UNIVERSITY OF CALIFORNIA

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Motion Study of Violin Bow Technique:

A Study Comparing the Motor Patterns of Professional and Student Violinists

A dissertation submitted in partial satisfaction of the

Requirements for the degree Doctor of Musical Arts

by

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ABSTRACT OF THE DISSERTATION

Motion Study of Violin Bow Technique:

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by

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Doctor of Musical Arts

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The biomechanics of violin bowing is extremely complex and involves balancing a variety of physical parameters. Much of the previous research on violin bowing has investigated bowing techniques away from the context of actual repertoire or utilized extremely advanced equipment that is unavailable for pedagogic use. This study used motion analysis technology to investigate the mechanics of the bow arm during six basic bow strokes (détaché strokes with string crossings, détaché strokes without string crossings, slurred string crossings, sautillé, up bow staccato, and hooked bow strokes). The excerpts investigated were taken directly from the violin repertoire and performed by six subjects of different experience and skill levels. One of the primary goals of the study was to encourage performers and teachers to explore the possibilities of acquiring an understanding of the mechanics involved in violin bowing. The results demonstrate that there is more than one possible motor control strategy for some of the basic strokes. This study gives support to teaching methods that utilize a learner-centered approach where the teacher guides the student to find the best movements for his/her unique physical make-up. In addition, this study has displayed some of the capabilities of motion analysis software as a pedagogical tool.

Chapter 1: Introduction

Important contributors to violin pedagogy, including Galamian, Flesch, Rolland, and Suzuki agree that the art of using the bow is fundamental to producing a good tone on the violin. In their efforts to continually improve tone production, violin students spend a considerable amount of lesson and practice time refining the bow grip as well as the arm motions involved in creating basic bow strokes. Tone production is extremely complex and involves balancing a variety of physical parameters[1]. The string player learns to adjust the mechanics of playing by monitoring how these parameters affect the musical output[2]. Students usually derive their understanding of the biomechanics involved from their teachers, who, in turn, derived their understanding from their personal exploration with the instrument, information provided by their teachers, and/or treatises they have read. Treatises and books written by pedagogues such as Carl Flesch, Paul Rolland, Kato Havas, Ivan Galamian, and Shinichi Suzuki provide information about the physical aspects of playing that should improve understanding of the complexities involved in violin bowing. In addition, researchers such as Polnauer, Marks, Hodgson, Schoonderwalt, and Wanderley have conducted studies in effort to understand how the biomechanical actions of the player impact the sound produced.

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[1] Some of the physical parameters affecting tone production include bow grip, contact point of the bow on the string, force applied to the bow, bow speed and acceleration, bow tilt, angle of the bow on the string (commonly thought of as how "straight" the bow is), finger/wrist/elbow/shoulder angles and motions, and the coordination of arm segments at different points in the bow.

[2] The musical output, especially the tone quality, is dependent not only on the physical motions used but also the student's concept of the sound. Setting up good motor patterns will mean nothing unless the student has a clear aural concept to accompany it.

Much of the research to date has investigated either simple bowing techniques away from the context of actual repertoire or utilized extremely advanced equipment that is unavailable for pedagogic use. In addition, studies have not compared bowing techniques of both expert and student performers to explore how any differences might relate to pedagogy.

This study used motion analysis technology to investigate the mechanics of the bow arm during six basic bow strokes. The excerpts studied were taken directly from the violin repertoire and performed by six subjects of varied experience and skill levels. A primary goal of the study is to demonstrate how this type of motion analysis technology can be applied to the study of violin performance and pedagogy. The analysis in this study does not require complex or expensive lab equipment, nor does it require the user to have a degree in physics or computer science. It employs equipment which allows string teachers to completely analyze their own students with a video camera and motion analysis software in their own studios. Teachers would be utilizing skills that they already have (i.e., visual analysis of movements) rather than dealing with the intimidating analysis of forces and muscle activation firing patterns obtained from other biomechanics technology. This study will hopefully inspire performers and teachers to explore the mechanics involved in bow technique and its application to performance and pedagogy.

