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Ergotic Sounds: A New Way to Improve Playability, Believability and Presence of Virtual Musical Instruments

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Abstract

We explore how an 'ergotic gesture-sound situation' is a genuine way to improve the playability, believability and presence of virtual musical instruments. An ergotic gesture-sound situation is a situation where the instrumental gesture and the sound produced are intimately energetically linked. We perform two sets of experiments: the first aims at identifying the respective role of haptic and auditory perceptions in recognition of a virtual object, here a virtual bowed string; the second aims at evaluating the role of haptic and auditory perceptions with respect to action, in the achievement of a difficult musical task. The musical goal consists in maintaining the continuity of sound when changing bow direction. The first experiments are subjective experiments. They show that the feeling of presence of the bowed string is strongly reinforced when sounds and gestural friction are intimately linked, as is the case when the vibrations of the string are returned to the fingers. The second are subjective and objective experiments. They show that achieving the goal is significantly improved by instrumental force feedback. Further, they show that the main property of subjects' performance with the virtual bowed string is fast adaptive dynamic learning due to the physical relation between action plus gesture perception and auditory perception, and that playing and embodiment are notably improved by a strong physical haptic resistance.

1. Ergotic sounds

In a musical performance situation, it is useful to distinguish two types of relation between human gestures and the sound produced:

- Non-instrumental musical practices, like conducting, or when controlling synthetic musical parameters by mapping techniques (Figure 1) (Nichols, 2002; Hunt et al., 2003).
- Instrumental musical experience, like when an instrumentalist is playing a physical instrument (Figure 2).

In non-instrumental practices, there is no energetic exchange between the human gestures or body motor activity and the sound so controlled.

Conversely, in instrumental musical experience, the performer and the played object are physically coupled in a dynamic manner during playing. Essl and O'Modhrain (2006), and several authors quoted in their paper, insisted on the importance of tangibility in musical instrument design.

The sound produced traces the physical energy exchanged between the performer and the physical musical instrument. We employ the term 'ergotic sounds' to refer to 'ergotic relation to the sound' according to the typology of relations between humans and the environment proposed by Cadoz (1988), and Wanderley and Cadoz (2000).

As emphasized by O'Modhrain and Chafe (2000), we assume here that the experience of instrumental music in its elementary principles is an emblematic case of enaction. It exhibits the main features characterizing the enactive theory of cognition:

- The world without representation (Clark & Toribio, 1994): the representation of the instrumental situation can only be the situation itself.
- Cognitive shapes do not pre-exist (Enactive Interfaces, 2004): they emerge from the interaction with

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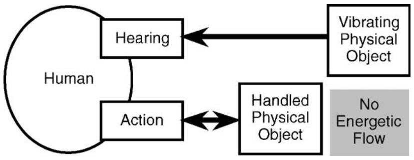


Fig 1. Non-ergotic relations to sound in musical practices.

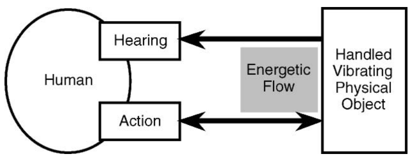


Fig. 2. Ergotic relations to sound in musical practices.

the environment: the means (musicality for ex.) emerge from the instrumental situation itself.

- Enactive knowledge (Pasquinelli, 2007) acquired during the experiment is a robust knowledge: the learning of the performance (the task) and of the musicality (cognitive category) emerging during the performance itself leads to a robust performance knowledge.

The role of energetic exchange between the instrumentalist and his/her instrument, or of the physical effort of the instrumentalist, is well recognized when playing mechanical musical instruments. In addition, there is a common acceptance of the lack of something in the interaction between musician and conventional digital musical instruments, at least until the arrival of force feedback interaction. We may assume that the ergotic relation to sound is an important feature for the playability, believability and presence of a musical instrument, which must be re-introduced in digital musical instruments.

However, we are confronted by a major obstacle in proving this common certainty, because of the difficulty of equipping a real mechanical situation with sensors without altering them. We may assume that virtual musical instruments may be a very new experimental set-up capable of contributing to knowledge of what happens during an 'ergotic instrumental situation'.

In the following, we describe first the implementation of a technical real-time platform and physically-based model of a virtual bowed string (cello or violin-like), to catch the main features of the ergotic musical situation. Second we describe a first qualitative experiment on the feelings of friction in a bowing gesture and third a second experiment, successive to the first one, aiming at eliciting the instrumental conditions for success in achieving a precise musical instrumental pattern. In each experiment, we analyse the results obtained in terms of feelings, object identification task successes, capability of learning, expressiveness and creative gestures.

2. The virtual cello-like experiment: Experimental set-up

2.1 The physical model of the bowed string

First of all, it is necessary to achieve an implementation of the ergotic relation to sound. Such an implementation should be different from an implementation based on the control-mapping concept, with or without gestural force feedback interaction. In the implementation of mapping concept (Figure 3), there is no modelled energetic consistency between the parameter-control part (composed of a gestural acquisition through sensors and a mapping process of the gestural inputs to the parameters of the computer sound synthesis process) and the sound-production part. The data flow between the two parts is unidirectional from the first part (gestural side at the top of Figure 3) to the second part (sound side at the bottom of Figure 3).

Equipped by force feedback gestural interaction (as in O'Modhrain & Chafe, 2000; Nichols, 2002; Rimell et al., 2002; Sinclair & Wanderley, 2007), the gesture side is improved by a local physical model to produce a force sent to the hand, but there is no bilateral interaction from the vibrating string to the manipulation part.

In the ergotic approach (Figure 4), we assume that even if the vibration of the string is not perceived explicitly by hand, the physical interaction from the string to the bow at the acoustical frequency of the string plays an important role in the bowing. Consequently, we must maintain a bilateral interaction, not only between the hand and the bow, but also between the bow and the string, in order to obtain a bilateral interaction between the hand and the string, and thus at the frequency of the string, i.e. without any implementation of signal-filtering.

The implementation of a virtual bowed string model, respecting the bilateral physical interaction all along the instrumental chain, between the hand and the bow and between the bow and the vibrating structure, is described in Florens (2002). As outlined in Figure 5, it exhibits:

- The two bilateral interactions between the bow and the vibrating string on the right side of the vertical line: (1) interaction for the transversal motion composed of a buffer interaction representing the collision and the pressure between the bow and the string and (2) interaction for the lateral motion that

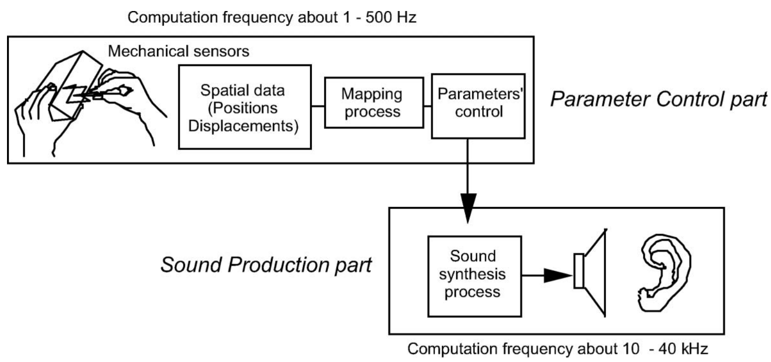


Fig. 3. Principle of the 'Mapping' process.

