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RESEARCH ARTICLE

Jessie Chen · Marjorie Woollacott · Steven Pologe

Accuracy and underlying mechanisms of shifting movements in cellists

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Abstract Accuracy of shifting movements between two notes was examined in nine cellists (intermediate-professional skill levels). Three pairs of notes separated by different distances were tested under the same movement rate. Finger position on the string was measured by a circuit. Angular velocities of the left upper arm and forearm were measured by two angular velocity sensors; thus elbow angular velocity during shifts was estimated. Results showed that with increased elbow velocity and shifting distance endpoint variability stayed constant. The force of gravity assisted elbow extension during shifts toward higher pitched notes compared to flexion towards lower pitched notes, but faster movement velocity did not result in increased landing variability. Performance for note E on the A string was found to be less variable than other notes, suggesting that physical cue from the cello body geometry was used as a landmark for finger position. Cutaneous feedback from the thumb when hitting the body–neck junction enabled faster elbow extension velocity compared to shifts towards other notes. Cellists who showed higher performance accuracy also showed higher perceptual ability and performance proficiency. These results suggest that long-term over-training of fast and accurate movements enables musicians to maintain accuracy and variability across different movement distances and velocities. Higher perceptual ability and performance proficiency are correlated with increased accuracy but not lower variability, indicating although perceptual ability and performance proficiency are important for pitch accuracy, movement variability is still constrained by the capacity of the motor system, which is highly fine-tuned and different than non-musicians.

Keywords Motor skills · Music · Kinematics · Psychomotor performance · Pitch perception

J. Chen (✉)
Department of Physiology and Neuroscience,
New York University School of Medicine,
550 First Avenue, MSB 442, New York, NY 10016, USA
E-mail: jessie.chen@med.nyu.edu
Tel.: +1-212-2632121
Fax: +1-212-2636964

M. Woollacott · J. Chen
Department of Human Physiology, University of Oregon,
Eugene, OR, USA

S. Pologe
School of Music, University of Oregon, Eugene, OR, USA

Introduction

Musicians are a class of extraordinarily skilled practitioners of sensorimotor coordination tasks. They possess fascinating speed, precision and dexterity (Kay et al. 2003; Winold et al. 2002). Music performance provides a rich domain for the study of both cognitive and motor skills. However, due to limitations in measuring methods and technology as well as the high variability between individuals, there has been very little research on the control of motor output required to produce accurate pitch (Palmer and Meyer 2000), and even less in the area of stringed instrument performance. A small amount of research has been conducted on musicians who play keyboard instruments (Kay et al. 2003; Palmer and Meyer 2000). Since keyboard instruments have discrete keys, pitch accuracy is rendered an irrelevant issue. Stringed instruments present real challenges for accurate pitch performance, because performers must place their finger on a string with almost no tolerance for position errors, on the order of millimeters or less if notes are to be perceived as in tune.

One previous set of studies on performance in stringed instrument players examined pitch accuracy in violinists (Fyk 1995). Melodic sequences involving various intervals were performed. Pitch accuracy and timing of pitch corrections were analyzed. It was found in this study that one way to approach the intended pitch was to glide into it (move the finger continuously) during the first 16% of the tone duration. Pitch corrections were typically made early after a pitch was initiated. This study provided some foundation for understanding performance issues related to intonation in string players. However, it was limited by the fact that the movement characteristics during the shift (involving extension/flexion movements of the arm to bring the finger to desired notes) were not examined. To our knowledge, there is no previous research examining movement characteristics during shifts in stringed instrument players.

Though little research has been performed on mechanisms underlying movement accuracy during shifting movements in stringed instrument players, considerable research has been carried out on control of arm movement in non-musicians toward specific targets in space (Keele and Posner 1968; Crossman and Goodeve 1983; Rosenbaum 1991; Schmidt et al. 1979; Meyer et al. 1988; Polit and Bizzi 1979; Kelso and Holt 1980). A number of experiments have been conducted to examine the specific variables being controlled when making accurate aiming movements (Adams 1971; Kelso 1977; Pepper and Herman 1970; Stelmach et al. 1975, 1976; Keele 1986; Imanaka 1993).

According to Schmidt et al. (1979), for reciprocal movements, in which subjects move between two targets at a fixed rate, variability in movement endpoints is linearly related to the movement amplitude. They hypothesized that arm movement involves the generation of a force impulse. Thus, the size of a subject's error increases in proportion to the magnitude of the force used. Therefore, when asked to make larger movements, the larger force required causes increased variability and reduced accuracy (Schmidt et al. 1979; Messier and Kalaska 1999; Loftus et al. 2005). In a similar experimental protocol using reciprocal movements Meyer et al. (1988) have shown that as movement velocity increases movement endpoint variability also increases. Thus fast movements lead to more error. Finally, Adamovich et al. (1999) noted that for fast movements subjects consistently overshot the target as compared to slow movements.

For stringed instrument players, it is possible that shifting movements would be constrained by similar principles to those found for non-musicians. However, because the distances between notes on a string are not distributed in a linear fashion (higher pitch notes are located closer together and lower pitch notes are farther apart on the same string) and the goal for the players is to play in tune, it is also possible that the requirements of pitch accuracy would constrain movement variability across different shifting distances and velocities. Another possibility is that because musicians are highly trained in fast and accurate movements, a moderately high movement velocity would not necessarily lead to increased variability or decreased accuracy unless maximum velocity is used. Therefore, in addition to different movement speeds, we also tested shifting movements at the fastest possible velocities. Moreover, because playing on an instrument involves not only motor control but also perceptual ability, it is also possible that musicians with higher perceptual ability and performance proficiency would show reduced variability and increased accuracy.

The first set of questions explored in this study was whether stringed instrument players (specifically cellists) utilize similar movement control principles as non-musicians in controlling shifting movements across (1) different distances and (2) different velocities. Do they show increased position variability and error (decreased accuracy) with increased movement distances or velocities? In addition, are there correlations between the level of pitch performance (variability and accuracy) and (1) perceptual ability and (2) performance proficiency?

