Influence of Afferentation from the Contralateral Hand during Imitation of Cello Bowing in Musically Untrained Individuals

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Abstract—We studied hand movement during imitation of cello bowing while the rectilinear movement of the right bowing arm should occur in parallel with the bow orientation along the arm trajectory. Musically untrained individuals moved the bow across the bar that imitated the cello. Motion analysis was used to investigate the influence of a variety of experimental conditions: (1) bow motion on the bar surface, (2) on the left hand lying on the bar, and (3) in the air without touching the bar. It was found that the trajectory of the marker on the index finger at the bow frog differed significantly from the marker trajectory at the bow tip. In all conditions the marker on the index finger moved along a trajectory close to a straight line with an orientation slightly deviating from perpendicular to the bar. The marker trajectory at the bow tip deviated more from the perpendicular direction. Differences in the trajectories of markers at the bow frog and the bow tip depended on the condition of bow movement. The smallest differences were observed when the bow was moved on the left hand. It is suggested that sensation from the contralateral hand was used to create the internal representation of the relative position of the bow and the bar.

Keywords: coordination, sensorimotor integration, cello, musical performance

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Playing musical instruments is the production of sound with the help of fingers, hands, and even the entire body. At the same time, a feature of playing string instruments is that, for example, a violinist “will never attempt to change the position of the right hand and the standard pattern of its interlink angles, either in relation to the instrument, or in relation to the upper body” [1]. Such a rigid coupling of the violinist’s hand with the instrument is associated with the unconditional orientation of the violin relative to the violinist’s hands by holding its position at the neck with his left hand. Playing the cello has a greater connection with the external space than playing the violin due to the fact that the neck of the instrument lies passively on the performer’s shoulder, and the instrument itself also has a hard stop on the floor. In addition, unlike the violinist, the cellist’s shoulder, being more mobile than the floor under his feet, is nevertheless a significant additional support due to the massiveness of the upper part of the seated cellist. Many studies are devoted to analysis of the violinists’ movements [2–4], while only one study is devoted to the comparison of playing the violin and the cello [5], and only studies of one group of researchers are devoted to playing the cello [6, 7]. At the same time, movements when playing string instruments belong to a large group of movements characterized by “oscillatory synergy of movement of the lower arm, hand, and fingers” united not only by purposefulness and cyclicity, but also by the use of a certain object held by a certain grip in the hand to achieve the goal. The features of hand coordination revealed in this way when playing string instruments can be taken into account when forming other movements of this class.

Since the structure of the hand involves a circular movement of the proximal joints, a coordinated change in the articular angles is necessary for rectilinear movements of the distal parts of the hand. From geometric considerations, it may be suggested that when playing a string instrument, the main contribution to bow movement in the longitudinal direction is made by the proximal joints, and the straightness of the trajectory of the hand is achieved by a coordinated change in the articular angles of the distal joints. The task is complicated by the fact that with a rectilinear hand movement, it is necessary to maintain the orientation of the bow held by the hand, which, in the absence of vision, is achieved through haptic afferentation from the hand.

In this paper, we consider a movement similar to playing the cello, when the rectilinear movement of the right arm with the bow must occur while maintaining bow orientation along the arm trajectory. We compared the movements of the bow in the right hand when moving it without touching the cello sham with
the movement of the bow on the cello sham and the movement of the bow on the left hand lying on the cello sham, when afferent information about bow movement also comes from the contralateral hand. The purpose of the experiment was to describe the formation of a rectilinear trajectory of the end of the hand and the bow and to find out to what extent the additional afferent information that occurs during bow movement can influence the coordination of hand movement and bow orientation relative to the hand and the instrument.