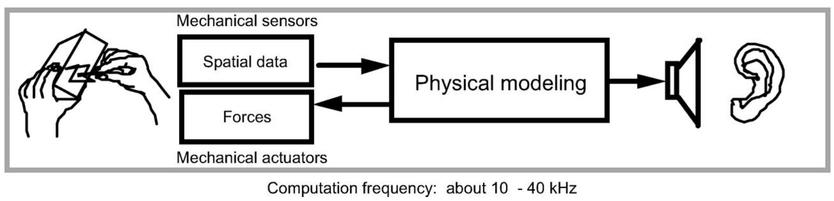


Fig. 4. Principle of the digital implementation of the 'Ergotic' process.

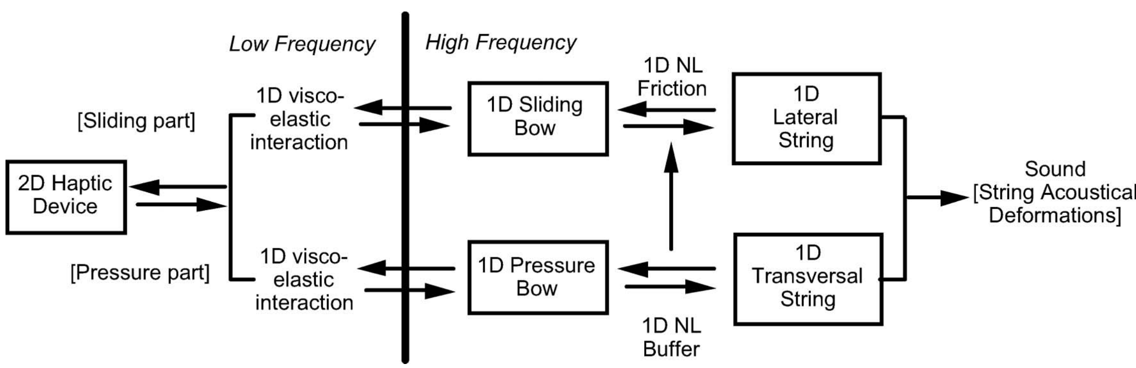


Fig. 5. The implemented physical model of the bowed string.

is friction interaction. These two interactions are coupled to satisfy a main characteristic of bowing: the friction law depends on the pressure, as shown in Figure 6.

- The bilateral interaction between the bow and the hand through a 2D force feedback device returning the pressure force and the friction force from the bow.

This implementation guarantees the 'ergoticity of the situation' as is the case in real mechanical instrumental playing: there is no break in the modelling of energetic consistency between the hand and the ear.

2.2 The high quality ERGOS experimental platform

The technical platform has to guarantee two constraints:

- real time simulation of the previous model,
- a sufficient quality to be sure that the main features of the real situation could be caught, or at least not biased too much by the system.

Implementations that do not guarantee physical reactivity at the level of the real system, such as those based on common existing architectures (Sinclair & Wanderley, 2007) cannot be exploited in such experimental evaluations.

Some years ago (Florens, 2002; Luciani et al., 2005), we developed the most reactive implementation based on a synchronous computer architecture and a high fidelity haptic ERGOS technology (Florens et al., 2004). In this implementation, the previous bowed-string model has been implemented with two coupled frequency loops: 3 kHz for the hand-bow loop and 44 kHz for the bow-string loop. Both the acoustical

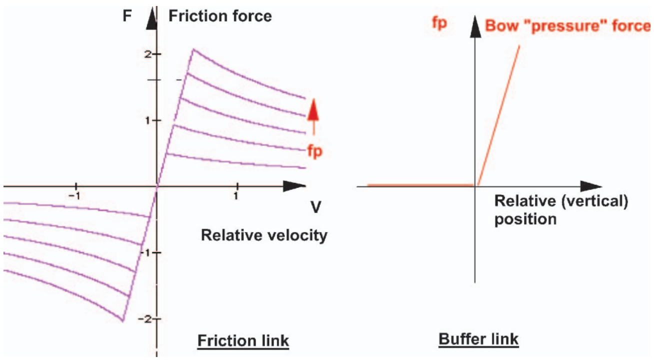


Fig. 6. Dependency between friction and pressure interaction.

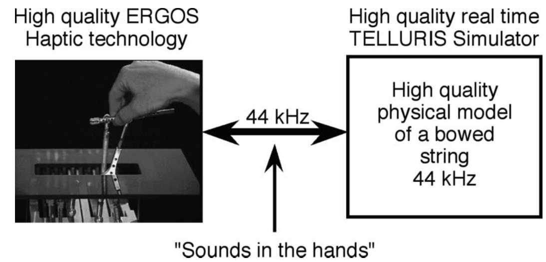


Fig. 7. Functional diagram of the high quality experimental ERGOS platform. The photograph on the left represents the bow-like force feedback device ERGOS.

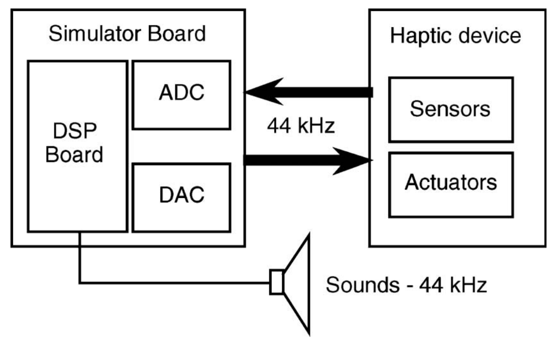


Fig. 8. Technical description of the platform.

results and the relation to the instrumental action were very impressive and have been tested several times by different users. However, we are not sure that the hand's sensitivity of the string does not play an important role, for example on the playability or on the cognitive or perceptual acceptance of this virtual instrumental situation, as it exists in the real mechanical situation. In other words, is the gestural sensation of the vibrating string important, even though it is filtered by the bow and by the mechanical human body, and if so why? Such a question has never been asked either in a real-life situation or in a virtual situation. But yet, the 'granularity' of the vibration in the fingers, which differs from the granularity of the rosin on the bow, is often noticed by instrumentalists. We assumed that, in order to test the role of the 'ergoticity', we had to find a way of experimenting with such a subtle feature: making possible the feeling of the vibrating string by the hand. Consequently, all the parts of the previous physical model have been implemented at the sampling rate of the sound, i.e. at 44 kHz (Figure 7).

To satisfy these requirements, the whole model has been implemented on a DSP board (Figure 8) directly connected to the force feedback ERGOS device (on the left on Figure 7) by high reactive DAC/ADC and the sound is directly produced on the Digital Signal Processing (DSP) board. The reactivity between input action and force feedback as well as between input action and sound are both of 1/44,000 ms, and are totally synchronous at that rate.

2.3 The experimental protocol: General conditions

The experimental protocol was composed of two successive experiments:

- Experiment 1 aims to evaluate the respective roles of sound and of friction sensations in the identification of a virtual object, here a virtual bowed string, and the playability of this object under various manipulation conditions. The subjects are invited to explore freely the virtual object by manipulating it through the ERGOS haptic device and to express freely their feelings and what they are perceiving. This experiment is also used to acquire the minimal know-how in manipulation of the system in order to be sufficiently dexterous for the second experiment.
- Experiment 2 consists of trying to perform a precise musical pattern, that is to maintain the continuity of sound while changing the bow direction.