A second question related to performance on a specific stringed instrument, the cello, was the role of gravity in the control of shifting movements and the inter-play between gravitational force and pitch requirements. Because shifts toward higher pitch notes (closer to the bridge) are downward in direction, they could be assisted by gravity; and shifts toward lower pitch notes would need to counter gravity. This could affect shifting movements in a variety of ways. It is possible that the downward shifts would be faster compared to the upward shifts due to the force of gravity; however, it is also possible that they would be slower, because the aimed note is higher in pitch and therefore has a smaller pitch window (in distance measurements). Thus, in this study we also examined the effect of movement direction on elbow angular velocity.

Finally, unlike normal arm movements in space, the cello has unique surface geometry. The accuracy and velocity used to reach certain notes could be increased due to cutaneous cues from landmarks on the cello body, specifically the point where the neck of the fingerboard meets the body of the cello. If this were the case, one would expect increased movement velocity in moving toward those notes and decreased position variability of those notes. The final question explored in this study was whether the variability and velocity of different notes along the fingerboard is related to these surface landmarks.

Methods

Subjects

A total of nine cellists with no known neuromuscular disease participated in the study, including two professional cellists from the Eugene, Oregon area, and seven intermediate to advanced students at the University of Oregon School of Music. It is common among the most respected schools of music and conservatories in the USA that advanced students at some point in their studies cross the threshold that defines the professional level. Two students in our study had clearly crossed that threshold. Thus four of the nine cellists were professional level performers. Informed consent was obtained before the experiment for each subject. All the protocols were approved by the Internal Review Board at the University of Oregon.

Experimental apparatus

Circuit. The basic method for determining the contact point between the string and the fingerboard is based on the fact that high-quality wire-wound cello strings are high-precision length-linear resistors. By cementing a 0.25 in. wide copper strip, with a low resistance, along the entire length of the fingerboard one can measure the resistance of the string between the bridge and the contact point. To do so, a custom-made Howland current pump (16 mA) was used (see Fig. 1a). It amplified the voltage drop across the resistance. The output of the circuit was configured to produce a signal between +7 and −7 V for a 68.5 cm length of string, with a noise level of less than 0.02 cm. The sampling rate was set at 360 Hz.

Angular velocity sensor system. Two 1,250°/s angular velocity sensors by Motus Bioengineering, Inc. (Benicia, CA, USA) were attached to the upper arm and forearm of the left arm to measure angular velocity of elbow flexion and extension during shifting movements. These sensors were sensitive to angular movement but not affected by gravity. The output of the sensors was configured to produce a signal between +2.5 and −2.5 V for 1,250°/s angular velocity in either direction with a negligible noise level.

Protocol

During the experimental session, each subject was asked to shift alternately between two notes on the A string using the index finger. Three pairs of notes were tested (see Fig. 1b for note locations): (1) note B natural (247 Hz) (we will call it note B hereafter) and note A (440 Hz) above it (a shift of 26.78 cm in distance), (2) note B and note E (330 Hz) above it (a shift of 15.31 cm in distance) and (3) note B and note D (294 Hz) above it (a shift of 9.71 cm in distance). Cellists performed these shifting movements under their normal performance conditions, with acoustic feedback (auditory input) from the use of the bow and with normal visual input (eyes open).

During the performance of each note the precise position of the finger on the string was measured by the string circuit. The finger position on the notes was characterized by the linear distance between the contact point and the bridge (in centimeter). The shifts occurred at a rate of one note per 2 s (a metronome was used to set the tempo) and continued for 2 m. In addition, trials in which the subjects were asked to move as fast as possible (one trial for each of the same note pairs described above) were also included. These trials lasted 30 s. Angular velocity sensors were attached to the upper arm and forearm of the left arm to determine angular velocity of elbow flexion and extension movements.

Each subject's auditory perceptual ability (ability to identify intervals between notes) was assessed by a computerized pitch perception test designed by EarMaster (Midi-tek, Norway). During the test, acoustic noise canceling headphones (Model: QC-2, Bose, MA, USA) were used to block background noise. A testing tone was given following a 1 s delay after a reference tone. The interval between these two tones ranged up to one octave excluding the prime note and the note one octave above (from minor second to major seventh). The cellists were asked to identify the interval between the two tones. All tones ranged three octaves. A total of 66 intervals were given to each subject. The percentage of answers that were correct was measured.

Each subject's performance proficiency was assessed by the head of cello performance at the University of Oregon. Subjects were evaluated under three categories: intonation, rhythm and technique on a scale of 1–10,

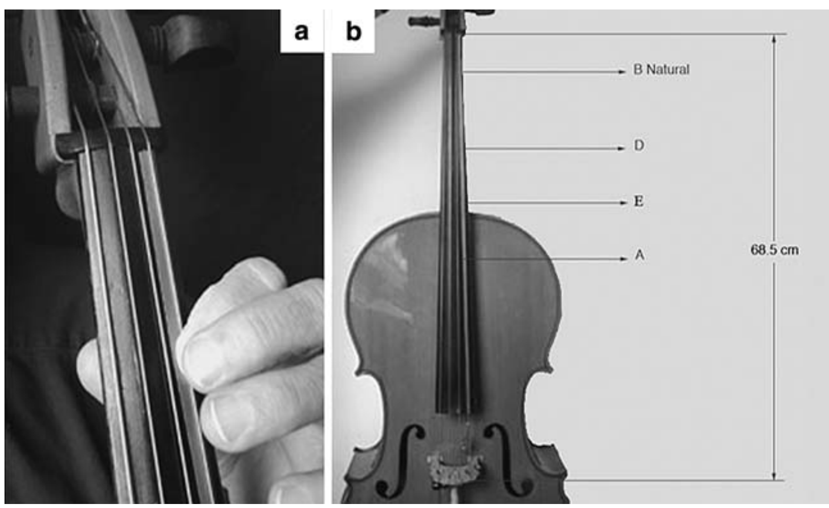

Fig. 1 **a** One cellist holds a note using his index finger. The finger placement depresses the string that makes contact with the copper strip affixed to the fingerboard. The string circuit measures the resistance of the string between the point of contact and the bridge. **b** Approximate positions of the testing notes, B natural, D, E and A on the A string, which has a total length of 68.5 cm