Chapter 2: Background

I. Methods for Developing Violin Technique: The Balance between Aural vs. Kinesthetic Feedback

The Kreisler transcription of the Mozart Rondo[3] is a virtuoso piece, requiring the violinist to perform a variety of bow techniques with speed, precision, and fluency. Violinists perfect these bowing techniques (e.g., sautillé, hooked bowing patterns, détaché strokes with and without string crossings, up bow staccato, slurred string crossings) by working through time-tested technical exercises over years of intense instrumental study. Typically, students begin developing these techniques by practicing simple exercises and pieces. The exercises and music studies gradually increase in difficulty, thereby challenging the young players to progress. Ideally, the persistent repetition and continual adjustment required by this learning process allows the violinist to adopt favorable motor patterns that enable consistent and reliable tone production[4].

In addition to using actual repertoire to develop performance skills, students and teachers use other available resources including pedagogical treatises and etude books. Treatises provide detailed descriptions of different bow strokes as well as instructions on how the bow stroke is to be performed. Etude books (exercise books designed to work on

[3] Wolfgang Amadeus Mozart (1756-1791) composed the Serenade for orchestra in D major K.250 for the Haffner family, in the year 1776. This eight movement orchestral work features violin solos in three of the movements, including the fourth movement Rondeau. Composer and violinist Fritz Kreisler (1875-1962) transcribed this piece in the year of 1913 making it a stand-alone virtuoso piece for violin and piano (Mozart 1990).

[4] Motor patterns are an important piece in developing a good sound. It is equally important, however, that students have a clear aural concept and musical intention during practice and performance.

one specific technical skill per exercise) provide the technical exercises necessary to develop these bow strokes. Developed by insightful teachers and players, the descriptions found in treatises are usually based on anecdotal understandings of the physical processes underlying bowing, and the etude books provide graded exercises needed to refine those processes. For the most part, development of bow technique through these methods depends on aural feedback[5] that is reinforced by a teacher. Ideally, the student analyzes his playing in real time and adjusts in order to make incremental improvements. Since excellent musical performance is dependent on proper motor control patterns developed through the practice of fundamental exercises, teachers and students try to identify which faulty motor patterns are causing any less than ideal sounds. Determining the exact motor patterns that are inhibiting the performance can be a difficult task. With the primary focus on aural feedback, the refinement of the motor skills and specific motor patterns central to the technique being learned is not always straightforward. In addition, sometimes the process of refining motor patterns produces less than ideal sounds during the learning process, leading the student and teacher to question whether the motor patterns are heading in a good direction. Therefore, teachers and students would benefit from a better understanding of how motor patterns during violin playing affect the quality of sound produced.

[5] Articulations, dynamics, style, acoustics, as well as other factors influencing personal interpretation and expression should be considered when evaluating the aural result of practice and performance.

Through the development process, student and teachers should continually remember the wise words of Ivan Galamian[6], "Interpretation is the final goal of all instrumental study… Technique is merely the means to this end, the tool to be used in the service of artistic interpretation" (Galamian 1985).

II. Development of technique is complex and is often based on individual differences of each player

The physical motions involved in violin bowing are highly complex. The acquisition of the motor patterns allowing expert control of those motions depends on multiple factors that can overwhelm and confuse both the student and teacher. The development of bow technique is complicated by the fact that there are multiple ways of achieving a desirable sound for any particular bow stroke because of individual physical differences (e.g., length of arms and fingers, flexibility in the shoulder and neck, etc.) as well as small variations in the construction of instruments and bows. Instruction might be enhanced if teachers and students were able to understand the physical actions underlying the various bowing patterns and the various ways to perform a bow stroke with favorable results. This study demonstrates that there is more than one way of performing a stroke.

In Kato Havas's treatise *The Twelve Lesson Course in a New Approach to Violin Playing*, she describes the concept of aural feedback in terms of the violin's "tone". She writes, "If a violin is properly played its tone closely resembles singing… and it is this aim of recapturing the quality of the human voice with all its warmth and expressiveness

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[6] Ivan Galamian (1903-1981) was a world-renowned pedagogue and performer who first published his book *Principles of Violin Playing and Teaching* in 1962.

that demands such great artistic responsibility from anybody who plays the violin." She goes further to imply that tone is linked to the motor patterns of the player producing the sound. She says, "An ugly sound simply means that the violin is maltreated and that erroneous limb and muscle actions are used (Havas 1964)." However, even though Havas and the other pedagogues innately understand this connection and have written many treatises explaining their views on violin technique, there is little research to elucidate their pedagogical ideas.

