order to compensate for the directivity effects due to the X-Y microphone position, equivalent sound level was obteined by averaging the values computed from the left and right microphones.

At separate occasions the following two experiments were run by the authors, each repeated five times for each key, providing data for assessing the uncertainty:

**Measurement of the "minimum triggering" force** This is the force exerted on a key needed to trigger the corresponding note. The apparatus, to our knowledge first introduced in [30] is sketched in Figure 2: a lever is used for each key and each voicing in order to determine the minimum force that one has to exert on the tip of the key to trigger the note. This measurement was made by the authors, having checked that the variability due to the operator is negligible, and that the lever was always kept horizontal (a frame having the same height as the top side of the keys was used in order to insure the lever is horizontal prior to each measurement). This measurement was consistent with cross-check dynamometer measurements, and each repeat of each measurement was made from scratch, meaning the ruler was removed from the key and the weight put away from its previous position;

**Sound recording of isolated notes** All keys on the harpsichord were played as isolated notes in a slow tempo with a medium-velocity pressing motion by the fifth

[1] If one subject happened to ask why she/he was involved in a second phase which appeared exactly the same at first sight, she/he was answered that we could not answer the question. Thus no information about the existence and nature (change of jacks/plectra/voicing) was provided throughout the test.

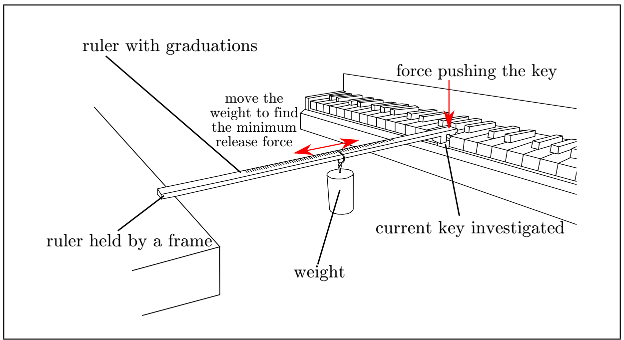


Figure 2. Sketch of the measurement apparatus for the minimum triggering force. A lever is held horizontally between the key tip (at the usual place of the playing finger) on one side and a frame on the other side. The minimum force for the triggering of the note is sought after by the displacement of a weight along the graduated lever.

author, who is an experienced harpsichord player. The task was repeated five times for each voicing. Experienced musicians have proven to have a highly reproducible gesture, in particular for musical string excitation, see [31] for instance. Furthermore, having an experienced harpsichord player do the measurements gives us access to data that is close to what is produced by a musician in a musical context. Instead of the two *Schoeps* microphones, a *Bruel & Kjær 4961* microphone was used for these measurements, at 21.5 cm above the G3-string, at 37 cm from the jack rail. A recent study has shown that a microphone position above the strings gives similar trends in extracted acoustical features as a position at the players' ears [26]. Due to schedule reasons, it was not possible to have one of the subjects play each note of the harpsichord for each voicing.

## 3. Semantic analysis

In this section an overview of the analysis method of the transcriptions of the verbalisations gathered during the free playing task (8 musicians having talked 1.25 hours in average) is given. The analysis was carried out in French (the language spoken during the tests), and afterwards the output of the analysis was translated into English. In the rest of the article we use word-to-word English translations in order not to introduce a further degree of interpretation from the experimenter's side. Original French wordings are presented in appendix **??**. More details about this analysis method can be found in [27]. Words in italic are words pronounced by the subjects (English translation is presented first, then the French original wording with *"FR"* as prefix), while words in quotes were not pronounced by the subject but inferred by the experimenters. Quotes of full sentences are followed by a code giving the number of the subject (*e.g.* S1), the voicing played when the sentence was pronounced (*e.g.* V1), and the current phase of the test ("first phase" for the voicing mounted and played before the break; "second phase" for the voicing mounted and played after the break).

### 3.1. General remarks

The method was proposed and used in previous work [26, 27]. In line with this work, the following observations can be made:

- There is only a few lexical resources of French that are primarily used to describe sounds: many lexical forms are borrowed from the lexicon of vision (*e.g.* bright, dull, clear) or of everyday life (*e.g.* flat, elegance) [32];
- The meaning of words used by experts of a specific domain in a particular context can differ from the common sense meaning, *e.g.* the "warmth" of a sound is not related to its supposed temperature;
- In general there is no one-to-one correspondence between a word ("signifier") and a concept ("signified") [33]: as a consequence, the same word can be given a different meaning by different speakers; and the same concept can be referred to by different words either in the discourse of a single speaker, or in the discourse of different speakers.

Therefore the analysis should start with the identification of the "semantics" of the harpsichord players, that is the identification of the meaning of the words used by the subjects, before comparing the two voicings. Section 3.2 defines the method for obtaining the six *semantic categories*, which give us a framework in which the different words used by different subjects can be compared.

### 3.2. Semantic categories

First all parts of the discourse describing either the instrument (in general, or parts of it such as jacks or plectra) or the sound or the touch were extracted, keeping track of the speaker (subject number) and of any relevant information about the context (voicing currently played, playing technique *e.g.* arpeggios of chords, repertoire, explicit comparison with the previous voicing or absolute evaluation, *etc.*).

Then the meaning of each word used in the extracted sentences was identified through semantic analysis. Linguistic marks (appositions, oppositions, reformulations, negations, metadiscourse, adverbs, comparatives, superlatives *etc.*) were sought in the sentences of the subjects in order to identify:

**semantic proximities** words referring to similar concepts and having similar meanings, *e.g.* the sentence *The plectra are a bit too hard, too strong* (S2) allows us to conclude that the words *hard* and *strong* are quasi-synonyms when referring to the plectra;

**semantic distances** words referring to similar concepts and having opposite meanings, *e.g.* the sentence *Louder, I have the impression that it has more sound than a bit earlier, it is not the hollow sound of earlier* (S7) allows us to conclude that *loud* and *hollow* are quasi-antonyms when referring to the loudness of the sound[2].

[2] Note that S7 also used the word "hollow" in the sentence "it was less hollow than before [...] it is rounder, more generous" (S2V1). In this

Table I. Identified semantic categories and words within the categories (tentative English translation). Labels of semantic categories and subcategories are in upper case. In each semantic category, meaning "A" (or positive, +) is opposed to meaning "B" (or negative, -). Abbreviations used: s. for sound, str. for string, i. for instrument, int. for interpretation, p. for plectrum, k. for key, kb. for keyboard, v. for voicing, t. for timbre, m. for musician, n. for note(s), j. for jack. The object qualified/described is put into parenthesis.

| |
|---|
| LOUD / HARD / STRONG |
| LOUD (S.)<br>**Meaning "A" (+):** stressed, amplified, attack, dental attack, attack with consonants, clear (s.), substantial, makes me want to play, hard (s., p.), emission, emotion, energy, easy to play, one must make efforts to make it sound, harmonics develop, loud (s.), strong (v., p.), intensity (s.), long (n.), dynamic leeway, plucks enough, range (s.), present/present, finger pressure, power/powerful (s.), reinforced, resistance, resonates more, satisfactory, sensation at fingertip, touch, makes more sound, sounds more, resounding, lively (v.), violent, volume<br>**Meaning "B" (-):** beautiful, convenient, hollow, one must attack stronger, some n. disappear, soft (s., v.), smaller thickness (p.), weak (s.), intime (i.), less p. length under the str., sluggish, soft, to play music for 2 or 3 people, the note is lost, music for a small room, flat (s.), j. row shifted to the right, smaller p. length under the str., one feels one must restrict oneself when playing, sensual, feels better, less sound, 1 str. per note<br>HARD (P.)<br>**Meaning "A" (+):** have more under the fingers, have sound (p.), thick (p.), hard (p., str.s), loud (p., s.), substance, resistance (p., finger, key), resounding, strong (p.), violent (s.)<br>**Meaning "B" (-):** weak (p.), false (n.), thin (p.), light (touch), dull (s.), sluggish (s.), soft (p., s., k.), smaller kb. of a two-kb. i., feather (p.), the j. does not go back well, flexible (p.)<br>STRONG (V.)<br>**Meaning "A" (+):** register brought forward, counterbalance the fact that there is only 1 str. per note, the p. oversteps (longer plectrum length under the str.), hard (p., s.), elegance (s.), have a longer plectrum length under the str., easiness of playing, strong (p., i. setup), strong (v.), leeway in dynamics, give power, register brought in, respond to the attacks, vigour (p.)<br>**Meaning "B" (-):** less p. length under the str., j. row shifted to the right, sounds weaker |
| LENGTH/RESONANCE |
| **Meaning "A" (+):** like a bow controlled in order to produce a very small decrescendo before interrupting the s., soft, echo, elegance, the damper dampens very slowly, the s. evolves with time/in its length, loud (s.), resonance halo, human (s.), long (s.), length (s.), sluggish (s.), do not release the keys when playing, harmonics pass by, enjoy the response of the i., deep/depth (s.), resonate/resonance (s.), reverberation, round/roundness (s.), the n. mix up, the harmonics spread out, the harmonics deploy, s., the s. lasts, the s. come and go<br>**Meaning "B" (-):** walk all over the s., brutally dampen the str. (corde), dampers like billhook strokes, machine, dull (s.), mechanical, resonance walked all over by the attack, dies out fast (s.), sharp (int.) |

Words referring to the same object or concept and sharing a semantic proximity or distance relationship were then grouped into six semantic categories. Each semantic category therefore refers to a perceptual concept, and can be split into subcategories according to the different aspects of the perceptual concept or to different objects described (*e.g.* the sound or the plectrum). Table I shows the semantic categories identified through the linguistic analysis. Table II presents the corresponding French original wording of Table I. Label of the categories and subcategories are in upper case. In each subcategory, the column "Meaning A (+)" groups together words having been attributed a meaning similar to the label of the subcategory in a particular context by a particular subject (we kept track of both context and subject): for example *generous* has been given a similar meaning as *round* by S7 when referring to the sound. The column "Meaning B (-)" groups together words having been attributed a meaning opposite to the label of the subcategory (*e.g. soft* has been given a meaning opposite to loud by S2 when referring to the sound). The labels "A", "B", and "+" and "−" are arbitrary and are no judgements made by the experimenters. Note that the dichotomy Meaning A/Meaning B is not relevant for some categories: REACTION TO THE ATTACK, BALANCE, KEYBOARD and TECHNIQUE).

sentence, "hollow" is opposed to "round" and "generous" and these three word turn out to be part of the category ROUND. S7 has been the only subject to use the word "hollow", so only two meanings were identified for this word.