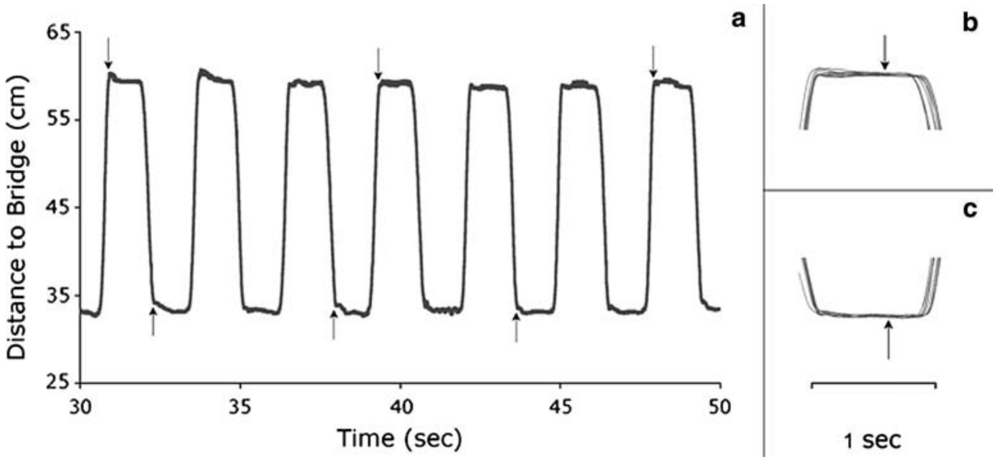

Fig. 2 **a** Finger position of a cellist performing alternating B-to-A shifts. Superimposed low pitch notes (**b**) and high pitch notes (**c**), along the time frame where the initial contact occurs. *Arrows* indicate the location of the initial contact (**a**) and the final note positions (**b**, **c**)

with 1 being beginner level and 10 being world-class performance level. The sum of the scores from each category was assigned to each subject as their performance proficiency rating.

Data analysis

Unlike reaching/pointing movements in which movement is completed when the target is reached, string players often adjust finger position before coming to their steady state or final note position even after the finger has made contact with the fingerboard (Fyk 1995). Therefore, in this study, finger position was examined at two stages. Figure 2a shows the finger position (measured as the distance from the bridge) as a function of time when the cellist performed alternating B-to-A shifts. The flat portions of the trace are the periods when the finger stayed in a relatively static position, after the performer had completed the movement to the new note. Note B is at the top of the figure, while note A is closer to the bottom. As demonstrated, there are often adjustments after the initial contact, indicating error correction. The first finger position identified in this study, "initial contact position," is equivalent to the end point in previous reaching/pointing studies. It is defined as the first contact position at which the primary movement (shifts) is completed and holding a note starts (shown as arrows in Fig. 2a). A second finger position, "final note position," is identified to represent the finger

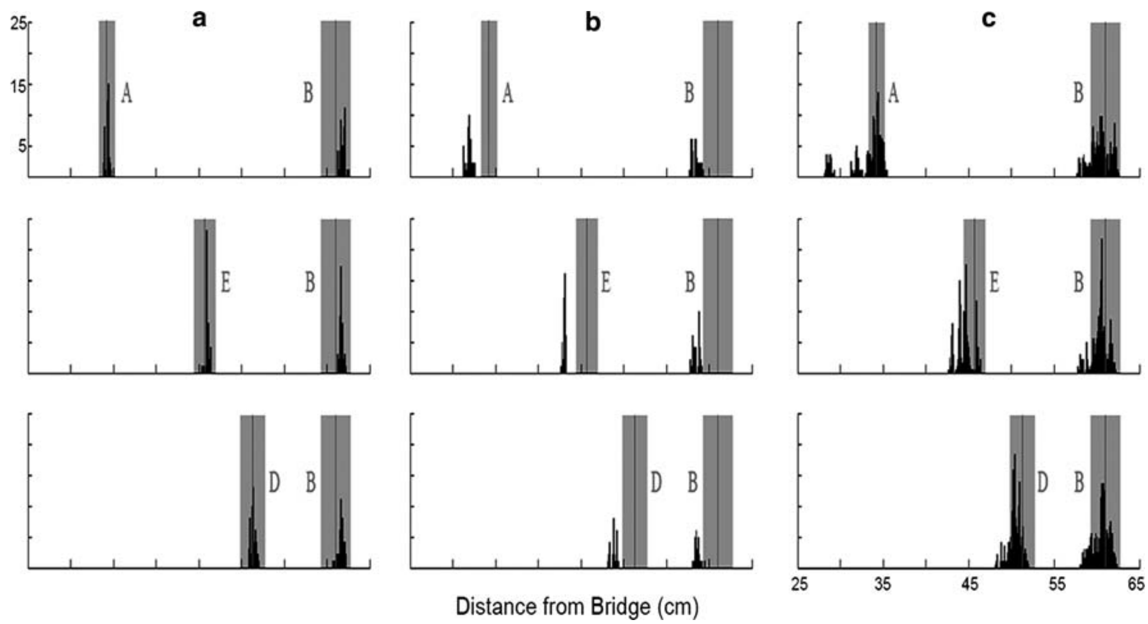

Fig. 3 Histograms of final note positions in B-to-A, B-to-E and B-to-D shifts. **a** Example from an advanced cellist. **b** Example from a less advanced cellist. **c** All nine subjects combined. *Vertical lines* indicate true note positions. *Grey bars* indicate pitch window of the notes (quarter step above and below the true pitch)

position after adjustment following initial contact of the fingerboard. It is measured as the lowest position variability point during the time when the note is held. To do so, first, all notes in the trial were superimposed along the time frame when the initial contact occurred. Then the standard deviation of finger position from 300 ms before to 700 ms after the initial contact (which covered the entire period during which the notes were held) was calculated and the lowest variability point identified. Finally the final note position of each note was determined based on the time interval between the initial contact and the lowest variability point measured in the second step (see Fig. 2b, c). The initial contact position and the final note position for each note were determined using a graphic-user interface in a custom written MatLab (The MathWorks, Inc., MA, USA) computer program. A reliability test from three independent observers confirmed the reproducibility of note positions of interest using this definition and method. In this study, the initial contact position was used to answer questions related to endpoint variability following shifts. In order to answer questions related to pitch accuracy, the final note position was analyzed.