Both experiments are performed with the same four simulations of bowed strings. The string is always the same and there are four cases of different simulated frictions:

F1: Null friction,
F2: Soft friction, lighter than the friction in the real case,
F3: Normal friction, close to the real case,
F4: Exaggerated friction, much higher than in the real case. Here, the bow can be stuck hard to the string.

Both experiments, 'experiment on friction feeling', and 'experiment on maintaining sound continuity', have been conducted on ten subjects (25 to 55 years old), four females and six males, six non-professional musicians (three total novices and three with a slight instrumentalist expertise) and four musicians. All the performances, performers' and audience comments were recorded in video and audio.

3. Experiment 1: Friction-sound feelings

3.1 Experimental protocol

Subjects were invited to bow the virtual string described in the previous paragraph by means of the ERGOS haptic devices in each of the four cases corresponding to the four values of friction (F1, F2, F3, F4). The experiment was composed of two successive situations:

- Situation 1: The subjects heard the sound produced by the virtual string.
- Situation 2: The subjects did not hear the sound produced by the virtual string.

Situation 2 started once situation 1 was performed by all the subjects.

During the first situation, the subjects were simply invited to express freely their feelings on what they were manipulating. During the second situation, they were invited to express freely their sensations by answering to the following questions:

> Question 1: 'How do you qualify what you are feeling (several answers are permitted)?'
> Question 2: 'According to you, what is the object you are manipulating (several answers, as well as doubts, are permitted)?'
> Question 3: 'Is the haptic feeling the same than in the previous situation? Describe freely the similarities and the differences'.

The manipulation is totally free both in the type of gestures and in the duration of playing, without constraints nor guidelines from the experimenter.

3.2 Results concerning the first situation 'bowing the string and hearing the sound'

First of all, all the subjects concluded unanimously that the manipulated object was undoubtedly a bowed string, even people who had never played bowed string instruments. The friction case F3 was considered unanimously as the most playable and for musicians, more playable than a real cello. One of them said explicitly: 'I remember on a cello, it is more difficult to produce the sound'. The friction case F4 was considered unanimously as the most unplayable: 'It is terrible', 'I cannot, it is impossible to play', 'Quite unplayable'. The friction cases F1 and F2 were considered similar by the subjects with respect to playability. Some of them preferred the first and some of them the second.

3.3 Results concerning the comparison between both situations: With and without hearing the sounds

The first major observation is a clear-cut difference between the two situations: in the second situation, nobody recognized a bowed string, although it was objectively exactly the same as in the first situation.

At the first question ('How do you qualify what you are feeling?'), the word often used has been 'roughness' instead of 'friction', unanimously used in situation 1. One person even said clearly 'It is not a friction, as it was in the first situation [when the sound was heard]. It is a roughness, or a rough surface'.

At the second question, 'what is the object you are manipulating?', while in the first situation, everybody believed strongly that they were playing a cello, in the second situation, when they did not hear the sounds, nobody *ever* evoked a bowed string, and everybody focused on other types of object. The subjects were surprised, astonished, perplexed. One of them, a confirmed musician, said nothing, raising eyebrows for each four cases, as if it was the first time he was confronted with such feelings or as if there is no object corresponding to such haptic sensations. Here are some expressions used by the subjects: 'It is like a rattle, more or less rough'; 'It is like a zipper'; 'It is like a toy car with crenulated wheels' and 'it is like the teeth of a comb while we move the finger over it'. One subject described the sensations as being like those of a 'cheese grater'.

At the third question, 'Is the haptic feeling in the second situation (without hearing the sound) the same than in the first situation with sound?', all of the subjects believed not. For example, one said 'it is impossible to recognize that it is the same bowed string', and another, for each of the fours value of friction (F1, F2, F3, F4) said 'it seems rougher without the sound than with sound'.

3.4 Results concerning the description of the haptic feelings

The second major observation is about the description of the haptic feelings: all the persons focused more on the description of their haptic sensations in the second situation (without hearing) than in the first situation (with hearing).

In the first situation, with sound, the descriptions are not very developed. Subjects compared only the playability according to the four different friction cases. Unanimously, the two medium cases (cases F2 and F3, corresponding to the soft and normal friction cases) are more playable than the fourth (exaggerated friction). For 50%, the first case (no friction) could be playable with more training.

Conversely, in the second case (without sound), the exploration and the description of the friction are more developed and more precise. Three persons related that the 'resistance is not the same all along the trajectory'.

Persons tried to quantify what they called 'the sticking effect', for example the fact that in cases F2 and F3 (smoother frictions) 'the duration of sticking is smaller than in the case F4' (hard friction), or 'when we move with a quite constant velocity, the impression is of a zipper, but when we accelerate, it seems more like white chalk on the blackboard', and 'when the accelerations are very short, we are disturbed', or 'the sticking distance is longer when the velocity is constant and it could be shorter when I regulate the velocity'.

All the subjects were surprised when we told them that the virtual objects were exactly the same in situation 2 as in situation 1. One person, who never played a bowed string instrument, said 'Sound is very very efficient to conclude quickly that it is a kind of violin'.

3.5 To conclude

Although the experiment was only qualitative, it was very fruitful as it revealed very different and clear-cut behaviours when there is the sound and when there is not.

With sound, the description of the nature of the friction and the exploration of its properties are very poor. We may conclude that haptic sensations are only ways to play but they are not the focus of perception. The fact that people do not recognize that the friction values are the same in the two situations of the experiment leads us to conclude that the friction sensation in a mechanical bowed string is not really known, even for musicians, neither explicitly nor implicitly. This means that we are not able to speak about friction 'in itself', without sounds, in real instruments, and that we probably are not used to 'putting specific words' to our haptic sensations when we are bowing an acoustical string. We can conclude that the cognitive pattern represented by the words 'bowed string' masks the perception of the friction itself, and it acts as a very strong cognitive attractor.

The fact that in all the friction cases (null, slight, normal and exaggerated frictions), all the subjects conclude that it is a bowed string, means that, when it is present, sound is predominant in object identification and that it influences the haptic sensations. If this result is confirmed in further more quantitative experiments, it would provide a useful comparison to results obtained in haptic-vision cooperation, in which most research suggests that the vision predominates over haptic sensations (Lécuyer, 2009).

4. Experiment 2: Maintaining sound continuity while changing bow direction

4.1 Objectives

The objective of the second experiment was to evaluate if the ergotic relation between sounds and action as discussed in the first paragraph is a better condition for acquiring instrumental musical ability. In other words, we wanted to evaluate the implications of the physical properties of the audio-haptic system constituted by the virtual bowed string, with respect to the ability of performers to perform an instrumental musical task.