Note that some words can be listed in several categories. This indicates that the words have been attributed different meanings by one or several players, depending on the context. Therefore it is very important to keep the information about the speaker and the context throughout the analysis. This remark can also be viewed as an experimental confirmation that the word/concept correspondence is more complex than a simple "one-to-one" correspondence and that the identified semantic categories and associated perceptual concepts have loose boundaries, and may share some interdependences.

Table I. Continuation I.

**ATTACK**

GOOD BALANCE, ATTACK/RESONANCE

**Meaning "A" (+):** beautiful attack, good balance between attack and resonance, the p. oversteps, elegance, strong (p.), resonance halo after the attack, attack responds, satisfactory attack, resounding, vigour (p.)

**Meaning "B" (-):** too much attack, harshness of the attack, more rustic attack, present attack, tough attack, rough attack, hard to give the s. an elegance, weak (p.), false (s.), dull (s./i.), harmonics not in tune, resonance walked over by the attack, rough (s.)

DYNAMICS

**Meaning "A" (+):** entertaining, manage to play with dynamics, the i. offers leeway in dynamics, beautiful, change the nature of the attack, counterbalance with touch, difference if one puts more energy in the attack, difference in s., give impetus, dynamics, be soft = attack gently ≠ put more weight, avoid that n. sound "splash", build the homogeneity, soft v. (one can play soft n.) and lively (can develop more harmonics), get what you want, one has more elasticity on the v., one can play with the i., on can play more with the attack, one can attack gently or strongly, relationship between the musician's request and the i.'s response, i. reacts quickly, reaction, receptive (i.), respond (str., s.), response, fullness (s.), all works well, to sound, vary the attack, alive/live (i.)

**Meaning "B" (-):** common, soft (kb.)

REACTION TO THE ATTACK

**Meaning "A" (+):** attack, p. oversteps (longer p. length under the str.), give impetus, dynamics, equality of strength in the fingers ⇒ equality of n., elegance, make some n. stand out just with touch, soft v. (one can play soft n.) and lively (can develop more harmonics), immediate (s.), italian, works (n.), there is a s. difference when playing repeated n. with different fingers, one hardly has to touch and one get exactly and immediately what one hears, ornaments work, fullness (s.), pressure, v., height and position of the playing finger, speed of the reflex of the j., react/reaction/reactive (attack, finger, kb., s., i., p.), make the i. react, register brought in, respond (note, i.), the tongue goes back, the j. lifts, sensation at fingertip, sounds well, the s. starts, the s. is released, all works well, vigour (p.), XVIIth century

**HOMOGENEOUS**

EQUALITY

**Meaning "A" (+):** pleasant for the whole range, equal/equality (kb., fingers, touch, key depression, force, n.) for the whole range, equally elegant on the whole kb., equality of force in the fingers ⇒ equality of n., balance/balanced, i. works over the whole tessitura, the transition between strong and weak p. is gradual, well voiced/good v./the i. pleases me, regularly voiced, homogeneous (i., s.), interesting over the whole range, pleasure, wood quality, good reaction to the attack, setting up of kb. and p., even sensation on the kb., beautiful s. over the whole range, beautiful bass s., all tessituras sound well, uniform

**Meaning "B" (-):** i. has qualities and defects, some n. harder, timbral difference, some n. disappear, some n. feeble, some n. louder, large disparity between 2 consecutive p. (weak and strong), one has to avoid ugly n. and regions, i. unequal, non-homogeneous (s., resonance), some n. not pretty, p. a bit long, lack in a tessitura, unequal (timbre), some n. are lost, problem, some n. are stiff, p. does not go down, some n. repeate not so well, some n. stand out too much, some regions are better than others

EVOLUTION

**Meaning "A" (+):** light trebles, manage to play with background and foreground in contrapuntic music, each note has its character, each note has more personnality, evolution of the response with the tessitura, evolution towards the trebles, make the polyphony audible, make the different voices audible, hard basses, soft v. (one can play soft n.) and lively (can develop more harmonics), unequal/unequality (v.), unequality in v. is interesting, open (s.), gradually lighter and lighter from bass n. to treble n., quality, more resistant in the bass n. than in the treble n., alive

**Meaning "B" (-):** equal, uniform

We give a brief overview of the identified semantic categories:

- LOUD/HARD/STRONG groups together words and expressions describing either the *volume* of the sound (*loud* vs. *soft*), or the *hardness* of the plectrum (*hard* vs. *soft*), or the "strength" of the voicing (*strong* vs. "weak"). For ease-of-interpretation reasons, this category have been split into three subcategories, each of them referring primarily to a different object (sound, plectrum or voicing). However, these subcategories are obviously not independent: some words (*e.g. loud* or *soft*) appear in several subcategories. This emphasises the strong interconnection between the sensation of sound "loudness" and of plectrum "strength";

- LENGTH/RESONANCE groups together words and expressions describing the way the sound *lasts* and *evolves* after the short instant of note onset (the notes *resonate* and *evolve* in time vs. the notes *die out fast*).

Table I. Continuation II.

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|---|
| SOUND DESCRIPTORS |
| CLEAR<br>**Meaning "A" (+):** clear (s., i.), have difficulty with legato, makes me want to play, lights up, loud, hear the n. clearly separated in chords, presence, sounds like a succession of attacks, transparent<br>**Meaning "B" (-):** chord resonates globally, low-mids., muddled (s.), nasal (s.)<br>ROUND<br>**Meaning "A" (+):** sweet, beautiful, a lot of harmonics, beautiful attack, beautiful fundamental, character, warm/warmth (s.), soft (s.), echo, balance/balanced (s.), the damper dampens smoothly, very small decrescendo before the s. dies out, be comfortable (m.), the way the s. develops, weak (s.), flexible (p.), generous/generousity, harmonics, 5th harmonic sounds longer, human, play more (m.), calm play, let the n. ring (m.), brass (str.s), ties (n.), play with legato (m.), magnificent, best, sluggish (s.), easy to make the i. sing, a lot of harmonics, harmonics spread out, harmonics pass by, deep/depth (s.), s. quality, resonance, round/roundness (s.), sensation of 2nd clavier, dull, sounds well, sounds long, play with resonance<br>**Meaning "B" (-):** dental attack, have difficulty make the i. sing, play virtuoso pieces, play staccato, basic (i.), bright/brightness, practice i., constrained (s.), str. not well stretched, steel str.s, hollow (s.), loud, no/less harmonics, machine, mechanical, dead (s.), new (i.), flat (s.), precise (s.), this p. does not look like the other ones, infertile, uniforme (s., i.) |
| VOICING, SETUP |
| TECHNIQUE<br>**Meaning "A" (+):** sharpen the p., change the i., change the j., choose the p., search for a s., comfort/comfortable, travel of the j., cut the p., temporal distance between the 2 attacks, harden the p., equal over the whole kb., depth (p.), make the i. talk, thin (p., plucking point), louder, to balance the kb., voice/v., height (j.), hollow out under the k./on the front of the k., very important, play with the p., wide plucking point, mechanical link between the fingers and the s. production, length of the p., operations on j. and p., optimise the i. (make it give ist best at s. and kb.), reaction of the i., the p. goes down, set up/setup the kb. and p., repeated n., location of the balance pin, put weights, place the balance pin, the p. goes back (over) well, s. (i.), carving of p., felt in the upper rail, transform the i.<br>COME BACK (DOWN)<br>**Meaning "A" (+):** m. adapts to the i., articulate more (m.), relaxed hand, one really has to act for the i. to play, hard (p.), equal/equality, be active (m.), ornaments work, loud (i.), v., play with a lot of hand moves, play Scarlatti's sonatas, release the p., oil the feather, the i. works well, the p. obbeys, be able to continue the trill, bounce (j.), go back (p.), repeat/repetition (n.), respond (n.), return of the k. not too quick, resistance/resistant/resist (kb., f., k.), go back (n., j., p.), good i.<br>**Meaning "B" (-):** f. grips, p. not cut exactly where it should be, demands a lot of relaxation in the f., soft, for playing continuo, one has to watch out when playing ornaments, on has to completely release the f. in order the p. to go back completely, one has to pull up the f. in order the k. to go back up enough, the j. does not go back up, p. too long, sluggish n., soft (p., k., plucking), i. does not respond, the tongue does not come back precisely and rapidely, force to pull up the f. in order the j. to go back down properly, p. goes by slowly, smaller kb. of a 2-k. i., problem (setup, mechanical, with ornaments), when one is less reactive the p. does not go down, less resistance (k., kb.), some n. repeat not so well, less s., p. remains hung above the str., not a good balance between the front of the k. and the j., j. does not fall down fast enough |