Two-way factorial ANOVA tests were used to analyze the effects of the fixed factors and random factors on several position and movement parameters. Pearson correlation tests were also used to estimate the correlation between performance parameters and perceptual abilities and performance proficiency ratings.

Results

To assess the effects of movement distance and velocity on pitch performance accuracy and variability, cellists were asked to shift between three pairs of notes separated by different distances. Figure 3a, b shows the histograms of the note positions when an advanced cellist and a less experienced (intermediate) cellist performed alternating B-to-A shifts, respectively. The results show that variability of note E for the advanced cellist is lower than the other three notes (B, D and A) and its accuracy is the highest among the four notes, although this performer was consistently slightly flat on note B (but still within the pitch window). On the contrary, for the less experienced cellist, all four notes are more variable and outside the pitch window, although just as for the advanced cellist, note E is still the most accurate and tightly distributed among the four notes. Figure 3c shows the histograms of final note positions for the different shifting pairs from all cellists. When data are combined across performers, variability is much higher when compared to histograms of individual cellists indicating high inter-subject variability.

Table 1 shows the distribution of final note position in all cellists. As demonstrated earlier in the histograms (Fig. 3), there is a high inter-subject variability in both the mean position and variability. Interestingly, subjects were almost always sharp for all four notes.

In a stringed instrument, the pitch windows of lower pitch notes are larger than those of higher pitch notes (gray bars in Fig. 3); therefore, the variability and accuracy constraints are lower for the low pitch notes compared to the high pitch notes. To avoid this inherent pitch–constraint difference for different notes, elbow flexion velocities in shifts from notes A, E and D to note B were used to correlate with the variability of note B, since note B was the common note in all three pairs. Figure 4a demonstrates that initial contact position variability of note B did not change with an increase of shifting distance ($r = 0.184$, $P = 0.182$). Since all shifting movements were performed at a tempo of 1 note per 2 s, a longer shifting distance resulted in faster movement velocity. Figure 4b shows that shifting velocity increased with increased shifting distance in both metronome paced and fastest possible movement conditions, and the trials with the fastest movements had higher movement velocities compared with those in paced conditions. ANOVA tests showed that there was a significant difference among the three shifting pairs ($F = 13.455$, $P < 0.001$) and between paced and fastest

Table 1 Distribution of final note position in all cellists

Cellist	Variable	Note					
		B (BA)	B (BE)	B (BD)	A	E	D
1	Mean	59.23	58.78	58.37	33.71	43.75	49.55
	Error	−1.80	−2.25	−2.66	−0.54	−1.97	−1.77
	SD	0.59	0.30	0.29	0.41	0.16	0.20
2	Mean	58.99	59.06	59.01	33.23	43.85	49.52
	Error	−2.04	−1.97	−2.02	−1.02	−1.87	−1.80
	SD	0.43	0.35	0.26	0.17	0.20	0.22
3	Mean	58.72	59.44	59.71	27.78	43.05	48.91
	Error	−2.31	−1.59	−1.32	−6.47	−2.67	−2.41
	SD	0.51	0.30	0.42	0.26	0.13	0.25
4	Mean	57.49	57.59	57.71	30.96	42.13	47.92
	Error	−3.54	−3.44	−3.32	−3.29	−3.59	−3.40
	SD	0.42	0.35	0.28	0.34	0.13	0.34
5	Mean	61.28	59.77	59.82	33.53	43.67	49.30
	Error	0.25	−1.26	−1.12	−0.72	−2.05	−2.02
	SD	0.15	0.25	0.20	0.19	0.14	0.07
6	Mean	60.15	59.99	60.28	33.02	43.95	49.78
	Error	−0.88	−1.04	−0.75	−1.23	−1.77	−1.54
	SD	0.40	0.38	0.50	0.25	0.19	0.25
7	Mean	59.58	59.74	59.89	34.06	45.03	49.75
	Error	−1.45	−1.29	−1.14	−0.19	−0.69	−1.57
	SD	0.27	0.25	0.23	0.20	0.14	0.10
8	Mean	60.93	60.76	60.75	33.38	45.10	50.46
	Error	−0.10	−0.27	−0.28	−0.87	−0.62	−0.86
	SD	0.30	0.20	0.32	0.19	0.19	0.26
9	Mean	59.58	59.10	60.30	32.40	43.21	50.11
	Error	−1.45	−1.93	−0.73	−1.85	−2.51	−1.21
	SD	0.30	0.31	0.35	0.22	0.15	0.06

Mean represents mean final finger position of a note in one block of alternating shifting movements typically consisting of 50 repetitions. Error represents deviation of the mean final finger position from the true note position; positive value indicates deviation towards the flat direction and negative value indicates deviation towards the sharp direction. SD represents standard deviation (variability) of the mean final finger position of a note

B (BA), note B in B-to-A shifts; *B (BE)*, note B in B-to-E shifts; *B (BD)*, note B in B-to-D shifts; *A*, note A in B-to-A shifts; *E,* note E in B-to-E shifts; *D,* note D on B-to-D shifts velocity conditions ($F = 7.13$, $P = 0.01$). Figure 4c shows the correlation between mean peak elbow flexion velocity and initial contact position variability of note B from all nine cellists. A Pearson correlation test showed that there was no correlation between mean peak elbow flexion velocity and note B position variability ($r = 0.089$, $P = 0.522$). These results suggest that skilled cellists do not increase landing position variability as either shifting distance or velocity increases.

It was found that extension velocities at the elbow in all three shifting pairs were faster than those in the flexion direction (Fig. 5). Moreover, the extension velocity toward note E was proportionately faster than that for the other two notes. In order to confirm that moving toward E was different than moving toward any other note a two-way ANOVA test was performed on both movement direction and shifting pair. Significant main effects of both movement direction ($F = 47.92$, $P < 0.001$) and shifting pair ($F = 361.953$, $P < 0.001$) were found and there was also a significant interaction between direction and pair ($F = 5.56$, $P = 0.004$). This supports our hypothesis that note E is a landmark note on the A string, since it resides at the junction of the cello body and neck. Thus, higher velocities could be used in moving toward note E, since the movement could be stopped by the thumb hitting the neck–body junction. In addition, we also found that note E had a much lower variability than the other three notes (Fig. 6). A one-way ANOVA contrast test revealed that position variability on note E was significantly lower than that of the other three notes ($t = 2.678$, $P = 0.01$).