MATERIALS AND METHODS

The experiment involved 7 healthy subjects (age 43.7 ± 18.8 years; height, 170.2 ± 10.9 cm). The subjects stood with a cello bow (69 cm long) in their right hand, while at the subject’s left shoulder there was a cello sham that was 159 cm long bar, which rested on the floor with its lower end and its upper end resting freely on the shoulder. The middle of the bar was wrapped with a soft cloth to give it softness of the hand, and the left hand could lie freely on the bar or hold it from below, depending on the experimental conditions. This posture of the subject with additional support on the bar was chosen because, on the one hand, it reduced the postural oscillations of the subject, and, on the other hand, it was more “standardizable” than the sitting position. Before starting the investigation, the experimenter showed the subject how to take the bow, and after the subject took it in the appropriate way (Fig. 1a), put his hand with the bow on the soft zone of the bar so that the bow was perpendicular to the bar. The subject followed the instructions to “move the bow while maintaining its initial orientation” in three conditions: (1) while resting the bow on a bar (in this case, the freely lowered left arm turned the hand so that the hand was holding the bar from below); (2) when resting the bow on the left hand (in this case, the freely lowered left arm turned the hand so that the hand lay on the bar from above); and (3) without support, when the bow was held by the right hand at a height of 3–5 cm above the bar and did not rest on anything, and the left lowered arm lay freely on the bar. The movements were performed by the subject using a metronome set at a frequency of 60 movements per min, with comfortable individual maximum amplitude of movement. The subject trained the execution of the instruction in all three conditions before the start of the experiment with open and closed eyes, and during the experiment he performed it with his eyes closed. The duration of bow movement in one direction was 500–1000 ms, with a comfortable amplitude of movement of the end point of the hand for the subject, which is 30–50 cm.

Established motion (approximately 2 to 3 cycles after it began) was registered for each condition for 2 trials of 20 s each according to the position of 8 markers mounted on the right arm, the bow, and the bar (Fig. 1b), including:

1. The shoulder (acromion).
2. The elbow (edge of the articular surface of the radius).
3. The wrist joint (styloid process of the radius).
(4) The back of the hand, on the metacarpophalangeal joint of the index finger.

(5) The distal phalanx of the index finger at the site of the bow frog, which also served as the coordinate of the bow frog.

(6) The bow tip.

(7, 8) The bar markers.

In order to reduce data scatter, the movement of the markers was analyzed in a moving coordinate system coupled with markers on the shoulder and bar, given that the movement of these markers was small. The moving coordinate system was formed by three mutually perpendicular axes (Fig. 1b): (1) X or the “axis of the main movement of the bow” directed perpendicular to the bar; (2) Y or the “bar axis” defined by its two markers (7) and (8); and (3) Z or the “height axis” perpendicular to the X–Y plane, whose coordinates were used to estimate the height of the markers above the X–Y plane. The movement of the hand markers in the new coordinate system had less variability associated with the movement of the subject’s body and the difference in the height of the subjects, their position relative to the cameras, and the location of the bar relative to the subject himself. At the same time, the mutual position of the markers, as well as changes in the articular angles, did not depend on the coordinate system. In addition, the use of the new coordinate system helped to evaluate the execution of the instruction by the subject, since in the ideal case, the trajectories of the marker on the index finger at the bow frog and the marker at the bow tip in the new coordinate system should form a straight line orthogonal to the bar. In this case, the main change in the position of these markers should occur along the X-axis and the changes in the coordinates of these markers along the other two axes when moving the bow should be insignificant.

To assess the quality of instruction execution, the maximum (MAX) and minimum (MIN) position of the marker at bow frog (5) along the X-axis was determined, and the average coordinate values of all markers for all motion cycles at the MAX and MIN moments were then calculated. For statistical analysis, marker displacements were calculated for each of the three coordinates as the difference between the average values of the marker coordinates at the MAX and MIN time points.

To determine the preferred direction of movement of the markers for bow passage, the main and secondary trajectory components were singled out from the marker trajectory using the principal component analysis. The main component, which accounted for more than 95% of the movement variations, gave an approximation of the trajectory of the marker by a straight line, which allowed us to calculate its angle of inclination of the trajectory to the bar.

In addition, based on the marker coordinates, the three-dimensional articular angles of the arm, as well as the angles between the hand and the bow, the bow and the bar, were calculated, including

— The angle at the shoulder joint as a three-dimensional angle between the segment connecting the marker on the bar and on the shoulder (7–1, Fig. 1b) and the segment connecting the markers on the shoulder and the elbow (1–2):

— The elbow joint angle between segments (1–2) and (2–3), respectively.