Note that in contrast with the acousticians' description distinguishing between the duration of a sound and its time evolution (*e.g.* amplitude modulation), these two elements (duration and evolution) are clearly interweaved in the harpsichord players' discourse;

- ATTACK has three subcategories organising words and expressions referring either to the note onset with respect to the *resonance* (subcategory GOOD BALANCE ATTACK/RESONANCE: *good balance between attack and resonance* vs. *too much, rough attack*), to the DYNAMICS (whether one can or cannot play the instrument both *gently* and *strongly*), or to the REACTION TO THE ATTACK (how the keyboard and the instrument react to the finger gesture, including both *dynamics* and *instrument settings* aspects);
- HOMOGENEOUS groups together words and expressions focused on the *equality / unequality* of sound and touch across notes and tessituras. Harpsichord players seem to prefer instruments that are both *equal* and *unequal* but in different senses. The following two subcategories are an attempt to take this into account: EQUALITY opposes words describing a desirable *equality* (adjacent notes are very similar in terms of sound and touch) to *problems* (consecutive notes are very different, in terms of sound and touch); EVOLUTION groups words and expressions showing that unequality is desirable when it is gradual enough over the whole tessitura (*gradually lighter from bass notes to treble notes*).
- SOUND DESCRIPTORS gathers words and expressions referring to the sound quality ("timbre") only. Two aspects of sound quality were identified: CLEAR (*notes*

Table II. Identified semantic categories and words within the categories (French original wording). Labels of semantic categories and subcategories are in upper case. In each semantic category, meaning "A" (or positive, +) is opposed to meaning "B" (or negative, -). Abbreviations used: a. for "attaque", s. for "son", c. for "corde", i. for "instrument", int. for "interpretation", d. for "doigt", b. for "bec", t. for "touche", to. for "toucher" cl. for "clavier", h. for "harmonisation ", ti. for "timbre", m. for "musicien", n. for "note(s)", sa. for "sautereau", ha. for "harmonique(s)". The object qualified/described is put into parenthesis.

| |
|---|
| FORT / DUR |
| FORT (S.)<br>**Meaning "A" (+):** amplifié, attaque, attaque dentale, attaque a des consonnes, clair (s.), consistant, donne envie de jouer, dur (s., b.), émission, émotion, énergie, facile à jouer (i.), faire des efforts pour que ça sonne, faire se développer (ha.), fort (s., h., b.), intensité (s.), longue (n.), avoir / donner une marge de manoeuvre dynamique, pincer suffisamment, portée (s.), présent/présence, pression à mettre, pression du doigt sur la touche, prise du s., puissant/puissance (s.), renforcé, résistance, résonne +, satisfaisant, sensation qu'on a au bout du doigt, to., s'entend plus, sonne plus, sonore (i.), tonique (h.), violent, volume<br>**Meaning "B" (-):** beau, commode, creux, devoir faire l'attaque + fort, disparaissent au milieu du reste (n.), doux (h., s.), épaisseur réduite (b.), faible (s.), intime (i.), - de longueur sous la corde (b.), moelleux, mou (i.), musique à 2 ou 3 personnes, perdue (n.), petit salon, plat (s.), rangée de sa. décalée vers la droite (b.), sensation de devoir se limiter, sensuel, se sentir mieux, - de s., 1 c. par n.<br>DUR (B.)<br>**Meaning "A" (+):** avoir + sous les d., avoir du son (b.), épais (b.), dur (s., c., b.), fort (b., s.), matière, résistance (b., d., t.), sonore, violent (s.)<br>**Meaning "B" (-):** doux (s.), faible (b.), faux (n.), fin (b.), léger (to.), mat (s.), molasson (s.), mou (b., s., t.), petit cl. d'un deux-cl., plume (b.), ne remonte pas (sa.), souple<br>FORT (H.)<br>**Meaning "A" (+):** avancé (registre), compenser le fait qu'il n'y a qu'1 corde par note, dépassement (b.), dur (b., s.), élégance (s.), engager + les sa. sous la c., facilité de jeu, fort (ha., i., b.), marge de manoeuvre dynamique, puissance, rentré (registre), répondre (a.), vigueur (b.)<br>**Meaning "B" (-):** - de longueur sous la c. (b.), rangée de sa. décalée vers la droite, sonner + faible |
| LONGUEUR/RÉSONANCE |
| **Meaning "A" (+):** archet contrôlé avec un tout petit decrescendo avant d'interrompre le s., doux, écho, élégance, étouffer très doucement (étouffoir), évolue dans la durée (s.), fort (n.), halo de résonance, humain (s.), long (s.) longueur, longtemps (s.), moelleux (s.), ne pas lâcher les n. (jeu), passer (ha.), profiter de la réponse de l'i., profond/profondeur (s.), résonner/résonance (i., s.), réverbération, rondeur/rond (s.), se mélanger (n.), se déployer (ha.), se développer (s.), sonner, tenir (s.), va et vient (s.)<br>**Meaning "B" (-):** bouffer le s./la résonance, étouffée de manière brutale (c.), étouffoirs comme des coups de serpe, machine, mat (s.), mécanique, résonance mangée par l'attaque, s'éteindre vite (s.), sec (jeu) |

*are clearly separated in chords* vs. *chords resonate globally*) and ROUND (*deep* and *generous* vs. *bright* and *hollow*);

- VOICING, SETUP groups together words and expressions describing the way the harpsichord is voiced or set up (plectra, jacks, keys, keyboard *etc.*). Two subcategories are identified: TECHNIQUE lists the actions of the maker or player to voice or set up the instrument (*e.g. cut the plectra* or *hollow out under the keys*) and COME BACK (DOWN) opposes words describing the sensation of jacks and plectra coming down under the string properly when the key is released vs. *plectra remaining hung above the strings*.

Note also that some semantic categories or subcategories are not shown here because they did not prove relevant for discriminating V1 and V2. These categories are:

- HARPSICHORD, gathering general considerations about the harpsichord, such as its size and specifications: 7 subjects, in absolute evaluations, tell the harpsichord is a *practice instrument* which is *rather adapted to continuo* or for playing music *for a small audience* because of its being *small* and its having *only one string per key, only one register*;
- HEDONIC, gathering hedonic evaluations, such as *I wouldn't buy the instrument* (S4), *I like the resonance* (S8), *this is a pretty instrument* (S5), not relevant to compare V1 and V2 because a) they were not accompanied by explanations, b) we are interested in characterisation of each voicing, and not in personal preference;
- COMFORT (synonyms *comfortable, practical, feel better, etc.*), because the comparative evaluations according to this criteria actually do not compare V1 and V2 but the first phase of the test with the second phase of the test, the latter phase being preferred to the former one: even- respectively odd-numbered subjects prefer

Table II. Continuation I.

ATTAQUE

BON ÉQUILIBRE A./RÉSONANCE

**Meaning "A" (+):** trop d'a., âpreté de l'a., a. rustique, a. présente, a. rude, a. rugueuse, difficile de donner une certaine élégance dans le s., faible (b.), faux (s.), mat (s., i.), pas justes (ha.), résonance mangée par l'a., rude (s.)

**Meaning "B" (-):** belle a., bon équilibre a./résonance, dépassement du b., élégance, fort (b.), halo de résonance après l'a., répondre (a.), satisfaisante (a.), sonore, vigueur du b.

DYNAMIQUE

**Meaning "A" (+):** amusant, arriver à faire des nuances, avoir de la marge (i.), beau (impersonnel), changer la nature de l'a., compenser avec le to., différence si on met + d'énergie dans l'a., différence de s., donner de l'élan, dynamique, être doux (attaquer doucement) vs. mettre davantage de poids, éviter que les n. sonnent "plac", fabriquer l'homogénéité, harmonisation douce (jouer des n. faibles) et tonique (développer plus d'ha.), mettre davantage de poids, obtenir ce qu'on veut, on a + d'élasticité sur l'h., on peut jouer avec l'i., on peut jouer + avec l'a., on peut l'attaquer doucement ou fort, rapport entre la sollicitation et le rendu, réagir vite (i), réaction, réceptif (i.), répondre (c.), réponse à la sollicitation, plénitude (s.), tout fonctionne bien, sonner, varier l'a., vivant/vivre (i.)

**Meaning "B" (-):** banal, mou (cl.)

RÉACTION À L'ATTAQUE

**Meaning "A" (+):** a., dépassement (b.), donner de l'élan, dynamique, égalité de force dans les d. ⇒ égalité de n., élégance, faire sortir des n. juste avec le toucher, faire sortir des n. particulières, h. douce (jouer des n. faibles) et tonique (développer plus d'ha.), immédiat (s.), italien, marcher (n.), n. répétées en changement de d. (différence de s.), on a à peine besoin de toucher et on a exactement tout de suite ce qu'on entend, passer (ornements), plénitude (s.), pression, position/hauteur de d. qui joue, rapidité de réflexe des sa., réaction / réagir / réactif (a., d., cl., s., i., b.), registre + rentré, répondre (n., i.), revenir (languette), se relever (n.), sensation au bout du doigt, sonne bien (i.), le s. prend, le s. sort, tout fonctionne bien, vigueur (b.), XVIIe siècle

**Meaning "B" (-):** certaines n. un peu fortes, il faut rester près du cl., il faut rester collé au cl., on peut donner - d'élan, mou (i., cl.), le s. ne prend pas, problème au niveau de la répétition, se dérobe sous les doigts (i.), ne sonne pas du tout (i.)