As shown in Fig. 7a, both initial and final position errors are moderately correlated with perceptual ability (light solid and dashed best fit lines, respectively), when data are pooled from all subjects, including one outlier (located at the upper left corner). If the outlier is excluded, perceptual ability and position error are highly correlated, with a Pearson correlation coefficient of 0.932 and P value of 0.002 for the initial position error (dark solid best fit line) and a Pearson correlation coefficient of 0.89 and P value of 0.007 for the final position error (dark dashed best fit line) indicating that the position error decreased with increased perceptual ability. Figure 7b shows that perceptual ability is not

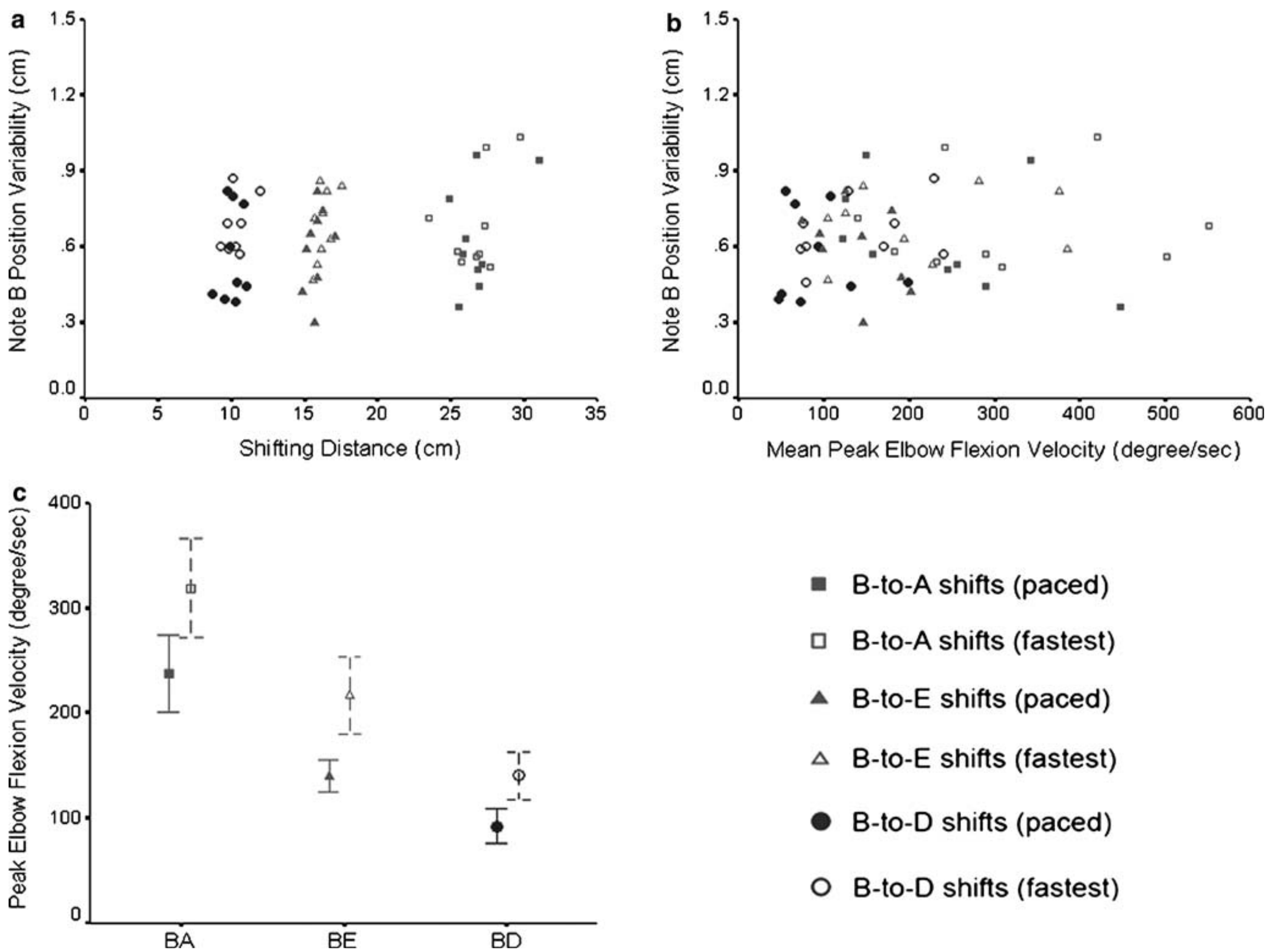

Fig. 4 Correlation of note B position variability (SD) of each cellist and shifting distance (**a**) and peak elbow flexion velocity (**b**). **c** Elbow flexion velocity in different shifting pairs in metronome paced and fastest velocity conditions

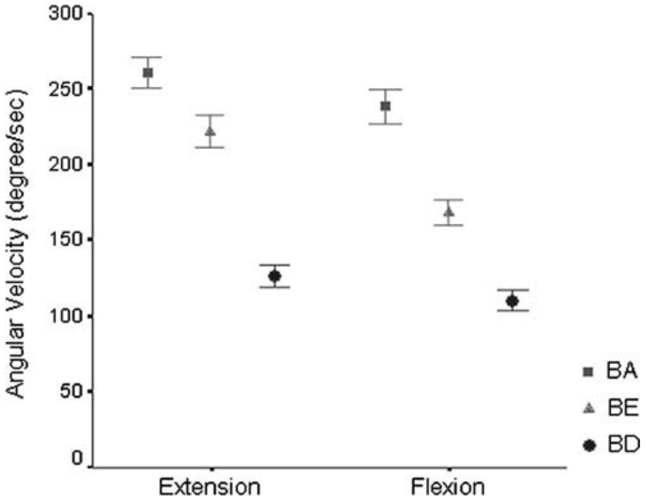

Fig. 5 Elbow angular velocity in extension and flexion direction in different shifting pairs

correlated with position variability at initial contact (r = 0.303, P = 0.465) or at final position (r = 0.081, P = 0.849). Pearson correlation tests reveal that there was a significant correlation between performance proficiency and position error (r = 0.708, P = 0.049 for initial contact; r = 0.747, P = 0.033 for final position), see Fig. 7c, but no correlation between performance proficiency and position variability(r = −0.021, P = 0.961 for initial contact; r = −0.653, P = 0.079 for final position), see Fig. 7d.