The subjects who performed the task were the same as in Experiment 1. During that first experiment, they had gained a sufficient level of expertise to handle the system correctly. In the second experiment, the instrumental musical task they were invited to perform consisted of preserving the continuity of sound when the bowing direction is inverted. This task cannot be considered as a simple control of the instrument that would simply consist in performing precisely a pre-defined bow motion. Indeed, obtaining sound continuity all the time would require an accurate synchronization of the controlled movement with the oscillation cycle of the string. This implies that there is a strong correlation at each time between gestural action, haptic perception and auditory perception, each of them influencing permanently the others, as occurs in a dynamic closed-loop system. Accomplishment of the task therefore relies on a more complex scheme than a simple relation between auditory perception and gestural action. The hypothesis of the embodiment seems here more appropriate to characterize such a situation. In this perspective, the manipulated bow and the string constitute a whole dynamical system, the evolution of which the person has acquired the ability to control in the same manner as he/she has the ability to control his/her own body. This embodiment is intrinsically multimodal since it encompasses haptic interaction and sound generation with audio feedback.

The haptic and multi-sensorial simulation context described in Section 2 allows evaluation of this hypothesis by varying a parameter which controls the importance of the haptic feedback. The task requires the user to control accurately the correlation between the playing variables, in particular the bow speed, and the instant of motion inversion. In the case of higher physical interaction, the condition of embodiment—in the sense that the performer has to be 'within her/his instrument'—may be better realized than in the case of null or low force feedback (cases F1 and F2). Evaluating the influence of this parameter on the successful accomplishment of the task therefore brings elements of validation of the hypothesis.

Practically, this audio-haptic pattern presents five interesting properties. First, it articulates a 'musical constraint', that is the continuity of the sound, and a non-musical constraint, that is the necessity to change the direction of the movement due to the mechanical limitations of the instrument and of the gesture of the instrumentalist. Consequently, the chosen task is of a medium complexity, not very simple but not too complex. In addition, it is difficult to perform with real instruments on which it requires several years of practice. It is of course a very common task in bowed string playing.

Above all, accomplishment of the task is perceptually easily identified by the performer as well as by the audience and it is also objectively observable in the resultant signals. As shown in the snapshot in Figure 9, when changing the direction of the bow while maintaining the continuity of the sound, the bowing movement is inverted (signal 3), but the phase of the string vibration is not changed (signal 1). This phenomenon is well known in the physics and perception of bowed strings. Even though the perceived sound is changing in its timbre or its amplitude, it is perceived as continuous when the phase is not changing. The theories about the physical and the perceptual aspects of the continuity of the sounds are developed in Section 4.2.

Successful accomplishment of the task was determined by observations made on the objective signals as shown in Figure 9 and by asking the performer and the audience: performer and audience were invited to point out when they believed that the goal had been reached.

Subjects played freely as they wanted. The audience was composed of the other subjects and ten other persons of the laboratory, most of them not aware of the activity of the laboratory (students external to the laboratory) and three other external persons (one confirmed composer, one student in music and one scientific researcher). The four scenarios (F1, F2, F3, F4) corresponding to the different values of the bow-string friction were randomly presented to the subjects.

4.2 Sound continuity: Physical and perceptive aspects

To provide precise criteria for observation of the task, we must examine more precisely several points concerning the signal and string oscillation properties when the bowing direction changes.

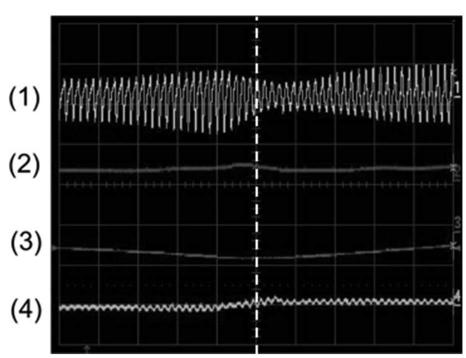


Fig. 9. Signals corresponding to change of bow direction. (1) Acoustical vibration of the string, (2) pressure force of the bow on the string, (3) displacement of the bow, (4) sliding force of the bow.

4.2.1 In stationary modes, the two bowing directions cannot be distinguished by audition

According to the basic Helmholtz theory (Cremer, 1984) a bowed string motion in a stationary regime of constant bowing speed produces a periodic triangular wave $S_1(t)$ shown in Figure 10. The bowing direction determines the sign of the two slopes of this wave since the smaller slope corresponds to the bow speed when the string sticks to the bow hair. Therefore, given an equal bowing speed, we can assume that both waves S_1 and S_2 only differ in their phase and are consequently identical regarding their amplitude spectrum. Since the acoustical perception of a stationary periodic signal does not depend on the phases of its spectral components (Plomp quoted in Risset (1990)) these waves are perceptually identical.

The signals S_1 and S_2 can be defined by the following formulas where t_0 is a delay parameter that defines their relative temporal positioning:

$$S_1(t) = \sum_n a_n \sin n\omega_0 t, \tag{1}$$

$$S_2(t) = \sum_n -a_n \sin n\omega_0 (t + t_0). \tag{2}$$

4.2.2 Continuity of sound is obtained by designing a specific transition signal

Considering only the signal properties, we can wonder which type of transition between the two S_1 and S_2 stationary phases presents a minimal or null perceptible effect, for obtaining a 'continuity of sound'. It is clear that slowly shifting the phase of the spectral components from S_1 to S_2 can meet this goal. The simplest transition signal S_3 that would realize this interpolation is defined as follows:

$$S_3(t) = \sum_n a_n \sin\left(n\omega_0 t + \varphi_n(t)\right) \tag{3}$$

with $\phi_n(t) = \alpha_n t$; at $t = 0$ we have $S_3(0) = S_1(0)$ and at $t = t_1$ we have $S_3(t_1) = S_2(t_1)$ so that $\phi_n(t)$ must satisfy the following conditions:

$$\varphi_n(0) = 0 \quad \text{and} \quad \varphi_n(t_1) = n\omega_0 t_0 - \pi - 2k\pi. \tag{4}$$

We can therefore choose the following linear evolution of the phase of each component from $t = 0$ to $t = t_1$:

$$\varphi_n(t) = \frac{n\omega_0 t_0 - \pi - 2k_n \pi}{t_1} t. \tag{5}$$

Since the integers k_n and the time t_0 are arbitrary constants, we can choose them so that a subset of harmonic components remain non-phase-shifted. This shows that the continuous transition from S_1 to S_2 is still possible even if some harmonics remain unchanged

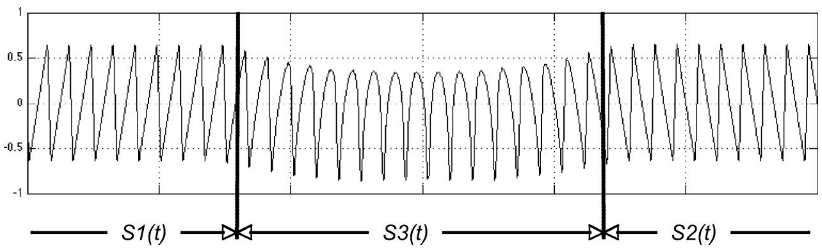


Fig. 10. Theoretical sound continuity. The sound waves $S_1(t)$ and $S_2(t)$ generated by two constant and opposite bowing speeds are perceived identically. $S_3(t)$: a continuous transition from S_1 to S_2 is obtained by slow phase-shifting of the even harmonics.

during the transition. Indeed for each n (each harmonic component) this invariance condition can be:

$$\varphi_n(t) = 0 \Leftrightarrow n = (2k_n + 1)\frac{\pi}{\omega_0 t_0}. \tag{6}$$

The first solutions of Equation (6) are presented in the following table (Table 1).

