1pMU6. Perception and production of complex bowing movements in violin performance
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In bowed-string instruments the primary function of bowing movements is to control the parameters that govern the stick-slip interaction between the bow and the string, giving the performer control of the sound. Not less importantly, bowing movements have to be planned ahead in order to anticipate future events. In fast, repetitive bowing movements involving string crossings and bow changes the primary and anticipatory movements become integrated, forming an overall, in the simplest case circular movement pattern. The relative timing of string crossings and bow changes is an inherent property of the shape of these patterns, which therefore has an important influence on the quality of the note transitions. We will present two complementary studies that provide insight in this coordination phenomenon. A perceptual study has been conducted using a virtual violin, in which the participants could influence the relative timing between string crossings and bow changes by a simple slider, giving insight in the perception of such transitions and typical temporal constraints. Analyses of bowing movements show in detail how the coordination is realized in performance, giving insight in the freedoms and constraints in the performance of this type of bowing patterns.

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INTRODUCTION

Background

In bowed-string instrument performance, the interaction between the player and the instrument is for a large part mediated via bowing gestures, the movements of the bow across the instrument. The primary function of bowing gestures is to control the sound. The stick-slip interaction between the bow and the string imposes strict constraints on bow speed, bow-bridge distance and bow force (the normal force exerted on the string), as has been shown for steady tones by Schelleng [1, 2] and for note beginnings (attacks) by Guettler [3]. Additional constraints of the player's movements are related to the geometry of the instrument, for example, for the bowing angle for selecting the individual strings. The player has to learn how to respond to the instrument by regular practice under guidance of the ear, or in other words, bowing movements are internalized via an auditory feedback loop.

Secondary, but not less important functions of bowing gestures include variations in time for expressive purposes and anticipation of future events. Thus, the resultant bowing gestures integrate sound control, timing and anticipation, and consequently they can become rather complex already in relatively simple note sequences.

Scope

The focus of this paper is on the coordination of bow changes and string crossings in fast repetitive bowing patterns (see Fig. 1A for two note examples). In this type of bowing patterns the motion trajectories of the bow form fluent, typically circular or figure-of-eight-shaped two-dimensional patterns. The coordination (or relative timing) of string crossings and bow changes, which is critical for a good performance, is inherent in the shape of the motion trajectory of the bow. It can therefore be expected that auditory perception of the quality of the produced note sequences plays an essential role in the formation of motor patterns.

Insight in the mutual relation between auditory perception and motor behavior is obtained by two complementary studies of fast, repetitive bowing patterns involving bow changes and string crossings. The first study deals with auditory perception of simulated bowing gestures controlling a virtual violin, and the second with coordination of bow changes and string crossings in performance assessed by motion capture. Earlier preliminary analyses of bowing gestures revealed that string crossings were consistently timed earlier than bowing bow changes [4, 5]. The studies presented here were conducted to shed more light on this sophisticated form of motor control and its importance in instrumental performance. More detailed accounts of the two studies will be published elsewhere.

The structure of this paper is as follows. In the following section, a model is presented to describe the coordination of bow changes and string crossings in bowed-string performance in relation with the movements of the bow. The main results of the perceptual study and the motion capture study are summarized in Sections 3 and 4, respectively, followed by a discussion in Section 5.

COORDINATION OF BOW CHANGES AND STRING CROSSINGS

It has been shown by Guettler that the quality of the attack is dependent on the initial combination of bow force and bow acceleration at a given bow-bridge distance [3], and that violation of the constraints leads to pre-Helmholtz transients, that can be clearly perceived by string players [6]. In complex bowing patterns the initial conditions in turn are critically dependent on the relative timing of bow changes and string crossings. This requires a precise
coordination of bow velocity (associated with bow changes) and bow inclination (associated with string crossings), which are both quasi-sinusoidal at fast tempi.