Discussion

This study aimed to examine movement accuracy and underlying mechanisms in skilled cellists. Using a novel methodology, a circuit that measured the resistance of the string between the fingerboard–finger contact point and the bridge, we were able to precisely measure the initial contact position and the final note position when cellists shifted between two notes. Two angular velocity sensors were also used to estimate elbow movement characteristics associated with the shifts. The reasons we chose three pairs of notes separated by different distances and located in different portions of the fingerboard are: (1) note B is a common note in all three pairs. We wanted to begin with a note that is one of the most frequently accessed positions (first finger, first position) by cellists. (2) We chose one commonly used shift to E natural, which utilizes the cello's neck–body junction and two notes without this convenient anchor. These two notes were deliberately designated to be at distances far from each other: one in the lower position (D), where the thumb can retain its relationship with the rest of the hand, and the other in a higher position (A), where the hand must essentially change position relative to the thumb, in order to reach a higher frequency.

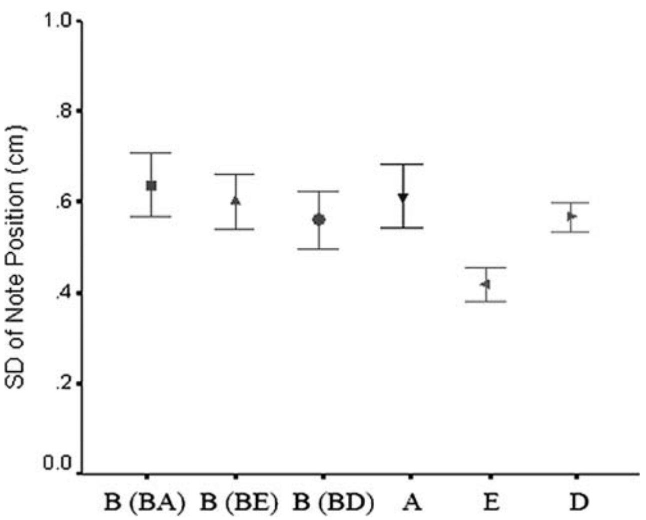

Fig. 6 Initial contact position variability of the different notes. *B* (*BA*) note B in B-to-A shifts, *B* (*BE*) note B in B-to-E shifts, *B* (*BD*) note B in B-to-D shifts, *A*: note A in B-to-A shifts, *E*: note E in B-to-E shifts, *D*: note D in B-to-D shifts

The study was centered on four main questions and the four key findings are discussed below.

Control principles underlying shifting movements across different distances and velocities

The first set of questions explored was whether stringed instrument players (specifically, cellists) use similar movement control principles to non-musicians in controlling shifting movements. We found that neither increased distance nor increased velocity (even in the fastest possible velocity condition) resulted in increased endpoint variability. This contradicts the results of previous studies on pointing movements in non-musicians. One difference between our study and the previous research on non-musicians is that previous studies focused on the visual contribution to pointing accuracy whereas our study involved both visual and auditory feedback. One contributing factor to the extraordinary ability to maintain low variability across a variety of shifting distances and velocities is that these shifting movements are highly over-trained in musicians. In addition, in our study, the mean movement velocity in the fastest possible condition was around 300 deg/s, which is equivalent to what was used in previous research (Meyer et al. 1988; Schmidt et al. 1979). Interestingly, the initial contact variability only showed a tendency to increase but did not reach a level of significance. This is surprising; nevertheless it could be explained by a high degree of over-training of this type of movement in cellists.

We are not aware of any research regarding other human contexts that would produce the same variability with greater distance and speed as found in the performance of cellists in our study, though studies may exist. It is possible that any skill requiring highly precise movements at multiple movement distances and speeds