4.2.3 *How can the bowed string produce a quasi stationary sound at bow movement change?*

One can show that there is a simplified model of bowing gesture applied to the virtual violin model which produces a transition between stable signals S_1 and S_2 which presents some similarities with the proposed phase shift transformation. For that reason, it can generate a transition signal that could be perceived as continuous.

The absence of phase shifting for some harmonic components of the string movement can also be observed in the bowed string model. It is probably a characteristic feature of successful accomplishment of the bow inversion task that several main low rank harmonics should present such invariance. This can be explained by considering the dynamic properties of the bowed string. The internal energy of the oscillation is shared by the modal oscillators which constitute the spectral model of the string (Benade, 1976; Fletcher & Rossing, 1998). The bow-string contact and the friction properties of the rosin result in a non-linear coupling of the modal oscillators to each other and to the movement of the bow. When a stationary regime is reached, the mechanical energy exchanges between these different elements are low in comparison with the internal energy of the different modal oscillators. Consequently, each modal oscillation is robust against the various external perturbations and against the other modal oscillations. We can observe that the first solution indicated in Table 1 is the most efficient, since it consists of minimal changes of the internal evolution of the system regarding its natural stationary movement: in this case only half of the modal oscillators are constrained to shift their oscillation phase.

Table 1. The first solutions of continuity based on the invariance of some harmonic components. The most efficient corresponds to the invariance of the odd harmonics.

$\pi/\omega_0 t_0$	n Rank of the non-phase-shifted harmonics	Amount of invariant (non-shifted) harmonics
1	1,3,5, ...	1/2
2/3 or 2 or ..	2,6,10, ...	1/4
4/3 or 4 or ...	4,12,20, ...	1/8

4.2.4 *Criteria of success/non-success for the proposed task*

The role of the player during the transition period is to drive the system within the best solution to jump from S_1 to S_2. Three distinct situations can occur, among which only the first is successful:

(a) The first situation corresponds to a transition where only the even harmonics are phase shifted. In this case, the task is performed successfully.
(b) The second situation corresponds to quasi-continuity of the amplitude which is generally associated with conservation of only the first or second harmonics, but great phase perturbations take place in all the higher rank harmonics. In this case, the string movement presents a long transitory period after the bow direction has changed. This transition period corresponds generally to secondary Helmholtz motions (Cremer, 1984) in which several stick-slip phases take place at each string oscillation cycle. In this case, the task is unsuccessful.
(c) The third situation corresponds to a significant decrease or even extinction of the oscillation. It usually results from too long a duration of low speed phase when the bow movement changes. In this case the oscillation energy is dissipated in the bow. In this situation too, the task is unsuccessful.

Figure 11 shows signal snapshots obtained by the subjects performing the proposed tasks, illustrating the three situations.

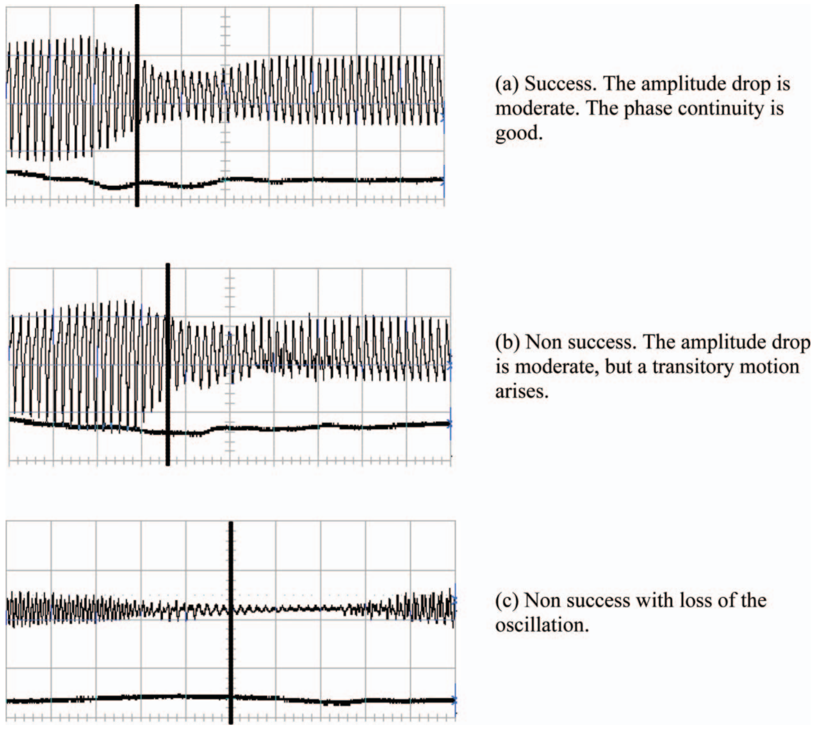


Fig. 11. Oscillograms of the bowing signals illustrating the three cases of success/non-success. Upper curve: string oscillation. Lower curve: bow pressure. The dotted line indicates the inversion instant. The time scale is 50 ms/div.

4.3 Occurrences of success at the task

The duration of each experiment varies from 2 min to 5 min 35 s. Figures 12 and 13 show the quantitative results. The Y axis represents the number of successes summed on all the subjects normalized at a duration of 60 s. Figure 12 represents the results derived from signal observations (i.e. objective results) and Figure 13 represents the results derived from the audience assessments (i.e. perceptual results). Figure 14 is a comparison of the two diagrams.

The main relevant results are the following:

- The best case is the case corresponding to normal friction (case F3) in both the objective observations and the subjective perceptual observations from the audience.
- Exaggerated friction (case F4) obtains better scores than obtained with the soft (case F2) and null friction (case F1) in both observations (from signals and from the audience). These results are very surprising as all the subjects declared that this F4 case was 'unplayable' in Experiment 1 ('feeling the friction', see Section 3) and in this experiment.
- Another surprising observation is that when the goal is achieved in the case F4 (exaggerated friction), then the objective figures are very well shaped. This is shown in the following snapshots of the oscilloscope (Figure 18, oscillograms c and d, Section 4.5). We can

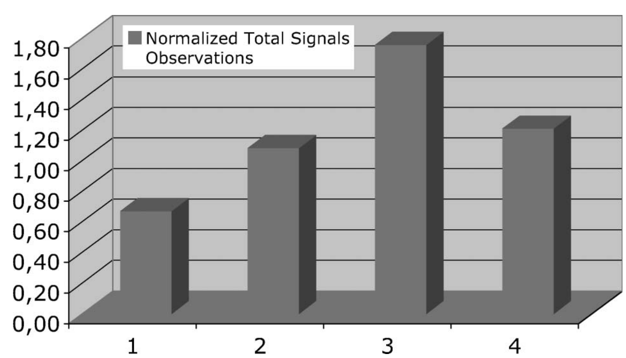


Fig. 12. Number of successes observed in the signals, normalized at a duration of 60 s.