— The angle at the wrist joint between segments (2–3) and (3–4), respectively.

— The angle at the metacarpophalangeal joint of the index finger between segments (3–4) and (4–5), respectively.

— The angle between the hand and the bow between segments (4–5) and (5–6), respectively.

— The angle between the bow and the bar between segments (5–6) and (7–8), respectively.

The angle between the indicated segments was calculated as the inverse cosine of the scalar product of the segments divided by the length of each of them. The amplitude of angle changes was calculated as the difference between the average angles at the MAX and MIN points for all motion cycles.

The calculated parameters were used for statistical analysis. To compare the parameters, a nonparametric analysis of variance of means with repeated measurements in different experimental conditions (Friedman ANOVA) was used. The Wilcoxon test was used to detect differences. The significance level of differences was set at 0.05.

RESULTS

Figure 2 shows the trajectories of movement of the hand and bow markers for one subject in all three conditions, the movement of the bow on the bar (BAR), hand (HAND), and in the air (A). It is seen from Fig. 2 that during the passage of the bow from MIN to MAX, the subject’s elbow (2) moved along an arc of a circle with the center at shoulder joint (1), and markers of the wrist (3), root of the index finger (4) and bow frog (5) moved with slight variations in a direction close to the perpendicular to the bar in all three experimental conditions. However, the movements of bow tip (6) differed from the movement of bow frog (5) as a result of which the original orientation of the bow during its passage from MIN to MAX was not preserved.

Table 1 shows the relative displacement of markers at bow frog (5) and bow tip (6) on average for all subjects under all experimental conditions along three axes (along the axis of the main movement of the bow, across the bar, and above the plane of these two axes). As can be seen from Table 1, the movement of the bow in the air was significantly greater than when it moved across the hand and across the bar, and greater when it
moved across the hand than across the bar (Table 1). At the same time, bow tip (6) approached the shoulder most of all when moving in the air and least of all when moving on the hand (Figs. 2a and 2b). The marker at the bow frog moved slightly in this direction under all conditions (Table 1). A pairwise comparison of the displacements of the bow frog and bow tip showed that the displacement of bow tip (6) was significantly greater than the displacement of bow frog (5) both when moving on the bar and when moving in the air, and when moving on the hand, the differences in the displacement of markers (5) and (6) along the bar were nonsignificant. A pairwise comparison of the displacements of the bow frog and bow tip markers in height showed that the displacement of bow tip (6) was significantly greater than the displacement of the bow frog (5) both when moving along the arm and when moving in the air (Table 1).

The average values of the inclination of the trajectory of all markers to the bar under all conditions for all subjects are presented in Table 2. As seen from the data in Table 2, when the bow moved along the bar, the marker on the metacarpophalangeal joint of the index finger (4) and the bow frog (5) moved almost perpendicular to it. The trajectories of the proximal hand markers, elbow (2) and wrist (3), were inclined toward the bar by an average of $10^\circ - 20^\circ$ more than the distal markers. At the same time, the inclination of the trajectory of bow tip (6) differed significantly from the inclination of the trajectory of the hand markers under all conditions, including the trajectory of bow frog (5). Analysis of variance showed that the differences in the inclination of the trajectory for different conditions were significant only for the elbow marker and the bow tip. A pairwise comparison of the trajectory slopes showed that the inclination of elbow trajectory (2) to the bar when moving the bow along the arm was significantly less than when moving in the air and along the bar (Table 2), and when moving in the air, the deviation of bow tip (6) orthogonality increased.

When the bow passed from the the MIN to MAX position, the subject’s elbow moved along the circumference (Fig. 2), which was accompanied by adduction of the shoulder joint angle by $30^\circ - 40^\circ$ (Table 3). At the same time, the passage of the bow along the bar was accompanied in some subjects by flexion and in others by extension of the elbow joint so that the amplitude of the elbow angle change was an average of about zero for the group of subjects. Fine adjustment to a rectilinear trajectory was achieved by changing the angle at the wrist. The index finger almost did not move relative to the hand, i.e., the changes in this angle were about zero (Table 3).