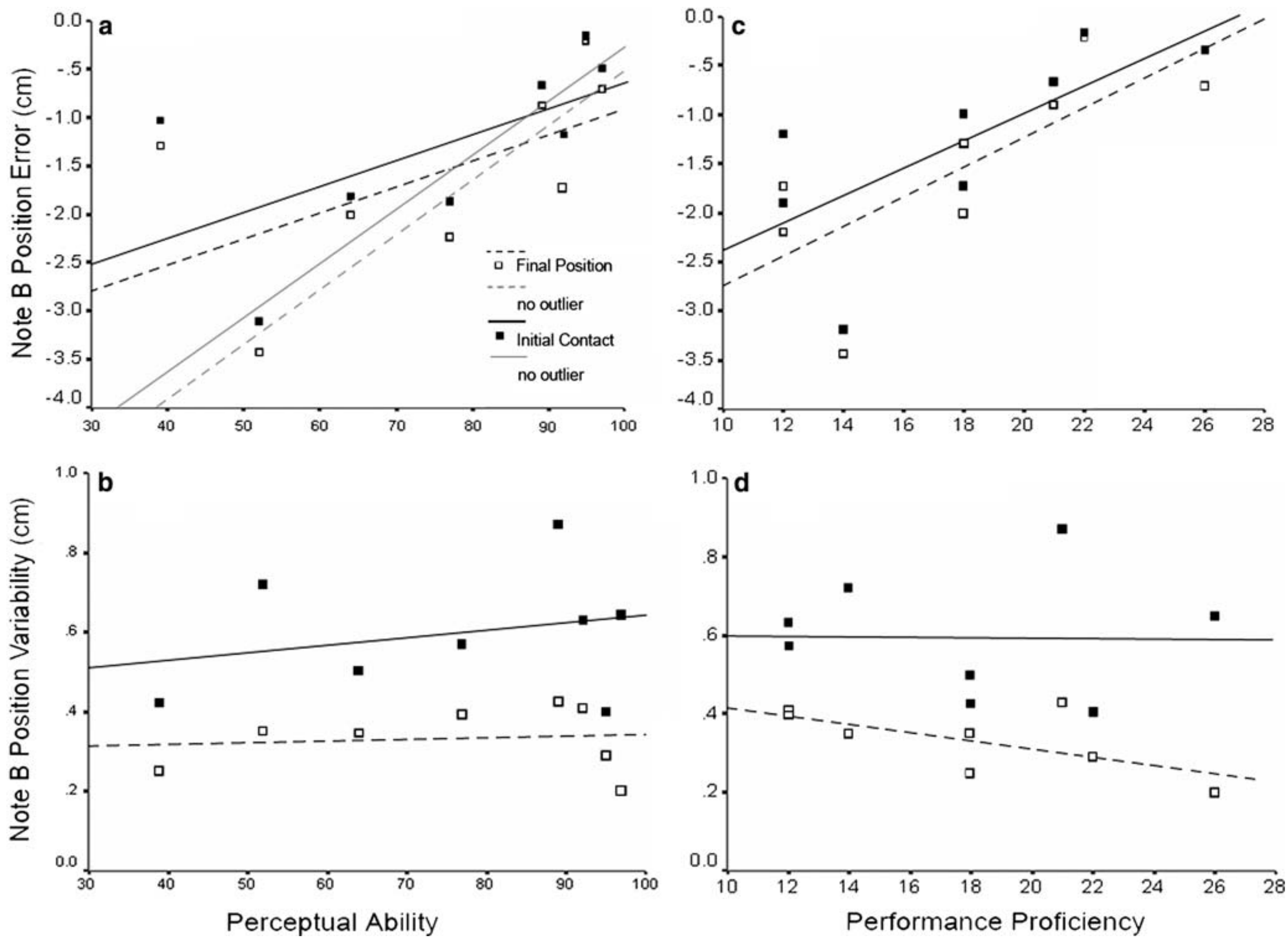

Fig. 7 Correlation of note B position accuracy and perceptual ability (**a**) and performance proficiency (**c**). Correlation of note B position variability and perceptual ability (**b**) and performance proficiency (**d**)

would show similar results. This may indicate that extensive practice in a high precision environment can yield different perceptual-motor control processes than those normally encountered.

The role of gravity and the effect of landmarks

The second and third questions related to performance in a specific stringed instrument, the cello, were the role of gravity in the control of shifting movements and whether landmarks on the cello affected performance accuracy.

One hypothesis regarding the effect of gravity on movement characteristics is that movement in the extension direction towards higher pitches (closer to the bridge) would be faster because it is assisted by gravity. Previous studies (Smyrnis et al. 2000; Flanagan and Lolley 2001) that compared arm movement speed in different directions in the horizontal plane showed that there was no difference between forward and backward directions. Papaxanthis et al. (1998) examined the movement speed in vertical arm pointing movements in upward and downward directions. They found no effect of direction on speed. However, research in the oculomotor system showed that vertical saccades differed in the up and down directions: tending to be quicker and more accurate upward than downward (Collewijn et al. 1988; Schlykowa et al. 1996). Moreover, vertical saccades are slower and less accurate overall compared to horizontal saccades. An alternative hypothesis is that moving toward higher pitch notes would be slower because it is aiming at a smaller pitch window. There have been a large number of studies concerning the speed–accuracy trade-off in pointing movements that showed reduced speed when aiming at a smaller target (Woodworth 1899; Fitts 1954; Meyer et al. 1988, 1990; Plamondon and Alimi 1997; Kelso 1977, 1980; Crossman and Goodeve 1983). Contrary to previous findings in arm movements and the speed–accuracy trade-off hypothesis, it was found in this study that extension velocities (gravity assisted) at the elbow in all three shifting pairs were faster than those in the flexion direction (counter to gravity).

Moreover, despite the faster extension velocities, the initial contact variability of note B was found to be approximately the same for all other notes, except note E. This again contradicts the null hypothesis that velocity would decrease in movements toward higher pitch notes (smaller pitch windows), indicating that musicians are able to maintain their pitch performance even when different movement velocities are involved. It is also possible that this finding (faster extension than flexion velocities) could be due to a training-related phenomenon. If a cellist were to more commonly practice position changes toward higher frequencies on a string (gravity assisted) this could cause a training bias favoring shifts from lower to higher pitches. However, all scale and arpeggio work at the University of Oregon as well as most major schools of music involve equally ascending and descending exercises and therefore equally emphasize both upward and downward shifts.

The extension velocity toward note E was proportionately faster than that for the other two notes and the initial contact position variability was found to be lower in E than all the other notes. This result would be unexpected for normal pointing movements because shifting from B to E is not the shortest shifting distance within the three pairs we tested. However, from the point of view of cello geometry, we noticed that note E resides at the junction of the cello body and neck. Therefore, higher velocities could be used in moving toward note E, since the movement could be stopped by the thumb hitting the neck–body junction. Researchers have shown (Marteniuk et al. 1987) that movement velocity depended on the goal of the task. The movement speed would be higher if the goal of the task were to point and hit the target compared to reaching and grasping it. In addition, as shown in Table 1, although the intra-subject variability of note E was low, the inter-subject variability was still high, indicating that each subject used the neck–body junction as a landmark to reduce endpoint variability on note E. Nevertheless, each individual had a different memorized angle between the thumb and index finger (used to play note E). Although the cutaneous feedback helped to reduce endpoint variability, it did not ensure accuracy.

The contribution of perceptual ability to pitch performance

Fourth, we determined the contribution of perceptual and performance abilities to pitch performance in the above paradigms. We correlated pitch performance (both variability and accuracy) with auditory perceptual abilities (interval identification) and performance proficiency in all cellists. We found that there were significant positive correlations between the perceptual ability and the pitch accuracy, and performance proficiency and accuracy, but pitch variability was not correlated with either perceptual ability or performance proficiency. This suggests that perceptual ability is important for accurate pitch, but movement variability is still constrained by the capacity of the motor system. However, the fact that variability stayed constant with increased movement distance and velocity suggests that the motor system of musicians is highly fine-tuned and different than that possessed by non-musicians, which would result in an increase of variability as movement distance or velocity increases.