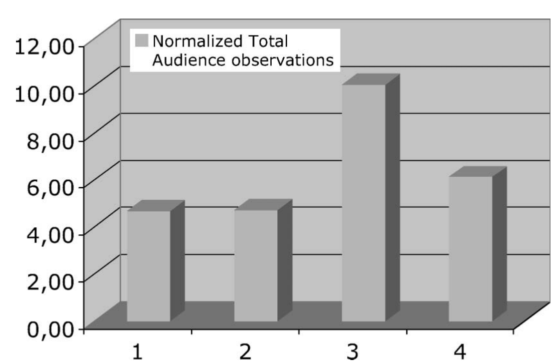


Fig. 13. Number of successes perceived by the audience, normalized at a duration of 60 s.

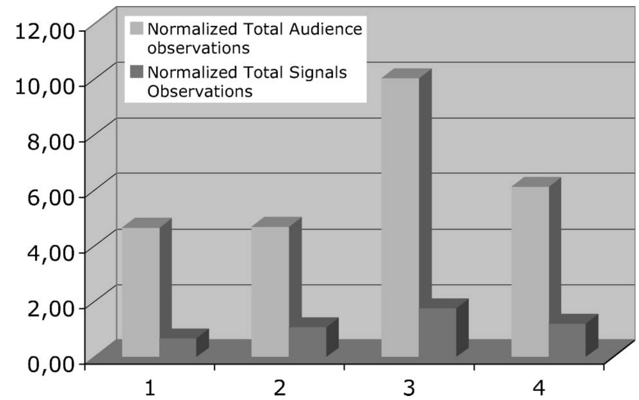


Fig. 14. Comparison of the numbers of successes respectively from the objective and perceptive observations, normalized at a duration of 60 s.

say that in this case, when the goal is achieved, it is quite perfectly performed without doubt.

- The successes of case F1 (null friction) and case F2 (soft friction) are comparable: for the audience the results are similar while the objective observations suggest that soft friction is better than null friction.
- The number of successes observed by the audience from hearing only are five to seven times greater than those observed in the objective signals. But the successes detected from the objective signals are also detected by the audience from auditory perception only.
- Figure 15 shows the total duration of each playing for each of the four cases. We observe again that the exaggerated friction is here slightly lower than soft friction but slightly greater than the null friction. This is somewhat in contradiction with the affirmation by the performers that the case F4 is impossible to play.

The main conclusion is that the resistance of the object (here the level of friction) plays a significant role in the performance of the task, even if it is felt by the subjects as a difficulty. The task is better achieved with a significant resistance (here a significant friction) than with no or low resistance. Above all, an adequate well-tuned ergotic relation to the sound is important to achieve the goal, but more friction is preferable to low friction.

4.4 Cognitive styles

It was immediately apparent that subjects' ways of exploration depended on a priori cognitive styles.

- Initial focus on spatial properties rather than on dynamic ones:
  During the first minutes of playing, people who had never played a bowed string instrument focused more on non-dynamic features such as spatial features. They started by focusing on geometrical properties such as curvatures: 'There is a surface, like a curve. It is like a grainy surface. It could be a ball, a pretty big ball'. They went slowly, quite statically, focusing on the exploration of the shape they felt. There is objectively a slight curvature due to the morphology of the force feedback device. However, it has not been remarked on by other subjects.
- Initial focus on musical properties:
  Composers started by focusing on musical features such as the quality of the sound 'The sound is nice. It is very good' or 'I can make modifications in the sound very naturally, in the texture of the sound'. Some of them explored for a long time, including the apparition of the harmonics during the turn, by relaxing the pressure. One of them explored the different types of conventional bowing patterns: legato, martelé, spicatto, stacatto. For all of them, quite quickly, no more than two minutes after their first contact with the system, their focus shifts from their initial cognitive attractors to the dynamic of the playing, exploring various types of playing and gestures with different forces, accelerations, velocities, correlating gesture trajectories and dynamic variations.

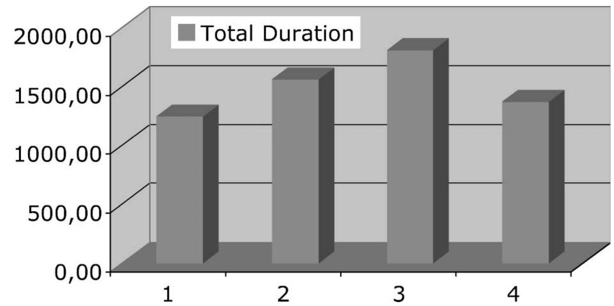


Fig. 15. Total duration of playing for each of the four cases of friction.

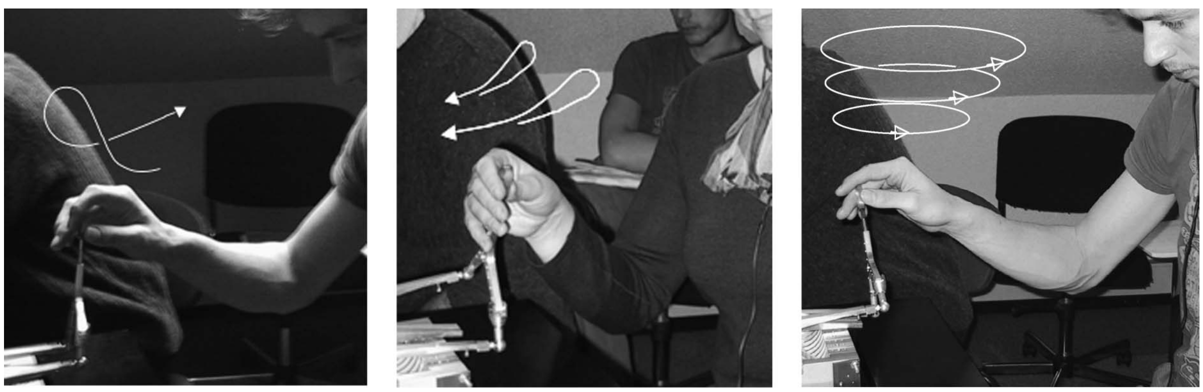
4.5 Modes of playing and dynamic adaptation

A very obvious observation was made by all the members of the audience and confirmed when examining the video recordings: there is a continuous adaptation of gestures to find the best way of manipulation to achieve the goal. Some examples are:

- Exploration of various modes of grasping and postures (Figure 16): holding with the fingertips (a), hand palm contact (b), deployed arm (c), strong full hand grasp (d).
- A wide exploration of bowing trajectories (Figure 17): we have observed that the trajectories of the handling point were rarely linear. Users often combined elliptic trajectories, half-turn in the frontal plane or 'Moebius like' movements with the basic transversal movement.

(a) (b) (c) (d)

Fig. 16. Photographs of the experiments illustrating the exploration of different ways of grasping and postures.



(a) (b) (c)

Fig. 17. Photographs of the experiments illustrating the exploration of different bowing trajectories. (a) Half turn in the frontal plane. (b) Moebius-like movement. (c) Elliptic trajectories.