Comparison of the angles at the joints when bowing across the bar, the hand, and in the air showed significant differences for the angle at the shoulder joint depending on these three conditions (Table 3), namely, the angle at the shoulder changed more when the bow moved in the air than when it moved across the bar surface or hand. Changes at other hand angles did not depend on the conditions of bow movement. When the bow moved in the air, the angle between the bow and the hand was smaller than in the other two conditions, and the angle of inclination of the bow relative to the bar during bow movement in the air increased significantly compared to its movement across the bar (Table 3).

DISCUSSION

During bow movement, the subjects easily moved the end point of the hand almost along a straight line (Fig. 2), and the main direction of movement of the distal parts of the hand was perpendicular to the bar with minor deviations from this direction. Thus, the data obtained confirmed the assumption that the straightness of the trajectory of the end of the hand at the site of bow frog (5) was achieved by a coordinated change at the shoulder joint angle, together with changes at the elbow and wrist joints, and the motion
Table 1. The displacement of markers 5 (index finger/bow frog) and 6 (bow tip) along the axis of the main movement of the bow, the bar axis, and the height axis in the conditions of bow movement on the bar (BAR), hand (HAND), and in the air (A) (mm)

| Parameter | Bow movement conditions | Statistical analysis |
|-----------|-------------------------|----------------------|
|           | BAR | HAND | A | Friedman ANOVA result | significant differences confirmed by pairwise comparison using the Wilcoxon test, $p < 0.05$ |
| Displacement along the axis of the main movement of the bow | | | | |
| Marker 5 index finger/bow frog | 433 ± 37 | 445 ± 33 | 532 ± 35 | ChiSqr. ($N = 8$, $df = 2$) = 12.00, $p < 0.01$ | A > BAR, A > HAND |
| Marker 6 bow tip | 401 ± 28 | 448 ± 30 | 523 ± 26 | ChiSqr. ($N = 8$, $df = 2$) = 9.00, $p < 0.05$ | A > BAR, A > HAND |
| The result of comparing the displacement of markers 5 and 6 using the Wilcoxon test | $p = 0.12$ | $p = 0.78$ | $p = 0.58$ | |
| Displacement along the bar axis | | | | |
| Marker 5 index finger/bow frog | $-16 ± 9$ | $-4 ± 7$ | $-6 ± 13$ | ChiSqr. ($N = 8$, $df = 2$) = 3.00, $p > 0.22$ | |
| Marker 6 bow tip | $124 ± 35$ | $80 ± 31$ | $271 ± 59$ | ChiSqr. ($N = 8$, $df = 2$) = 14.25, $p < 0.001$ | HAND < BAR, HAND < A, A > BAR |
| The result of comparing the displacement of markers 5 and 6 using the Wilcoxon test | $p < 0.05$ | $p = 0.09$ | $p < 0.05$ | |
| Displacement along the height axis | | | | |
| Marker 5 index finger/bow frog | $-5 ± 23$ | $39 ± 20$ | $46 ± 25$ | ChiSqr. ($N = 8$, $df = 2$) = 3.25, $p > 0.19$ | |
| Marker 6 bow tip | $-122 ± 69$ | $-94 ± 42$ | $-194 ± 56$ | ChiSqr. ($N = 8$, $df = 2$) = 9.25, $p < 0.01$ | HAND < A |
| The result of comparing the displacement of markers 5 and 6 using the Wilcoxon test | $p = 0.09$ | $p < 0.05$ | $p < 0.05$ | |

In the moving coordinate system, a positive displacement along the axis of the main direction of bow movement corresponds to movement to the left; a positive displacement along the bar axis corresponds to approaching the head; a positive displacement along the height axis corresponds to marker rise.
control system took into account afferent information from different joints to achieve a rectilinear trajectory of the end of the hand.