One interesting finding in this study is that all cellists tended to play the notes sharp (see Table 1). This result is in agreement with a previous study by Morrison (2000), in which wind instrumentalists were often found to have pitch deviations in the sharp direction from the target pitches within a melody. Thus our result adds evidence to suggest that the tendency toward sharpness is present among different categories of instrumentalists.

In summary, this is the first study of skilled stringed instrument players who possess extraordinary precision, speed and dexterity. There are several findings that contradict previous research in non-musicians. We have found that different movement principles contribute to shifting movements in cellists compared to pointing movements in non-musicians. (1) With higher elbow velocity and shifting distance the endpoint variability stayed constant. (2) Gravity appeared to assist extension movements in shifting toward higher pitched notes, but the faster movement velocity did not result in higher landing variability. (3) Note E on the A string was found to be a landmark. The cutaneous feedback from the thumb when hitting the body–neck junction enabled faster elbow extension velocity compared to shifts towards other notes. (4) Higher performance accuracy was associated with higher perceptual ability on an interval identification task, indicating the importance of perceptual abilities to movement accuracy involved in pitch performance. The lack of correlation between perceptual abilities and pitch performance variability suggests that variability is constrained by the capacity of the motor system, which is highly fine-tuned in musicians and different than non-musicians.

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References

Adamovich SV, Berkinblit MB, Fookson O, Poizner H (1999) Pointing in 3D space to remembered targets. II. Effects of movement speed toward kinesthetically defined targets. Exp Brain Res 125(2):200–210

Adams JA (1971) A closed-loop theory of motor learning. J Mot Behav 3:111–149

Collewijn H, Erkelens CJ, Steinman RM (1988) Binocular coordination of human vertical saccadic eye movements. J Physiol (Lond) 404:183–197

Crossman ERFW, Goodeve PJ (1983) Feedback control of hand-movement and Fitts' law. Q J Exp Psychol 35A:251–278

Fitts PM (1954) The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psycol 47:381–391

Flanagan JR, Lolley S (2001) The inertial anisotropy of the arm is accurately predicted during movement planning. J Neurosci 21(4):1361–1369

Fyk J (1995) Melodic intonation, psychoacoustics, and the violin. Organon, Zielona Gora

Imanaka K (1993) Information-processing mediating the location–distance interference in motor short-term memory. Ann Physiol Anthropol 12(5):269–283

Kay BA, Turvey MT, Meijer OG (2003) An early oscillator model: studies on the biodynamics of the piano strike (Bernstein & Popova, 1930). Motor Control 7:1–45

Keele SW (1986) Motor control. In: Kaufman L, Thomas J, Boff K (eds) Handbook of perception and performance. Wiley, New York

Keele SW, Posner MI (1968) Processing visual feedback in rapid movement. J Exp Psychol 77:155–158

Kelso JAS (1977) Motor control mechanisms underlying human movement reproduction. J Exp Psychol 3:529–543

Kelso JAS, Holt KJ (1980) Exploring a vibratory systems analysis of human movement production. J Neurophysiol 43:1183–1196

Loftus A, Murphy S, McKenna I, Mon-Williams M (2005) Reduced fields of view are neither necessary nor sufficient for distance underestimation but reduce precision and may cause calibration problems. Exp Brain Res 158(3):328–335

Marteniuk RG, Mackenzie CL, Jeannerod M (1987) Constraints on human arm movements trajectories. Can J Psychol 41:365–368

Messier J, Kalaska JF (1999) Comparison of variability of initial kinematics and endpoints of reaching movements. Exp Brain Res 125(2):139–152

Meyer DE, Abrams RA, Kornblum S, Wright CE, Smith JEK (1988) Optimality in human motor performance: ideal control of rapid aimed movements. Psychol Rev 95:340–370

Meyer DE, Smith K, Kornblum S, Abrams RA, Wright CE (1990) Speed–accuracy tradeoffs in aimed movements: toward a theory of rapid voluntary action. In: Jeannerod M (ed) Attention and performance XIII: motor representation and control. Hillsdale, New Jersey, pp 173–227

Morrison S (2000) Effect of Melodic context, tuning behaviors, and experience on the intonation accuracy of wind players. J Res Music Educ 48:39–51

Palmer C, Meyer R (2000) Conceptual and motor learning in music performance. Psychol Sci 11:63–68

Papaxanthis C, Pozzo T, Stapley P (1998) Effects of movement direction upon kinematic characteristics of vertical arm pointing movements in man. Neurosci Lett 253:103–106

Pepper RL, Herman LM (1970) Decay and interference effects in the short-term retention of a discrete motor act. J Exp Psychol 83(2):1–18

Plamondon R, Alimi AM (1997) Speed/accuracy trade-offs in target-directed movements. Behav Brain Sci 20:279–349

Polit A, Bizzi E (1979) Characteristics of motor programs underlying arm movements in monkeys. J Neurophysiol 42:183–194

Rosenbaum D (1991) Human motor control. Academic, New York

Schlykowa L, Hoffmann KP, Bremmer F, Thiele A, Ehrenstein WH (1996) Monkey saccadic latency and pursuit velocity show a preference for upward directions of target motion. NeuroReport 7:409–412

Schmidt RA, Zelaznik HN, Hawkins B, Frank JS, Quinn JT Jr (1979) Motor output variability: a theory for the accuracy of rapid motor acts. Psychol Rev 86:415–452

Stelmach GE et al (1975) Preselection in short-term motor memory. J Exp Psychol 1:745–755

Stelmach GE et al (1976) Preselection and response biasing in short-term motor memory. Mem Cogn 4:62–66

Smyrnis N, Evdokimidis I, Constantinidis TS, Kastrinakis G (2000) Speed–accuracy trade-off in the performance of pointing movements in different directions in two-dimensional space. Exp Brain Res 134:21–31

Winold H, Thelen E, Feng J (2002) On the rebound. The Strad 514–521

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev 3(13):1–114