- A wide exploration of dynamic strategies (Figure 18): similarly, various dynamic behaviours were observed from the oscillograms. Control of bow pressure around the point of speed change appears to be an important element of users' strategies. It consists in some cases of a simple release (Figure 18, oscillogram a). In other cases oscillations can be observed in the bow-pressure signal (Figure 18, oscillograms b and c). The bowing motions also present various characteristic shapes: one of the most remarkable consists of a pre-acceleration and post-deceleration around the turn-back instant that tends to 'sharpen' its temporal definition (Figure 18, oscillogram d). This strategy can be understood as an attempt to reduce the duration of the slow motion period of the bow during which the oscillation may collapse if the bow pressure is not released.

The instrument presents a peculiarity: it allows displacements, not only along the frontal axis, as is usual for the gesture of bowing, but also in the perpendicular saggital axis, with no effects on the sound. Figure 19 shows that the playing motions are not only along the frontal axis (line 1 in Figure 19), but also along the saggital axis (line 2 in Figure 19): on the photograph on the left side of the figure, the device is pushed away from the body and on the right, it is pulled closer to the body. This is an important difference from a real violin or cello, for which all bowing directions (frontal translations, rotations, saggital translations) influence the sound produced. In the instrument used here, the movements that excite the string's oscillation are only on the frontal plane (line 1 in Figure 19), but we have not mechanically constrained the stick to remain in that plane. Consequently, the stick can move freely along the saggital axis (line 2 in Figure 19), with no effect on the sound. When people had started bowing with a conventional pulling and pushing gesture along the frontal axis, they discovered the looseness of the device's saggital degree of freedom. We observed that many subjects were exploiting this possibility of movement to explore or to improve their gesture strategy.

The relaxation of the saggital degree of freedom probably explains that the dynamic strategies (i.e. a specific correlation between pressure and velocity before the change of direction) to achieve the goal is discovered

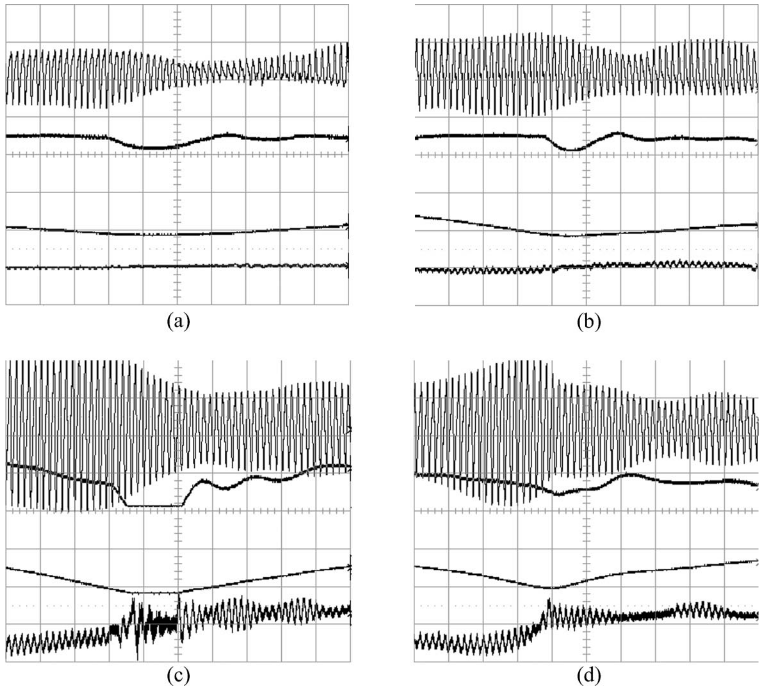


Fig. 18. Exploration of different dynamic strategies. From top to bottom: string oscillation, bow pressure, bow displacement and bow force (time scale: 50 ms/div). (a) Moderate pressure release around the turn-back point. (b) Pressure modulation and bowing speed change. The reverse speed is twice as slow. (c) Complete pressure release around the turn-back point. (d) Acceleration/deceleration around the turn-back point.

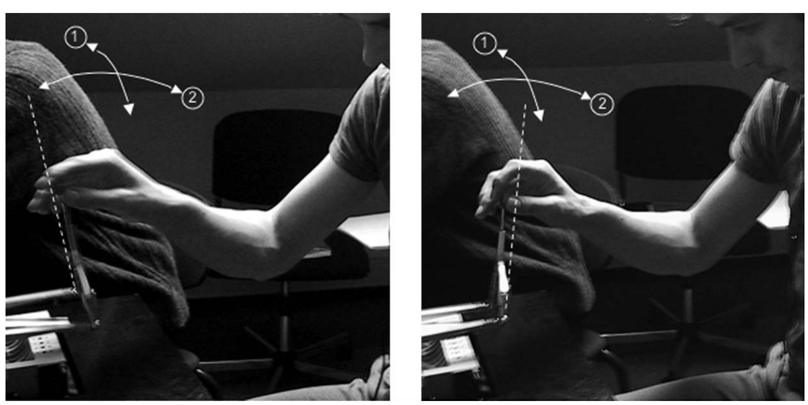


Fig. 19. Photographs of the experiments illustrating the exploration of different dynamic strategies: the use of the saggital free degree of freedom of the device.

faster than in the real case. Players discovered the correct dynamical patterns by accompanying the push-pull change of direction with a more or less accentuated turn. It would be useful to verify if the dynamic strategies found remain available if the bowing gesture is constrained to the conventional frontal plane push-pull. This could be a topic of further experiment.

4.6 Continuous dynamic learning

In Section 2, we presented the close similarities of the ERGOS virtual bowed string instrument to a real instrument, particularly regarding dynamic and energetic features. However, the virtual instrument presents also several morphological differences. The most obvious of these are that the bow is displaceable by only about 3–4 cm, that the motion of the bow in the saggital axis does not influence the sound and that the string is not visible. Despite all these morphological differences, all users learn very quickly how to make the instrument sound. To evaluate this, we can analyse the average duration of Experiment 1, keeping in mind that the experiment was performed freely for as a long time as the subjects wanted and that its aim was for subjects to acquire the minimal know-how in order to perform the more precise objective of Experiment 2.

Table 2 shows the average duration of Experiment 1 and Table 3 reports the average duration in Experiment 2 between the beginning of playing and the first success in achieving continuity of sound at a change of bow direction, as detected by analysis of the signals. After less than 2–5 min, everyone was at ease with the instrument, improving very quickly the quality of their gestures. Very quickly, they start to freely explore a wide range of dynamic strategies to reach the goal. They declared that strategies imagined a priori were not correct. They learned on the fly 'to be within the situation' and, so doing, they find very original strategies to reach the goal such as: 'Relax and let the bow act by itself just before the turn'.

Table 2 shows also that performers play longer with sound than without sound, which implies that they prefer playing with sound than without, even if they describe more what happens in the second situation, without sound. Surprisingly the shortest average duration before reaching the goal (Table 3), happens in the case F4, when the friction is a very sticky exaggerated friction.

An unexpected supplementary observation, not intentionally investigated in the experiments, was that when a user achieved a certain level of learning, it remained even in situations of negligible friction feedback. This raises the possibility of 'an ergotic memory', about which new studies could be specifically designed: does learning in an ergotic situation allow the performer to practice in a non-ergotic one, such as a pure mapping control situation, without altering playing or instrumental know-how?

Table 2. Average duration of Experiment 1, to get used to the system.

Experiment 1	Average duration (min)
Situation 1: With sound	4:09
Situation 2: Without sound	2:09

Table 3. Average duration from the beginning of playing to the first success in Experiment 2.