At the same time, taking into account the fact that there was no direct afferent information about the angle formed by the bow and the hand holding it, the trajectory of the end point of the bow was less controlled than the end of the hand. If we consider the bow held by the subject across the instrument as a console, then its weight begins to pull the hand down more and more as the bow passes from the MIN to MAX position, and the afferent information about the position of the bow depends not only on its current position, but also on the type of its grip by the subject’s fingers. In the present study, it is shown that the inclination of the trajectory of the bow tip to the bar surface was always greater than the inclination of the trajectory of the bow frog. At the same time, if the bow held by the right hand moved on the left hand, then the additional afferentation from it could be used to additionally control the bow tip trajectory, and the inclination of the bow tip trajectory was closer to orthogonal than in other conditions (Table 2). It cannot be ruled out that not only additional afferent information from the left hand, but also the transformation of movement from unimanual to bimanual, i.e., such, when afferen-
When moving with support on a hand or a bar, the mass of the bow is distributed between the hand and the bar. MAX, its entire weight falls on the hand, but when it is assumed that the bow on the bar and on the hand. When the movement of the bow in the air is different from the movement of the left hand to improve bow (as well as any other instrument) control of the right hand in order to achieve the correct orientation of the instrument. This information is used to create an idea of the mutual position of bow and bar.

It may be suggested that the additional afferentation obtained by contact of the bow with the left hand may be due to the absence of such interaction. Proprioceptive assessment of the position of the tip of one’s own finger in space is provided least of all by receptors located on it itself and is created synthetically based on the proprio-afferentation messages from all points of the hand; only in this case the skill of assessing the position is firmly automated since childhood” [1]. Indeed, in the present study, subjects who had never played a string instrument were aware of the position of the bow in space not on the basis of vision, but on the basis of their daily practice, which distinguished them from similar movements of a professional cellist developed by him as a result of everyday practice. Moreover, in this experiment, the subjects moved the bow on the bar instead of the cello, while their left hand rested passively on the bar or was held under it and did not participate in sound production, and the subject did not have the task of sound extraction. Despite this, our data showed the fundamental importance of the proprioceptive participation of the left hand to improve bow (as well as any other instrument) control of the right hand in order to achieve the correct orientation of the instrument gripped in it. This information is important for both professionals and musically untrained individuals and should be taken into account not only by teaching musicians, but also by teachers involved in the development of motor coordination in children and adolescents. Our results show that bimanual coordination rather than vision can be considered as a means of achieving the correct bow orientation when playing a string instrument. This is confirmed by the video lessons of highly professional teachers, who, based on their practice, intuitively recommend holding the bow with the left hand perpendicular to the cello and moving the right hand along the bow in order to “remember” its initial orthogonal position relative to the fingerboard [12].

From the point of view of mechanics, the movement of the bow in the air is different from the movement of the bow on the bar and on the hand. When the bow is held in air during its passage from MIN to MAX, its entire weight falls on the hand, but when it moves across the hand and across the bar, the weight of the bow is distributed between the hand and the bar. When moving with support on a hand or a bar, the right hand is more unloaded than when the bow moves in the air and is, therefore, likely to be more sensitive to deviations from the required trajectory. At the same time, changes in the angle between the hand and the bow when the latter moved along the bar and the hand were greater than when the bow moved in the air. Additional control of the bow angle relative to the hand resulted in a more orthogonal trajectory for the bow tip marker when the bow moved across the bar and hand. It is important to note that the mechanical interaction of the bow and bar facilitated the control of the position of the bow in the hand. It is possible that when the bow moves in the air, the decrease in the amplitude of the angle between the bow and the hand may be due to the absence of such interaction.

CONCLUSIONS

The trajectory of the movement of the bow tip marker is formed taking into account the afferent movement of the bow on the left hand. This afferent information is used to create an idea of the mutual position of bow and bar.
COMPLIANCE WITH ETHICAL STANDARDS

All procedures performed in studies involving human participants were in accordance with the biomedical ethics principles formulated in the 1964 Helsinki Declaration and its later amendments and approved by the local Bioethical Committee of the Institute for Information Transmission Problems, Russian Academy of Sciences (Moscow).

INFORMED CONSENT

Each participant involved in the study (or his legal representative) provided a voluntary written informed consent signed by him after explaining to him the potential risks and benefits, as well as the nature of the upcoming study.

CONFLICT OF INTERESTS

The authors declare that they do not have a conflict of interests.

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