HOMOGÈNE

ÉGAL

**Meaning "A" (+):** agréable sur toute l'étendue, égal/égalité sur toute la tessiture (cl., d., to., enfoncement, force, n.), également élégant sur l'ensemble du clavier, égalité de force dans les d. ⇒ égalité de n., équilibré/équilibre, fonctionne sur toute l'étendue, gradatif (le passage entre b. forts et faibles est progressif), bien harmonisé, harmonisé régulièrement (i.), homogène (i., s.), intéressant sur toute l'étendue, plaisir, qualité de bois, bonne réaction à l'a., réglage (cl., b.), sensation régulière (cl.), beau s. sur toute l'étendue, beaux graves qui sonnent bien jusqu'en bas, toutes les tessitures sonnent bien, uniforme

**Meaning "B" (-):** a des qualités et des défauts (i.), certaines n. + dures, différence de timbre, certaines n. disparaissent, certaines n. faiblardes, certaines n. + fortes, gros écart (entre 2 b. adjacents faible et fort), il faut éviter les n. et zones vilaines, inégal (i.), inhomogène (s., résonance), certaines n. pas jolies, un peu longs (b.), manque dans une tessiture, inégal (t.), certaines n. perdues, problème, certaines n. raides, ne redescend pas (b.), certaines n. répètent - bien, certaines n. ressortent trop, tessitures plus heureuses que d'autres

ÉVOLUTION

**Meaning "A" (+):** aigu léger, arriver à faire des plans (dans le contrepoint), chaque n. a son caractère, chaque n. a + de personnalité, évolution de la réponse en fonction des tessitures, évolution vers l'aigu, faire entendre la polyphonie, faire entendre les voix, grave dur, h. douce (jouer des n. faibles) et tonique (développer plus d'ha.), inégal/inégalité (h.), inégalité (h.) intéressante, ouvert (s.), progressivement de + en + léger du grave à l'aigu, qualité, + résistant dans les graves que dans l'aigu, vivant

**Meaning "B" (-):** égal, uniforme

V2 respectively V1 because they *get used to the instrument*, or *learn how to play with the instrument*).

### 3.3. Evaluation of each voicing

Once all words, and consequently all evaluations have been organised in semantic categories, these evaluations have to be reallocated to each voicing. This last stage of the analysis of verbalisations was conducted in the following order:

1. Go back to the verbal descriptions and evaluations of harpsichord, sound and touch extracted from the raw transcriptions at the beginning of the analysis;

2. Arrange them according to the semantic categories identified through the linguistic analysis. In order to avoid the effects of polysemy leading to assign a sentence to the wrong meaning associated with the contained word, the assignment of each sentence/description is made according to the information

Table II. Continuation II.

| DESCRIPTEURS DU SON |
|---|
| CLAIR<br>**Meaning "A" (+):** clair (s., i.), avoir du mal avec le legato (s.), donne envie de jouer, entendre les n. séparées dans les accords, fort, joli, présence, s'éclaire, s. du clavecin comme une succession d'attaques, transparent<br>**Meaning "B" (-):** accord qui résonne de façon globale, bas-médium, confus (s.), nasal (s.)<br>ROND<br>**Meaning "A" (+):** attachant, beau, beaucoup d'ha., belle (a.), belle fondamentale, caractère, chaleur/chaleureux (s.), doux (s.), écho, équilibré/équilibre (s.), étouffer doucement (étouffoir), être confortable (m.), façon dont le s. se développe, faible (s.), flexible, généreux / générosité, ha. de 5te qui reste, ha., humain (s.), jouer + (jeu), jeu calme, laisser sonner les notes (jeu), laiton (c.), liaisons/lier, magnifique, meilleur, moelleux (s.), naturel à faire chanter, n. liées, passer (ha.), prendre aux tripes (i.), profond/profondeur (s.), qualité de s., résonance, rond/rondeur (s.), se déployer (ha.), s'être habitué au cl., sensation de 2nd cl., sombre, sonne bien, sonne longtemps, tout petit decrescendo avant d'éteindre le s., type de jeu dans la résonance<br>**Meaning "B" (-):** a. dentale, avoir du mal à faire chanter l'i., basique (i.), brillance/brillant, clavecin d'étude, contraint (s.), mal tendue (c.), en acier (s.), creux (s.), détacher les n., fort, pas d'ha., - d'ha., jouer des choses sèches, jouer des choses virtuoses, machine, mécanique, mort (s.), neuf (i.), plat (s.), précis (s.), ne ressemble pas aux autres (b.), stérile, uniforme (s., i.) |
| HARMONISATION, RÉGLAGE |
| TECHNIQUE<br>**Meaning "A" (+):** affiner (b.), changer (i.), changer (sa.), choisir (b.), chercher (s.), confortable/confort, course (sa.), découper (b.), distance entre les 2 a., durcir (b.), égal sur tout le cl., épaisseur (b.), faire parler (i.), fin (b., point de pincement), + fort, garde, h./harmoniser, hauteur (sa.), super important, jouer avec le b., large (point de pincement), lien mécanique entre les d. et la production du s., longueur (b.), opérations sur sa., b., optimiser l'i. (donner le meilleur au s. et au cl.), réaction (i.), redescendre (b.), régler/réglage (cl., b.), répétition, bien repasser (b.), revenir (b.), son (i.), tailler / taille (b.), tissu dans le chapiteau, transformer (i.) balance, contact d./t., équilibrer (cl.), évider (sous la t., les t. par devant), évider les t. par devant, équilibre, équilibre entre ce que l'i. dégage et les sensations du cl., lieu de la pointe de balance, mettre des plombs, placer la balance, qualité du cl.<br>REVENIR, REPASSER<br>**Meaning "A" (+):** adaptation à l'i. (jeu), articuler (+) (jeu), détendu dans la main, devoir vraiment agir pour que l'i. joue, dur (b.), égalité/égal, être actif (m.), fonctionner (ornements), fort (i.), h., jouer avec beaucoup de déplacements, jouer des sonates de Scarlatti, lâcher (b.), mettre de l'huile sur la plume, bien marcher (i.), obéir (b.), passer (ornements), passer (b., ornements), pouvoir continuer à triller, rebondir (sa.), repasser (b.), répéter/répétition/répétive (n., i.), répondre (n.), retour de t. pas trop rapide, résistance/ résistant/résister (cl., d., t.), revenir (n., sa., b.), s'adapter, se relever, bien travaillé (i.)<br>**Meaning "B" (-):** accrocher (d.), b. pas coupé exactement là où il faut, demande beaucoup de détente, doux, continuo, il faut être attentif aux ornements, il faut lâcher/remonter le d. pour que le b. passe complétement/remonte suffisamment, le sa. ne remonte pas, trop long (b.), molasson (n.), mou (b., t., pincement), ne pas répondre (i.), ne revient pas précisément et rapidement (languette), oblige à relever les d. pour être sûr que le sa. redescende bien, passe lentement (b.), petit cl. d'un deux-cl., problème (général, réglage, mécanique, ornements), quand on est - réactif (m.), le b. ne redescend pas, - de résistance (t., cl.), certaines n. répètent - bien, - de s., rester suspendus au-dessus de la c. (b.), pas bon équilibre (bord de la t., s.), ne retombe pas suffisamment vite (sa.) |

about the subject and the context. For example the two descriptions using the word "hollow" discussed above are put in different categories "I have the impression that it has more sound than a bit earlier, it is not the hollow sound of earlier" (S2V2) belongs to the category LOUD, whereas "it was less hollow than before [...] it is rounder, more generous" (S2V2) belongs to the category ROUND;

3. Arrange them according to the voicing (V1 or V2) that was played when the evaluation was uttered;
4. Define and label "comparative" evaluations, within which the subject explicitly compares both phases of the test, *e.g. the harpsichord has less dynamics than previously* (S5V1);
5. Define and label "absolute" evaluations: evaluations within which the subject explicitely tells that she/he is talking about a general feature of the harpsichord, or evaluations within which no comparison between these two phases is possible (typically during the first phase of the test), *e.g. the instrument has a certain brightness* (S8V1, V1 was indeed the first voicing presented to S8);

Table III. Perceptual evaluation of Voicing V1, sorted by semantic category and subcategory. For each voicing and each type of evaluation (comparative or absolute), the columns "+", "=", "≠" and "−" summarises the number of subjects (and total number of evaluations in parentheses) having produced the corresponding evaluation. In the columns "Subject & occ." the subjects (followed by number of evaluations in parentheses) contributing to these numbers in the columns indicated by +, =, ≠ and −, respectively, are separated by dashes.