The coordination between bow velocity and bow inclination can be understood via a simplified model, shown in Fig. 1B. In the model string crossings are controlled by bow inclination (i) and bow changes correspond to zero crossings of bow velocity (ii). Both bow inclination and bow velocity are modeled as sinusoidal over time. For the sake of simplicity, it is assumed that bow inclination is centered around the string crossing (no offset). The string-crossing area is indicated by the shaded area in Fig. 1B (i). This is the angular range in which the bow is in contact with the two strings at the same time, while outside this region, the bow touches only one string. Indeed, the crossing of one string to the other is not instantaneous, but takes place in a finite angular range the extent of which depends on bow force due to the compliance of the bow hair and the strings [7]. During the string crossing, bow force (iii) is transferred from one string to the other.

The main coordination parameters in the model are 1) the relative phase $\Delta \phi$ between the bow velocity and bow inclination signals, which controls the timing of the bow change relative to the string crossing, and 2) the width of the string-crossing area. The relative phase is here defined positive for a phase lead of bow inclination. The width of the string-crossing area can be normalized by dividing the string-crossing extent by the inclination extent, further referred to as the normalized range. The combination of relative phase and normalized range determine the conditions for stopping the “old” note and starting the “new” note.

The finite width of the string-crossing area also gives rise to additional events, which might influence the perceived quality of the note transition. Two types of additional (false) attacks can be distinguished: an attack of the “new” note at the moment of entering the string-crossing area, and an attack of the “old” note at the bow change in case it takes place within the string-crossing area. In addition, there might be remaining vibrations in the “old” string at the moment of leaving the string crossing area, leading to additional after-ringing.

From this model it may be clear that there is no obvious solution to the problem of coordinating bow changes and string crossings, and that an optimal solution is likely to result from a trade-off between the quality of the attack of the new note and the audibility of the false attacks. In addition, the duration of the transition increases with the relative width of the string crossing area, leading to more prominent false attacks. It can therefore be expected that both relative phase and normalized range play a role in the trade-off.
PERCEPTUAL STUDY

The aim of this study was to shed light on the perception of the coordination of bow changes and string crossings in this type of complex bowing patterns. For this purpose we designed a perceptual test in which the participants could control the coordination of simulated bowing movements driving a virtual violin in real time via a simple interface. This allowed for controlled, yet realistic stimuli, in which the participants could optimize the coordination parameters based on their perception of the quality of the sound.

Method

In the perceptual test a virtual violin was used based on physical modeling of the bowed string [8, 9]. The violin model was implemented as a Max/MSP external allowing real-time control of the simulation through synthetic control signals. In the current study a four-string model was used, allowing to study string crossings in different adjacent string combinations. The control signals for bow velocity and inclination were modeled as pure sinusoids with a variable relative phase as shown in Fig. 1B. The relative width of the string-crossing range, the amplitude of bow velocity and the total bow force (constant) could be set by parameters. Within the string-crossing range bow force was proportionally distributed among the two adjacent strings (see “cross-fade” in Fig. 1B (iii)).

In the perceptual experiment, the two note patterns shown in Fig. 1A were used. Each pattern was played at two string combinations and at two dynamic levels (piano and forte), adding up to eight different stimuli. The bowing-parameter settings were adapted from measurements of real performances. The tempo was set to 100 beats-per-minute at quarter note level, corresponding to a note rate of 6.67 notes per second or a note duration of 150 ms.

There were four experimental conditions performed by each subject in a fixed order. In the first two conditions subjects could control relative phase with a simple 1D slider at two fixed values for normalized range per respective condition. In the third and fourth conditions subjects controlled both relative phase and normalized range with a 2D slider. The subjects were asked to adjust the slider in order to “find the clearest/best sounding note transition”. In the fourth (final) condition an additional constraint was added by asking the subjects to “move the slider until you find the clearest note transition, while striving to minimize the amplitude,” which corresponded to finding the lowest vertical position of the slider at which the note transitions were still acceptable.