III. Previous research on motor learning and violin technique

There have been a few studies of violin bowing and the physical motions required for effective tone production. An early biomechanics study by Polnauer and Marks in 1964 explored various aspects of violin playing including bow arm technique. Then, in 1974, Paul Rolland completed a study which focused on the pedagogy of violin playing. In this project, Rolland taught approximately one hundred students recruited from the public schools in Urbana, Illinois over a period of two years. During this time, he put into practice the principles of violin playing, developed during his teaching career. These principles centered on setting up good motor patterns allowing students to play with freedom and ease (Rolland 2000). As a result of the study, Rolland published numerous videos in 1970 (Rolland 1970) as well as a book in 1974 (Rolland 2000) guiding teachers in setting up good motor patterns in beginning violin students. More recently, in the first part of the 21st century, Schoonderwalt and Wanderley utilized specialized lab equipment to track bow movement in an effort to understand the biomechanics involved in violin bowing (Schoonderwalt 2007).

Perhaps the most relevant study (upon which the present motion study is modeled) is a motion study performed in 1934 by Percival Hodgson[7] (Hodgson 1958). In this study, Hodgson used cyclegraphs to track the bow hand during several basic strokes. At that time, many players and teachers focused primarily on whether or not the bow was "straight" or perpendicular to the bridge, and they did not consider the arm motions necessary to draw a straight bow. Hodgson was one of the first to hypothesize that the motion of the bow hand (when viewing the player from the sagittal plane) would consist of non-linear patterns. In order to prove his hypothesis, Hodgson completed one of the first motion studies demonstrating that the actual tracking of the bow hand consisted of curves, figure eights, and waves when violinists were playing basic strokes. Chapter 3 will provide an explanation of his findings in greater detail.

IV. Specific aims of this research

This study examined six different bow strokes that are required for playing the Kreisler transcription of the Mozart Rondo (détaché strokes with string crossings, détaché strokes without string crossings, slurred string crossings, sautillé, up bow staccato, and hooked bow strokes). The aim of this research was to determine the specific bow paths (by tracking the screw of the bow) used by both professional and student violinists when playing six different bow strokes in a piece of music. The term "bow path" in this thesis

[7] Although Hodgson completed the study in 1934, his research was not published until 1958 by the American String Teacher's Association.

is synonymous to the digitized path of the screw of the bow during the performance of the excerpt from the view of the sagittal plane. Because tone production on the violin is dependent on the interaction of the bow with the string, understanding the path of the bow has the potential of impacting both performance and pedagogy. The results of this study may contribute to the overall understanding of the motor control patterns involved in bowing. At the very least, this study will raise questions and provoke thought among violin students and teachers concerning the physical actions involved in violin playing and the simple motion analysis technology used to analyze them.

The specific research questions guiding this investigation include 1) Are bow paths for a given bow stroke similar from player to player? 2) Do the bow paths consist of curves, figure eights, and waves as found in Hodgson's research? 3) Are there differences in the bow paths of students when compared to professional players?

This experiment provides comparisons across six participants (three professional violinists and three university level violin students). Dartfish Motion Analysis Software was used to map the trajectory of the bow strokes and compare bow trajectory among participants (TeamPro 4.5.2.0, Dartfish). The Mozart Rondo was chosen as the piece of preference because it is a virtuosic piece containing a variety of different bow techniques (Mozart 1990). This piece requires the player to have the technical skills to execute all six of the bow strokes studied. The particular excerpts chosen were those that represented the bow stroke studied and were at a technical level that required a minimum of practice time for a relatively accomplished player (under one hour for those who were unfamiliar with the music) to learn the notes contained in the excerpts. At the same time, the excerpts chosen were difficult in the sense that the bow stroke being investigated would need to have been mastered prior to participation in the study.