| | | Comparative evaluation | | | | | Absolute evaluation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | Subcategory | + | = | ≠ | − | Subject & occ. | + | = | ≠ | - | Subject & occ. |
| LOUD / HARD / STRONG | SOUND | 3(11) | | | | S2(2), S3(8), S7(1) | | | | 1(2) | S6(2) |
| | PLECTRUM | 2(7) | | | | S2(3), S3(4) | | | | 1(3) | S6(3) |
| | VOICING | 2(6) | | | | S3(3), S5(3) | | | | 1(1) | S6(1) |
| LENGTH / RESONANCE | | 2(9) | 1(4) | | 1(8) | S1(1), S7(8)–S5(4)–S5(8) | 2(2) | | | 2(3) | S2(1), S8(1)–S2(2), S7(1) |
| ATTACK | DYNAMICS | 1(2) | | | 1(6) | S7(2)–S5(6) | 2(2) | | | 2(3) | S4(1), S7(1)–S6(1), S7(2) |
| | GOOD BALANCE ATTACK / RESONANCE | | | | 1(11) | S5(11) | | | | | |
| HOMOGENEOUS | EQUALITY | 1(2) | | 1(1) | 1(1) | S3(2)–S3(1)–S5(1) | 2(5) | | | 1(1) | S4(3), S6(2)–S4(1) |
| | EVOLUTION | | | | | | 3(5) | | | 1(1) | S4(1), S6(1), S8(3)–S2(1) |
| DESCRIPTORS OF SOUND | ROUND | 1(9) | | | | S7(9) | | | | 2(1) | S7(1), S8(1) |
| | CLEAR | 1(2) | | | | S6(2) | | | | | |
| VOICING, SETUP | TECHNIQUE | | | 1(1) | | S3(1) | | | | | |
| | COME BACK (DOWN) | 2(3) | | | 2(3) | S1(1), S3(2)–S1(2), S5(1) | 1(2) | | | 3(15) | S8(2)–S4(9), S5(1), S6(5) |

6. In line with [26], define "positive" (+) evaluations[3], using:
   - either a quasi-synonym (called a "positive" word in [26]) of the label of a given category or subcategory within an affirmative sentence, *e.g. it has a beautiful fundamental* (S1V2),
   - or a quasi-antonym (called a "negative" word in [26]) within a negative sentence *e.g. the sound is not as hollow as it was before* (S7V1)
7. Still in line with [26], define a negative (-) evaluation, using:
   - either a quasi-synonym within a negative sentence, *e.g. it is not generous* (S7V2),
   - or a quasi-antonym within an affirmative sentence, *e.g. the sound is hollow* (S7V2).
8. Simplify and convert each positive evaluation to a positive unit "+1", and each negative evaluation to a negative unit "−1";
9. Sum all positive evaluations on the one hand, and negative evaluations on the other hand, for each category/subcategory and each voicing, keeping absolute and comparative evaluations separated, and keeping track of the subjects and the number of occurrences.

Note that keeping track of the context and subject for each description prevents us from incrementing or decrementing the wrong category in case of words belonging to several categories.

Table III presents the outcome of this analysis method as a summary of evaluations produced on each of the two voicings. Again, note that "+", "=", "≠" or "−" judgements presented in Table III are in no case quality evaluations or preferences. They summarise how V1 and V2 differ according to each semantic category. Note also that some semantic category identified in Table I do not appear in Table III because no evaluation was produced by the

[3] Note the words "positive" and "negative" as defined here have a purely algebraic meaning and are by no means value judgements from the experimenters. The namings "positive" and "negative" have been arbitrary chosen in order to make the analysis easier, and they could be reversed.

Table III. Continuation for Voicing V2.

| | | Comparative evaluation | | | | | Absolute evaluation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | Subcategory | + | = | ≠ | − | Subject & occ. | + | = | ≠ | - | Subject & occ. |
| Loud / hard / strong | Sound | | | | 2(12) | S2(11), S4(1) | | | | 2(2) | S3(1), S4(1) |
| | Plectrum | | | | 3(9) | S2(1), S4(7), S8(1) | | | | | |
| | Voicing | | | | | | | | | | |
| Length / resonance | | 5(9) | | | | S2(5), S3(1), S5(1), S6(1), S7(1) | | | | | |
| Attack | Dynamics | 4(10) | | | | S2(2), S3(1), S5(4), S6(3) | | | | | |
| | Good balance attack / resonance | | | | | | | | | | |
| Homogeneous | Equality | | 1(1) | | 2(2) | S4(1)–S4(1), S6(1) | 4(10) | | | 1(1) | S1(5), S3(1), S4(1), S5(3)–S2(1) |
| | Evolution | 4(10) | 1(1) | | 1(1) | S1(1), S2(7), S4(1), S8(1)–S8(1)–S7(1) | | | | | |
| Descriptors of sound | Round | 1(7) | | | | S2(7) | 1(3) | | | 1(11) | S1(3)–S7(11) |
| | Clear | | | | 1(4) | S6(4) | | | | | |
| Voicing, setup | Technique | | | 2(2) | | S2(1), S8(1) | | | | | |
| | Come back (down) | 2(4) | | | 3(8) | S4(2), S6(2)–S2(2), S4(5), S5(1) | 3(6) | | | | S1(1), S3(4), S4(1) |

subjects according to the perceptual concepts described by these semantic categories.

## 4. Results

This section gives a summary and discusses the evaluations of each voicing presented in Table III.

*Category LOUD/HARD/STRONG*

- SOUND In comparative evaluations V1 is perceived as *louder* than V2. However, in absolute evaluations both V1 and V2 are evaluated as not loud generally speaking: *maybe we would need a harpsichord a bit louder — FR. il faudrait peut-être un clavecin un tout petit peu plus sonore* (S3V2, first phase)
- PLECTRUM In comparative evaluations plectra of V1 are perceived as *harder* than plectra of V2. Only 1 subject (S6) gave an absolute evaluation of the hardness of the plectra, which is found to be too soft in general: *One could imagine making the plectra slightly harder — FR. On pourrait imaginer de faire que les becs soient légèrement plus durs* (S6V1, first phase);
- VOICING During the playing of V1, V1 and V2 were compared by two subjects, and V1 was perceived as stronger than V2. Just like for the hardness of the plectra, only S6 evaluated this aspect in general (absolute evaluations), finding that the voicing was not strong enough: *One could voice this instrument stronger — FR. C'est un instrument qu'on pourrait harmoniser un peu plus fort* (S6V1, first phase).

Note that the "negative" absolute evaluations of the "loudness", "hardness" or "strength" are explained by the subjects themselves saying that the harpsichord of this study is a practice instrument, which has *only one string per key* (S6V1).

*Category LENGTH/RESONANCE* When playing V2, five out of 8 subjects (62.5%) agreed that notes produced by V2 have a better resonance, with *longer notes* (S2V2) than notes produced by V1. Comparative evaluations produced when playing V1 show a more unclear tendency, with V1 sometimes found as more resonant, sometimes less resonant, and sometimes as resonant as V2. No consensus is identified in absolute evaluations of the length/resonance.

*Category ATTACK*

- DYNAMICS While comparative evaluations produced when playing V1 do not show any consensus, one can observe that when playing V2 and comparing it with V1 subjects found that V2 has more dynamics than V1: *One really can make some notes stand out from others just with the fingers [...] a voicing which is soft enough to get weaker notes, but lively enough to respond when one wants a particular string to react — FR. On arrive vraiment à faire sortir des notes particulières juste avec le toucher [...] une harmonisation qui est suffisamment douce pour laisser des notes faibles, mais suffisamment tonique pour que quand on veut faire réagir une corde, ça réponde* (S5V2). No consensus is identified in absolute evaluations of the dynamics (only produced when playing V1);
- GOOD BALANCE ATTACK/RESONANCE S5 defined the *balance between attack and resonance* as a criterion relevant to him for discriminating V2 from V1 in comparative evaluations (the balance is more in favour of the attack for V1): *The attack is sufficiently present so that the halo of resonance is more difficult to hear afterwards — FR. L'attaque est suffisamment plus présente pour qu'on entende moins le halo de résonance après* (S5V1). This is quite in agreement with the comparative evaluations of length/resonance discussed above showing that V2 is perceived as producing *longer notes* (S2V2).

*Category HOMOGENEOUS*

- EQUALITY In comparative evaluations, three subjects found V1 better than V2 with respect to the achievement of equality between adjacent notes, and only 1 subject gave an opposite evaluation. Significantly more positive evaluation are produced in absolute evaluations, showing that subjects appear to appreciate the equality of sound and touch in this harpsichord in general;
- EVOLUTION In comparative evaluations, four subjects agree to tell that the evolution of sound and touch over the whole tessitura of the harpsichord is better achieved with V2. Absolute evaluations tend to show however that this evolution is appreciated in general on this harpsichord.

*Category DESCRIPTORS OF SOUND*

- ROUND Only two subjects made a direct comparison between V1 and V2 according to the *roundness*, each one finding a different voicing as the producing the *rounder* sounds. This indicates that ROUND is unlikely to be a relevant parameter for discriminating V1 from V2. Two subjects gave absolute evaluations when playing V1, which turned out to be negative: *The instrument has some brightness — FR. L'instrument a une brillance* (S8V1); while absolute evaluations produced by two subjects when playing V2 were more contrasted;
- CLEAR In comparative evaluations, S6 opposed a *muddled* (*a chord that resonates globally — FR. un accord qui résonne de faÃğon globale*) for V2 to a *clear* sound *[when playing chords] one really hears the notes more separated from one another — [dans les accords] on entendait vraiment les notes plus séparées* for V1.

*Category VOICING, SETUP*

- TECHNIQUE Although all subjects were able to hear and feel differences between the two voicings, three subjects explicitely told that the voicing (or the *setup — FR. réglage* of the plectra, keyboard or jacks) changed between the two phases of the test: *the registers have been changed — FR. les registres ont été changés* (S2V2) / *this is not the same key depression — FR. ce n'est pas le même enfoncement* (S8V2) / *I have the feeling of a register that has been brought forward — FR. j'ai l'impression d'un registre avancé* (S3V1);
- COME BACK (DOWN) There is clearly no consensus about the evaluations of this criterion, whether they are comparative or absolute: each of the voicings exhibited keys with repetition (trills) or note trigerring problems (these keys were not the same for the two voicings and not even the same for all subjects).