Within each condition, the stimuli were presented twice in a randomized sequence. The phase could be varied from $-72$ to $72$ deg. and the normalized range from 0 to 1. In order to avoid any visual reference, zero positions of phase and range were randomized within a central range of the sliders, and the direction of the phase slider was randomized as well. In the 2D slider conditions the direction of the normalized-range slider was mapped consistently to allow for the above mentioned additional constraint in the fourth condition.

A total of 16 subjects participated in the experiment. Since the experiment involved judgment of subtle aspects of tone quality specific to string-instrument performance, the main requirement was that the participants had actively been playing a string instrument (violin, viola, cello, double bass) for at least the last three years. The age of the participants was between 22 and 39 years ($M=30$, $SD=6$). The experience expressed in years of practice ranged from 8 to 31 ($M=21$, $SD=7$). The number of females and males was equal (eight each). The total duration of the experiment was about 3/4-1 hour. About half of the subjects performed the test in two separate sessions.
**FIGURE 2:** (a) Phase vs. range averaged per subject and condition. The semi-transparent dots show individual responses. (b, c) Histograms showing distributions of relative phase and normalized range (individual responses in 2D slider conditions).

**Results**

In all experimental conditions there was a significant phase lead of bow inclination over bow velocity, with average values between 15.6 and 24.1 deg., indicating that the bow changes took place towards the end or after completion of the string crossings. Furthermore, the average relative phase per condition showed an increasing trend with increasing normalized range.

The relation between relative phase and normalized range is further illuminated by the combined responses of the 2D slider conditions, shown in Fig. 2. The individual responses of the combined conditions formed a cloud covering the whole range of normalized range from 0 to 1. There was a clear separation between the distributions of the “optimum sound” condition and the “minimum amplitude” condition, as can be seen in panel (c). The former had its mode at a normalized range value of about 0.3, and the latter at about 0.6. In the “optimum sound” condition there were almost no responses at the high end of the normalized range interval, and even in the “minimum inclination” condition there was a rapid decrease in the number of responses, indicating that the perceived quality of the note transitions deteriorated when the normalized range value approached one. The distribution of relative phase responses had a mean of 19 deg, and a standard deviation of 12 deg (outliers removed).

The relation between bow changes and string crossings is well described by the phase versus range plot shown in Fig. 2 (a). The string-crossing area is indicated by the shaded area. At the upper limit of this area (an arcsine curve) bow changes take place at the moment that the bow leaves the string-crossing area. The mean responses reveal a weak tendency that the relative phase increased with increasing normalized range. However, the increase was less steep than the string-crossing limit. This gives an interesting insight in the trade-off for optimal transitions: at smaller values of range bow changes take place when the string crossing is completed, whereas at larger values of range the bow changes fall mostly within the string-crossing range. The latter could possibly be explained by an increasing prominence of false attack of the “new” note due to the prolongation of the duration between the bow change and the moment of entering the string crossing range.

**Motion capture study**

A motion capture study was conducted to gain insight in the coordination behavior in the performance of this type of bowing patterns, and the influence of factors such as dynamic level,
tempo and the degree of expertise of the player.

Method

Motion capture data (frame rate 240 fps) were collected with a 7 camera Qualisys 3D optical motion capture system, together with synchronized analog data from a sensor for measuring bow force, video and audio. Bowing gesture data (including bow velocity, bow force, bow-bridge distance and bowing angles) were obtained using the methods for measuring and extraction of bowing parameters described in [10, 11]. In addition, instantaneous data on the width of the string-crossing areas taking the compliance of the strings and the bow hair into account was calculated using the method described in [7].

A total of 22 violinists participated in the experiment (7 male, 15 female; age: M=28; SD=9.75). The participants were subdivided in three groups with varying level of expertise: amateurs (8), students with violin as major subject (8), and established professionals (6). The duration of the experiment was about 2.5-3 hours, including preparation of the subjects for full-body motion capture (full body data is not considered in this paper) and filling out a questionnaire for gathering biographic data on expertise. The participants agreed on participation by signing an informed consent form, and they received a compensation of 30 Euro.