Experiment 2	Average duration before the first success
F1	1:37
F2	2:00
F3	1:16
F4	0:32

4.7 Playability, creativeness and presence

In all experiments, the normal friction F3, which is closest to the real bowed string case, was considered by all the performers to be the most playable and pleasant case. In this case, the virtual instrument appears to all to be the most affordant. (Affordance is the ability of an object to suggest its own use, a concept currently widely used in Cognitive Psychology and introduced by Gibson (1977).)

Conversely, for all the performers, 'exaggerated friction' (F4) is considered unplayable and non-affordant: they do not understand clearly and quickly the convenient manner of manipulation for the task. For example, when a person starts with this case, they do not understand the task itself. However, the previous tables show surprising phenomena. First, the number of successes is notably high compared with what the performers thought and believed. (They thought that the task was really impossible.) Second, the time within which success was achieved is the shortest of all the cases. Above all, though, unlike in the case of the normal friction F3, during which the playing is long but the bowing gesture rather conventional, performers sought and explored in the case of F4 unexpected and original ways of handling and of playing, leading to the creation of new types of gesture and sound. Affordance and creativeness seem to be two different concepts, maybe opposed, perhaps complementary, that may constitute the two poles of new instrument analysis in ecological situations (Figure 20). We may also consider that the possibility of acting in a manner which does not have consequences in the sound corresponds to a non-affordant property of the device, since it has no direct use in what the instrument does: to produce sound. But here too, it increases the range of possible exploratory procedures, opening up new types of playing gestures. Figure 20 sums up this theoretical proposition.

Above all, an unexpected and very promising result, of which we are particularly proud, relies on the spontaneous remark made by performers happily surprised by the 'strong presence of the string in the hand'. Thanks to the 44 kHz audio-haptic simulation, subjects unanimously and strongly reported 'the string presence', 'the string in the fingers', 'the string is really here', 'the best is when you feel a vibration in the hand even if on a real violin you don't feel it', etc. Something new appears which goes further than in our first high quality implementation of ergotic sounds in which the haptic parts were running at only 3 kHz. This could explain the strength and the predominance of the sound in the identification of the object implemented in Experiment 1. Perhaps a co-reinforcement of the haptic and audio feedback, in the sense that the vibration of the string is perceived as sound plus the 'feeling of the string in the

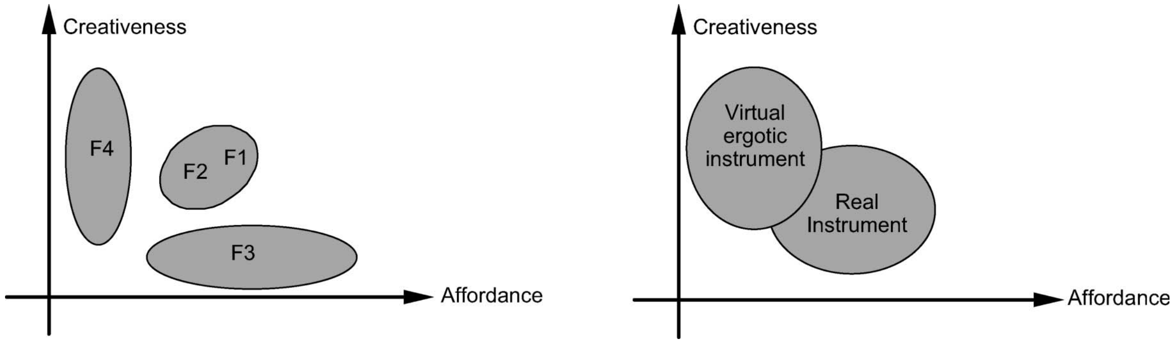


Fig. 20. Affordance and creativeness: two axes for ecological analysis of instruments. Left: illustration with the four values of bowing friction feedback (F1: null friction, F2: soft friction, F3: normal friction, F4: exaggerated friction). Right: comparing the real and virtual instrument with respect to the degree of freedom added in the virtual instrument.

hand by haptically feeling also its vibration', ensures the reliability of the indubitable presence of 'that instrument'.

5. Conclusions

The experiments presented here were motivated by a widely held assumption in the mechanical musical situation but quite impossible to evaluate without a specific virtual instrument implementation: to examine if the ergotic audio-haptic situation plays a core role in performing complex and subtle musical tasks, i.e. a situation in which the physicality of the interaction is maintained within the whole instrumental chain between the hand and the ear, the gesture and the sound. To achieve that aim, it has been necessary to implement a specific hardware audio-haptic simulator at the frontier of the state of the art in Virtual Reality platforms, able to simulate in real-time the whole instrument at the highest acoustical rate of 44 kHz.

In a first qualitative experiment, although the virtual instrument was exactly the same, two behaviours emerge, depending on whether the performers hear or do not hear the sound they are producing. Sound modifies the feeling of friction: when sound is present, it is predominant in the identification of the handled object; when it is not, the haptic feelings are more precise and detailed. With and without sounds, the haptic feeling is perceived as very different.

The results of the second experiment are promising. An adapted and well-tuned ergotic sound situation enhances instrumental learning and playability. It allows the performer to dynamically adapt her manipulation 'on the fly' to achieve the goal. It supports very fast instrumental learning through a very quickly acquired explorative strategy of manipulation. More resistance (for example, greater friction) of the instrument during bowing leads to better results than low resistance, when performing a precise musical task, even if people do not believe it. Observations suggest that when learning has been acquired, the haptic sensation may be suppressed a little bit, but this has not been investigated experimentally. This would be an interesting focus in future experiments in order to elicit if there is a kind of 'instrumental (or enactive) memory'.

Above all, though, the unexpected result is the strong presence of the string in hand, triggering a strong feeling of presence of the string, remarked on spontaneously by all participants. This is a result of the unprecedented 44 kHz audio-haptic simulation, really implementing what we called at the beginning of the research 'ergotic sounds'.

The ergotic sounds platform described above has been configured in order to extend the experiments performed in the laboratory by a few subjects to a large public audience. For this purpose, an experimental scenario has been designed in French and English and projected in Spanish. It runs autonomously, without an experimenter, and it could be a component of exhibitions in which the public is invited to perform the experiments and answer a questionnaire. A first trial has been made at the Enactive 07 Conference within the 'Touch the Future' exhibition during which 1000 people played the virtual violin, of whom about 500 answered the on-line questionnaire. All the answers of these 500 visitors have been recorded and constitute materials for future more detailed analysis and improvements of the experimental set-up.

An important field of research concerns the analysis of the properties of the instrument that makes enaction and embodiment possible. In the case of the task studied here—soft inversion of the direction of bowing—it has been observed that different distinct strategies were possible. In addition the analysis of the bowed string system shows that it may present some minimum energy paths to jump from one stationary state to another. It would be interesting to observe the possible relations between these objective paths and the strategies the subjects develop. More generally this poses the question of the influence of the non-linear properties of some objects which can lead by themselves to stable and categorized phenomena, and on the capability of human subjects to develop dynamic skills and enactive knowledge in the use of such objects. Finally the analysis of this 'enactive potential' of some objects could be a way towards more precise understanding of enaction.

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