It can be observed in Table III that some subjects gave both "+" and "−" evaluations in a similar context (semantic category and voicing), *e.g.* S2 in absolute evaluation of LENGTH / RESONANCE for V1. These variations in the evaluations illustrate the difficulty of a multimodal evaluation of complex objects (musical instruments), including the use of short-term memory of audio-tactile stimuli, and the fact that musicians are adapting to the instrument throughout the task.

*Summary of the perceptive description of the voicings*
The differences between V1 and V2, identified through comparative evaluations, can be summarised as follows:

- Sounds produced by V1 are perceived as louder than sounds produced by V2 (4 subjects agree — 50%);
- Plectra of V1 are perceived as harder than plectra of V2 (4 subjects agree — 50%);
- Voicing V1 is perceived as stronger than voicing V2 (2 subjects agree — 25%);
- Sounds produced by V2 are perceived as more resonant than sounds produced by V1 (4 subjects agree, 2 disagree — respectively 50 and 25%);
- V2 gives more dynamics than V1 (4 subjects agree, 1 disagrees — respectively 50 and 12.5%);
- The equality of sound and touch is better with V1 3 subjects agree, 1 disagrees — respectively 37.5 and 12.5%);
- The evolution of sound and touch over the whole tessitura is better with V1 (4 subjects agree, 1 disagrees — respectively 50 and 12.5%);
- One subject perceived that V1 produces clearer sounds than V2 (12.5%).

In Section 5, physical descriptors are computed on recorded sounds for comparison with this perceptive description.

## 5. Physical descriptors

Four physical descriptors of the mechanical response and sound of the harpsichord were computed for the two voicings, as defined below in Section 5.1. The minimum triggering force was measured for each key as described in Section 2.5. The equivalent sound level, spectral centroid, and decay time T10 were computed on the recordings of isolated notes described in Section 2.5. These descriptors might be sensitive to the noise proportion and (*e.g.* the spectral centroid takes higher values for lower signal-to-noise ratio, or SNR). In order to insure a high SNR, for the isolated notes the physical descriptors were computed on a 2-s long portion starting 0.5 s after the time at which the signal reaches its maximum value, allowing us to get rid of the noises occurring during the attack of the noise, in particular the jack hitting the jack rail.

In addition, the equivalent sound levels were computed for the recorded musical excerpts described in Section 2.4.

### 5.1. Definitions

*The minimum triggering force* is defined as in Section 2.5, as the minimum force exerted on each key needed to trigger the corresponding note. It is directly read on the apparatus shown in Figure 2. Note that the minimum triggering force is expressed in grams in this article, in line with the tradition of expressing "touch weight" in pianos in grams (the mass needed to lower a piano key to bottom position). This descriptor is aimed to be compared to the evaluations in category HARD / LOUD / STRONG.

*The equivalent sound level $L_{eq}$* is defined as the sound level computed from the squared pressure signal $p(t)$ of a microphone:

$$L_{eq} = 10 \log_{10}\left(\frac{1}{T}\int_{t=0}^{+\infty}\frac{p^2(t)\mathrm{d}t}{p_{\mathrm{ref}}^2}\right), \tag{1}$$

where $T$ is the duration of the signal. The equivalent sound level is weighted here with the A-scale in order to be closer to the human perception of loudness. Filters (according to [34]) are applied onto the spectra of the pressure signals in order to use the A weighting scale. The pressure signals actually used for the computation of the equivalent level are the inverse Fourier transform of these weighted spectra. For the musical excerpts $L_{eq}$ was computed across the durations of the entire musical excerpts, ranging between 9 and 31 s. This descriptor is aimed to be compared to the evaluations in category HARD / LOUD / STRONG.

*The spectral centroid SC* or centre of gravity of the spectrum [35], is computed from the discrete spectrum of the pressure signal as:

$$SC = \frac{\sum_{k=1}^{N} f_k a_k}{a_k}, \tag{2}$$

where $f_k$ and $a_k$ are respectively the frequency of bin k and its amplitude. It was observed that noise dominates the spectrum above 14 000 Hz. Hence the spectrum of each analysed signal portion was trimmed above this frequency, in order to insure that the spectral centroid accounts for the harmonic signal only. This basic descriptor of timbre is known to correlate with perceived brightness [39, 40]. It may also give information of variation in timbre between consecutive notes (possibly linked to the semantic category EQUALITY).

*The decay time T10* is computed from the energy decay curve EDC. The EDC is defined as [36]:

$$\mathrm{EDC}(t) = \int_0^t p^2(\tau)\,\mathrm{d}\tau, \tag{3}$$

where time $t = 0$ is the starting time of the 2-s long signal. EDC($t$) gives the remaning energy in the signal at time $t$. A linear regression of the EDC is then computed, from which the decay time T10 derives [37]. The T10 is defined as the time needed by the linear regression on the EDC to decrease by an amount of 10 dB from its maximum level. The T10 is intended to take into account the "sound duration" aspect of the category LENGTH/RESONANCE. It is expected that different voicings provide different string excitation and consequently change the balance between the horizontal and vertical components of the string vibration, which couple differently with the soundboard. Therefore the voicing has a possible influence on the decay time.

### 5.2. Isolated notes

Figure 3a presents the mean of each series of 5 measurements (main curves), as well as the expanded uncertainty, or 95% confidence interval as $U = 2\sigma/\sqrt{5}$ (vertical bars). Note that these vertical bar sometimes are hardly visible, *e.g.* for the equivalent sound level, indicating a very small uncertainty).

#### 5.2.1. Minimum triggering force

Figure 3a plots the minimum triggering force for each note of each voicing. The force curve shows pronounced peaks and valleys between adjacent notes in the bass notes with differences of up to 50 g (between C2 and C#2 for V2). However, no clear and systematic difference in the minimum triggering force is seen for bass notes (notes below C3 approximately). Differences however appear and become clearly visible (differences of about 5 to 10 g, larger than the largest measured uncertainty of 2 or 3 g) for notes above C3: notes of V1 need a force up to 20 g higher than notes of V2 to trigger the note (F2, G2, C#3, F#3, Eb5). This higher measured minimum force for V1 matches very well the perceptual evaluations indicating that voicing V1 is *stronger* with *harder* plectra. The irregular shape of the curves may indicate a certain level of *unequality* (meaning "B" in the category HOMOGENEOUS/EQUALITY) between adjacent notes, that is marked changes in loudness or sound quality between one note and the adjacent one.

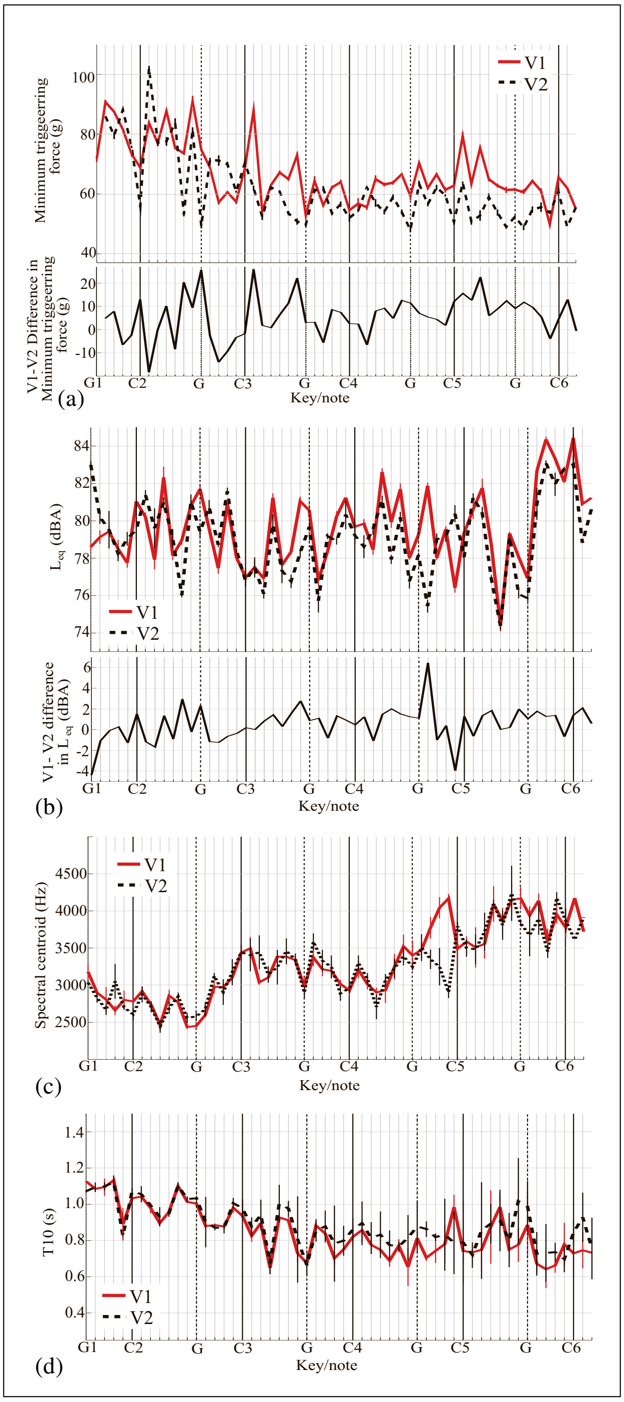


Figure 3. Physical descriptors measured and computed for each note of each of the two voicings (mean of 5 measurements). A solid red line is used for V1, a dashed black line is used for V2. Vertical bars denote the uncertainty as 95% confidence intervals. a) Minimum force required to trigger the plucking – lower panel shows the V1-V2 difference. Note that the force is expressed in kg in order to be consistent with the measurement protocol. b) Equivalent sound level (A-weighted) – lower panel shows the V1-V2 difference, c) Spectral centroid, d) Decay time T10.