The participants were asked to play simple repetitive musical patterns involving bow changes and string crossings, played on different string combinations (see Fig. 1 for an example). There was a total of 20 conditions covering three different bowing patterns, two string combinations, two dynamic levels (forte and piano) and four tempi (58, 72, 92 and 112 bpm, corresponding to note rates of 3.9, 4.8, 6.1 and 7.5 notes/s, respectively). Each condition was recorded three times in partly randomized sequences. In the tempo condition the participants played with a metronome; the dynamic level conditions were played without metronome in preferred tempo (between about 92 and 112 bpm). The total effective playing duration of these conditions amounted to about 12:30 minutes per subject, or 4:37 hours for all participants.

The focus of the analysis was on the coordination of bow inclination (timing of string crossings) and bow velocity (timing of bow changes). The signals were denoised using a low-pass second-order Butterworth filter (cut-off 30 Hz, applied back and forth to compensate for phase shifts). The instantaneous relative phase between bow velocity and bow inclination (both signals were approximately sinusoidal) was obtained from the Hilbert transforms. The data was segmented into single period cycles cut at interpolated zero crossings in bow velocity (i.e. at the bow changes), and the cycles were aligned by resampling them (close to the original sample rate) in order to compute average patterns of the parameters of interest. Finally, features characterizing the timing and other details concerning of the coordination of string crossings and bow changes were extracted from the unsegmented fragments, allowing for statistical analysis. All processing was done in Matlab®.

Results

For the analyses presented here a limited number of conditions was selected, allowing for a fair comparison with the results of the perceptual study. The selection comprised three conditions of the easiest to perform pattern (note pattern 1 in Fig. 1A), played forte at free tempo and at the two highest tempi (92 and 112 bpm), amounting to a total effective playing duration of 35:24 minutes.

As expected, there was a significant phase lead of bow inclination over bow velocity, with an average value of 16 deg. The distribution of the average values of relative phase and normalized range for the individual subjects is shown in Fig. 3. The normalized range was mainly between 0.2 and 0.4. The standard deviation of relative phase was 9 deg.
The phase versus range plot in Fig. 3 (a) shows the coordination strategies of the individual performers for the three conditions. Individual performers were more or less consistent. The between-performer variance was considerably larger, indicating that there was no common coordination strategy. Interestingly, no clear distinction was found between groups of different levels of expertise.

Even though the simplified coordination model presented above forms a reasonable first order approximation, of course the performance data showed significant deviations from the model. Two important differences are that bow force is not constant in performance, which leads to consistent within-period fluctuations of the string-crossing range. Furthermore, most performances showed a significant offset in inclination with respect to the center of the string crossing range. The effect of these deviations on the coordination can be appreciated from Fig. 4. In the selected conditions there was a clear asymmetry between down bows and up bows. Whereas the bow changes to down bow largely occurred on the “new” string after completion of the string crossing, bow changes to up bow largely fell within the string-crossing range. This was partly due to an offset of bow inclination, which was consistently present in almost all performers.
DISCUSSION AND CONCLUSIONS

Two complementary studies were presented to the perception and production of coordinated bow changes and string crossings in fast repetitive bowing patterns. The studies showed a large general agreement in the parameters governing the coordination, providing support for the notion that performance is to an important extent guided by auditory perception.

The performance study showed relatively large differences in the coordination strategies of individual performers compared to the perceptual study. It is plausible that this is due to the relatively controlled conditions in the perceptual experiment, whereas in actual performance there are much more parameters at hand that can be varied in time. The motion capture approach taken in this study has much potential to reveal interesting details of control and coordination in performance, that will provide new insights in auditory-motor interaction in instrumental performance.

REFERENCES