### 5.2.2. Equivalent sound level

Figure 3b plots the equivalent sound level for each note of each voicing. It can be observed that notes played with V1 have a slight tendency to be louder than notes played with V2. The typical difference in sound level between the two voicings is 1 dB (uncertainty ranging from less than 1 dB(A) to 1.5 dB(A) for note A1 produced by voicing V2), which may be audible [41]. This difference can be as high as 6 dB(A) for G#4. This is in good agreement with the description of sounds produced with V1 described as *louder* than sounds produced with V2. Note that the shape of the sound level curve does not depend on the voicing but seems to be inherent in the instrument: different string/soundboard couplings may be responsible for sound level differences between adjacent notes. This is in line with results from the literature, *e.g.* [1] found that “In a harpsichord the energy input is fixed by the nature of the plucking mechanism. The loudness of the note is therefore determined by the efficiency with which string energy is transferred to the soundboard.”

Peaks and valleys of minimum triggering force (Figure 3a) and sound level (Figure 3b) do not correspond. This may indicate that they are independent on a physical basis, which is not in agreement with the perception. A possible conclusion is that the minimum triggering force alone is not sufficient to predict the equivalent sound level. The string excitation by the plectrum is indeed not a pure pluck but also depends on the jack velocity (not taken into account here), as modelled in [13] or measured in [38].

### 5.2.3. Spectral centroid

Figure 3c plots the spectral centroid for each note of each voicing. No clear difference is seen between V1 and V2 in terms of spectral centroid. This is consistent with Section 4 showing that no evaluation according to the category SOUND DESCRIPTOR is relevant for discriminating V1 from V2 in a playing context. Moreover Figure 3c shows that both V1 and V2 have an irregular spectral centroid curve, which does not highlight the perceived differences in EQUALITY (see Section 4). An exception can be seen in Figure 3c: SC increases by approximately 500 Hz for notes A4, Bb4 and B4 played by V1, while V2 shows the opposite tendency. However, these differences were not meaningful to the subjects, as none of them spoke about timbre differences between the two voicings for these three notes.

### 5.2.4. Decay time

Figure 3d plots the decay time T10 for each note of each voicing. A tendency for notes played with V2 to have a slightly longer T10 than notes played with V1 can be seen. However, overlapping uncertainty bars indicate that the two voicings don’t really differ in terms of decay time. This is in line with the perceptual description summarised in Section 4 stating that sounds produced with V2 resonate more than sounds produced with V1. Figure 4 shows typical decay curves computed for all Gs on the keyboard and for each voicing. They are consistent with the computed T10, that is a curve decaying faster corresponds to a lower T10 value. However, no double-slope decay is identified that could have explained larger differences between the T10 of V1 and V2 (*e.g.* for G4 and G5). However, different strengths of string-soundboard coupling seem to appear, *e.g.* for D#3, showing a low T10 value and a high

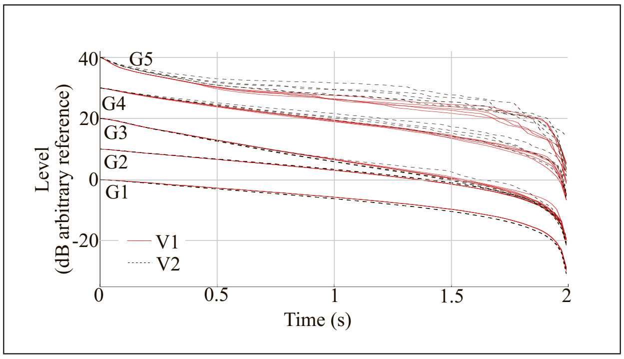


Figure 4. Typical computed decay curves for the note G in all five octaves on the keyboard, and each voicing. For each note, 5 repeats are shown. A 10-dB offset is used for each note for clarity.

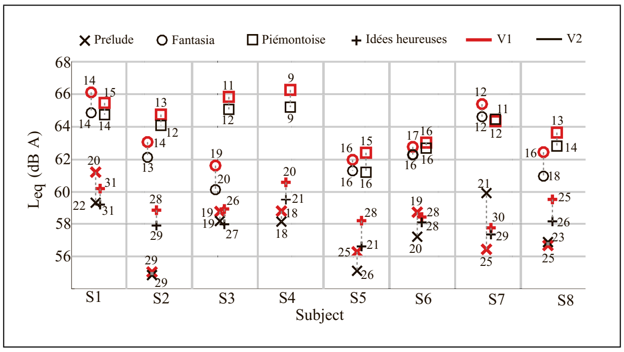


Figure 5. For each subject (x axis), equivalent sound level (A-weighted) computed on each of the whole musical excerpts (various markers). Thick red markers are used for V1, thin black markers for V2. In order to make the figure easier to read, gray dashed lines join together the recordings on each voicing for a given subject and a given musical excerpt. Each equivalent sound level is obtained by averaging the results from the left and right microphones. Numbers attached to each marker denote the duration of the excerpts, in seconds.

$L_{eq}$, or E5 with a high T10 and low $L_{eq}$. These two cases may illustrate a cases of strong and weak coupling, respectively.

### 5.3. Musical context

The $L_{eq}$ values computed on the whole musical excerpts (Figure 5) show large differences covering a span of more than 10 dB. The explanation is a combination of differences between the character and duration of the musical excerpts, the performances by the eight subjects[4], and between the voicings. The musical excerpt is the first explanation for equivalent sound level differences: *Prélude*, played freely with lots of breaks and slow arpeggios, necessarily exhibits lower equivalent sound levels than *Piémontoise* energically played with struck chords. A dense polyphony gives *Idées heureuses* (and to a lesser extent *Fantasia*) an intermediary equivalent sound level. Between-excerpt sound level difference can be as high as ~9 dB(A) (between *Prélude* and *Piémontoise* for S2 and both voicings). Closely related to the character of the excerpt is the duration of the excerpt performance (inversely related to tempo), shown as numbers attached to the markers in Figure 5. This duration decreases the equivalent sound level: slower performances give more space to note decays, which are necessarily softer and therefore lower the overall sound levels. This is confirmed for 3 out of 4 musical excerpts by the correlation coefficient between the duration and the sound level: R=-0.83 for *Fantasia*, R=-0.88 for *Idées heureuses*, R=-0.87 for *Piémontoise* (this is not clear for *Prélude*, where R=-0.26).

A second explanation for differences in the equivalent sound level is the player: S3 and S7 produced the loudest excerpts, whereas S5 produced the softest ones. Between-subject sound level difference can be as high as ~4 dB(A) for excerpts of approximately the same duration (S1 and S2, *Prélude*, V2).

Third, it clearly appears that for a given excerpt and a given musician, V1 systematically produces louder equivalent sound levels. The only exception is *Prélude* played by S7 for which the $L_{eq}$ of V2 exceeds V1 by 3 dB(A). This excerpt was, however, played considerably faster than with V1 (21 s vs. 25 s). For all other performances V1 surpasses V2 by 1.5 to 2 dB(A) and might therefore be audible [41]: This measured sound level difference is in line with the perceptual description of Section 4 attributing to the sound of V1 a *higher volume*

## 6. Discussion

This section discusses methodological issues and proposes interpretations or solutions for further studies.

In average V1 was played 41±9 minutes and V2 was played 36±9 minutes, so no significant difference in playing time between the two voicings was observed. It can be observed also that the duration of the first phase of the test (45±7 minutes, playing of V1 or V2 for even-numbered or odd-numbered subjects respectively) was significantly longer than the duration of the second phase (32±5 minutes, playing of V2 or V1 for even-numbered or odd-numbered subjects respectively). This is natural since in the first part musicians also discover the harpsichord, the room, the instructions for the test, *etc.* This is in line with the verbal comments (see Section 3.3), which clearly show that the judgements given during the first phase are either focused on global, overall evaluations (of the harpsichord, the sound, *etc.* in general), whereas the judgements given during the second phase are rather focused on comparison and relative evaluations (*e.g.* on what changed since the previous phase?). As a result, even though the order of presentation of V1 and V2 was balanced across subjects, each subject produced asymmetric evaluations: either absolute for the first voicing presented, or comparative (the second with the first, not the contrary). Although it clearly makes the test much longer, further tests may consider a 3-way protocol, presenting again the first voicing at the end of the test.

[4] S4 did not play *Fantasia*.

The equivalent sound level for the musical excerpts may be influenced by short peak values (*e.g.* shock noises). As a consequence, higher equivalent sound levels can be attained with louder notes in general but also with more and/or louder peak values, such as single, strongly accented notes, or loud shock noises caused by the depression of the key. As previously highlighted by [23], for higher jack velocities or more dynamic playing, the noise of the jack hitting the jack rail can become audible. This noise was indeed recorded and, according to the verbalisations, perceived by the subjects. This noise may have increased the sound level, in particular in more vigorous musical pieces such as *Piémontoise* and *Fantasia*. However, it can be argued that this noise is part of the sound of the harpsichord, that the jack rail remained unchanged, and that all jacks were identical. This makes the comparisons of and conclusions about sound level still relevant. Another remark to be made here is inspired by [44]: as the jack hits the jack rails, the whole structure of the harpsichord gets excited independently of the excitation provided by the string. As a result, there is more vibration energy to be radiated by the instrument, hence the sound level may be further increased.

Given the larger consensus about the LOUD, HARD and STRONG perceptual aspects, and in view of the support of these perceptual results by the measurements of equivalent sound level and minimum triggering force, one can suppose that differences in loudness and voicing/plectrum strength are the most striking ones. Furthermore, they may have masked other differences. Further tests should now concentrate on other aspects, producing and investigating set of plectra with constant strength and hardness.

However, the audio descriptors of the playing task are computed from recordings made by two almost orthogonal microphones quite close to the soundboard. Because the sounds were also aimed at being used for outreach activities or listening tests, we discarded other recording solutions such as microphone arrays or far-field recordings, though they might have helped getting rid of *e.g.* directivity issues and getting smoother curves for the audio descriptors. Conversely, the audio recordings made on the isolated notes made us very confident concerning the high-fidelity sound pressure rendering for precise measurement purposes, but their position (above the soundboard) do not reflect accurately what the players hear when playing the instrument: further studies have to address this point, combining the use of accurate measurement apparatus at locations consistent with the musicians' experience.

The strongest consensus obtained in the evaluations of a specific category was 50% of the subjects agreeing (no subject disagreeing). That result was obtained for two subcategories; V1 sounds louder than V2, and V1 plectra are harder than V2 plectra. The inter-subject consensus is clearly not as strong as it might be expected with a more guiding experimental method: If subjects had been asked to rate each voicing according to *e.g.* the "loudness" or the "roundness" of the sound, agreement could have been expected to be higher. However, such guided interviews with calibrated questionnaires can only be designed if we know in advance what criteria are relevant to the harpsichord players. In the absence of study aimed at identifying which criteria are evaluated by harpsichord players in a playing situation, only a free task was relevant. Further tests using guiding questions using the criteria identified in this study may give higher perceptual agreement.

An interesting result, with methodological consequences, is found about the relation between sound and touch. In this study, the experimental procedure (free playing task) was chosen in order to expose the subjects to both auditory and tactile stimulations. Results of this study showed that both aspects were evaluated (*e.g.* category SOUND DESCRIPTORS takes sonic aspects, category VOICING SETUP takes tactile aspects), and furthermore that sound and touch perception can be mixed up and, even more so, not easy to disentangle: subcategories LOUD, HARD and STRONG have many words in common. This clearly shows that the evaluation of sound and touch are not uncoupled (a result in line with evaluation tests of pianos [43]), and this validates the choice of the experimental procedure.

A final remark has to be made about the adaptation of a player to her/his instrument. In this study the musicians talked a lot about how they adapt and become used to the instrument they are given: for example *I have the impression that it sounds more. Maybe because I got used to the instrument and I am making it sound more* (S7V1); *I try to get to know the instrument and adapt to it, and make some music. The instrument is not giving me the inspiration at first, I already have something in mind, and [...] I am trying to make something beautiful.* (S8V1). It seems to be essential for a harpsichord player to be able to adapt quickly to an(y) instrument, because a) when on tour a harpsichord player usually plays a different instrument every day: *When there is a concert, we have a 1h30-sound check, so I come half an hour before in order to discover the instrument, because I never know what I will be given* (S4V2); b) there is no standard in harpsichord making: *We never have the instruments we wish, the harpsichord is not a standardised instrument like the piano, for which one is sure to find a Steinway* (S4V1) — French original wordings are given in Section A2. Further studies should investigate how the player adapts her/his way of playing to the instrument: this may give a valuable contribution in the field of musician/instrument interaction, and also give insights for studies of how one's mind changes when getting used to stimuli.

## 7. Conclusion

This article presented a perceptual study investigating the influence of different voicings on the sound and the touch of a harpsichord, from the musician's point of view. A blind, free playing and verbalisation task was proposed to 8 professional musicians asked to successively play the same harpsichord with two different sets of jacks. Linguistic tools were used to get to a perceptual description of each voicing. The importance of shaping plectra is confirmed, because it was shown that musicians perceived differences between the two voicings in terms of the following criteria, with various consensus strength: "loudness" of the resulting sound, "hardness" of the plectra and "strength" of the voicing (all in semantic category LOUD / HARD / STRONG), LENGTH / RESONANCE, DYNAMICS, EQUALITY between adjacent notes, and EVOLUTION of sound and touch over the whole tessitura of the instrument. Some physical descriptors give support to the perceptual evaluations, such as the minimum triggering force (in line with the perceived "strength" or "hardness"), and the equivalent sound level (in line with the perceived "loudness"). Now that it has been proved that these physical descriptors have a perceptual relevance, they may be used in the future to characterise and predict the sound and touch of harpsichords.

The criteria identified through the semantic analysis are not independent, showing that sound and touch perception can be strongly coupled. This suggests that, at least in the case of the harpsichord, active perceptual tasks such as playing tasks are well adapted to take into account the multimodal aspect of the musician's perception of her/his instrument.

No difference in spectral centroid was identified between the two voicings on isolated notes, and no difference in timbre was perceived or stated by the musicians in playing conditions, which shows a consistency between the perceptual and physical descriptions of the timbre.

Studies are underway using sensors of key depression and string displacement: a characterisation of the system key / jack / plectrum / string is expected, leading to explanations of the link between key velocity, plectrum shape and sound and touch, and of problems occuring when the key is released.

Another aspect of further work is the comparison of the perceptual descriptions of each of the voicings with mechanical and geometrical measurements that have been done on the same plectra [42].

## Appendix

### A1. Scores of the musical excerpts

Figures A1–A4 show the scores of the musical excerpts used in this investigation.

### A2. Original French wording of the sentences about adaptation

This section gves the original French wording of the sentence given as examples in Section 7 about the adaptation of the musician to her/his instrument:

- *J'ai l'impression que ça sonne plus. C'est peut-être aussi que je me suis habituée à l'instrument et que du coup c'est moi qui le fais plus sonner* (S7V1);

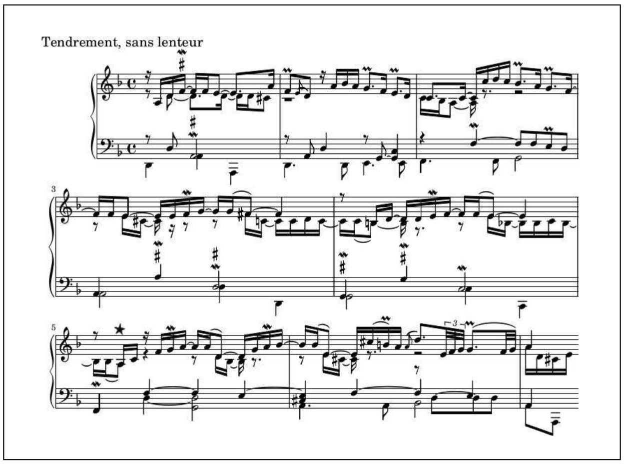


Figure A1. Score of the excerpt of "Idées heureuses" by François Couperin. The duration of the recordings of this piece is computed from the beginning until the note denoted by a star.

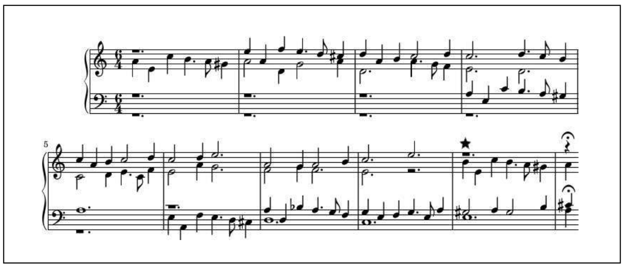

Figure A2. Score of the excerpt of the "Fantasia V" by Johannes Jakob Froberger. The duration of the recordings of this piece is computed from the beginning until the note denoted by a star.

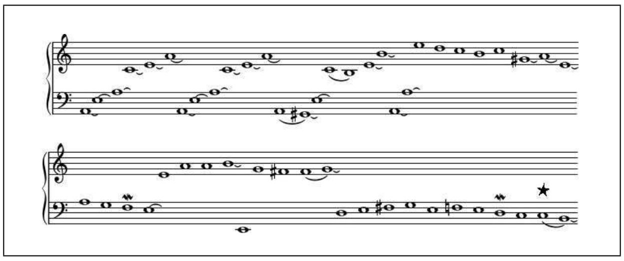

Figure A3. Score of the excerpt of the "Prélude en la mineur" by Louis Couperin. The duration of the recordings of this piece is computed from the beginning until the note denoted by a star.

Figure A4. Score of the excerpt of "Piémontoise" by Louis Couperin.

- *j'essaie de connaître et m'adapter à l'instrument, et faire de la musique. Ce n'est pas l'instrument au dé-*

*part qui va me donner l'inspiration, j'ai déjà quelque chose de conçu, et [. . . ] on va essayer de faire quelque chose de beau* (S8V1);
- *Quand on a un concert, on a un raccord d'1h30, donc moi je viens une demi-heure avant pour découvrir l'instrument, parce que je ne sais jamais sur quoi je vais tomber* (S4V2);
- *On n'a jamais les instruments qu'on voudrait, le clavecin ce n'est pas un instrument standardisé comme l'est le piano où on est sûr de trouver un Steinway* (S4V1).

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