It was hypothesized that 1) There would be individual differences in the bow paths among all violinists, regardless of whether they are students or professionals[8]. 2) Within the professional participants, Hodgson's curve/wave/figure eight pattern findings[9] would hold true but would vary depending on the preferred interpretation of the excerpt. 3) Within the student participants, Hodgson's curve/wave/figure eight pattern findings[9] would hold true but are less refined (i.e., show more jaggedness to the curves) and less consistent (i.e., show more variation from stroke to stroke) when compared to the strokes of professional participants.

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[8] Even if the tempo is standardized by having participants play to a metronome, each musician may choose to execute the bow stroke in different ways depending on: a) his physical make-up (e.g., length of arms, fingers, wrist flexibility) b) his technical abilities (i.e., comfort level of playing at certain parts of the bow, ease of performing the different bow strokes, consistency of the strokes) and c) his musical interpretation of the passage (i.e., Does the musician choose a stroke that emphasizes a playful character or a more intense character? How is the passage phrased? How does the musician interpret and carry out any dynamics?)

[9] See Chapter 3 for Hodgson's findings

Chapter 3: Percival Hodgson's Study

In his study performed in 1934, Hodgson utilized cyclegraphs to track the bow hand during various bow strokes. According to Hodgson's study, a cyclegraph is "a photographic record of the track covered by a moving object" (Hodgson 1958). In addition to the cyclegraphs, he explained his theories of violin bowing with hand drawn diagrams of the hand/bow motion during different strokes.

Unfortunately, Hodgson does not explain his data collection methods clearly, and it is unknown whether he studied many violinists or just one violinist to come up with his conclusions. The technical level and abilities of the violinists studied are not certain, nor are the sound recordings that go with the cyclegraphs available. Therefore, only limited conclusions can be drawn from the Hodgson study. The following summarizes his findings[10].

String Crossings: Hodgson findings

Hodgson determined that in repetitive string crossings from the D to A string, the bow hand moves in an ellipse (Figure 1).

[10] Images and results are taken from Percival Hodgson's *Motion Study and Violin Bowing* (Hodgson 1958). Images are reprinted with permission from the American String Teachers Association, 4155 Chain Bridge Road, Fairfax, VA 22030

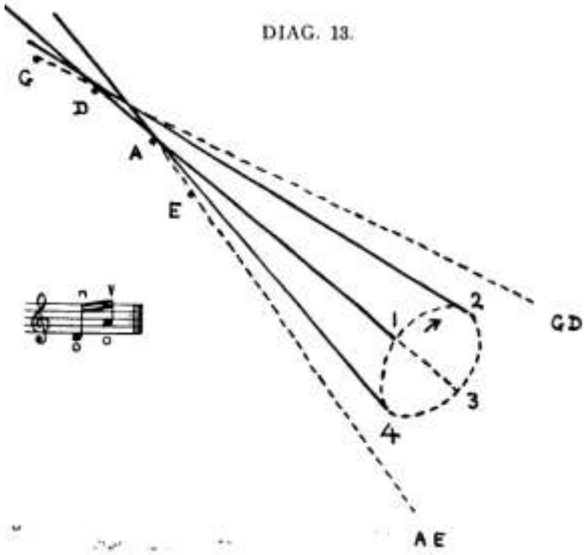

Figure 1: Hodgson's diagram for repetitive string crossings from the D to A string[10]

Hodgson's images were collected from the vantage point of the scroll of the violin pointing away from him. Since this experiment collected video data from the vantage point of the scroll of the violin pointing towards the camera (Figure 2), Hodgson images were flipped to provide consistency in vantage point to aid comparison and analysis (Figure 3 shows the flipped image of Figure 1). In addition, this experiment tracked the screw of the bow rather than the bow hand itself (as Hodgson did), since the Dartfish software tracks objects that contrast in color to the background. The screw of the bow is silver and shiny, so tracking this portion of the bow results in a more accurate bow path. Since the bow hand and screw follow similar paths, results from this study may still be compared to Hodgson's findings.

Figure 2: Experimental set-up in the sagittal plane, flipped images reflect this vantage point

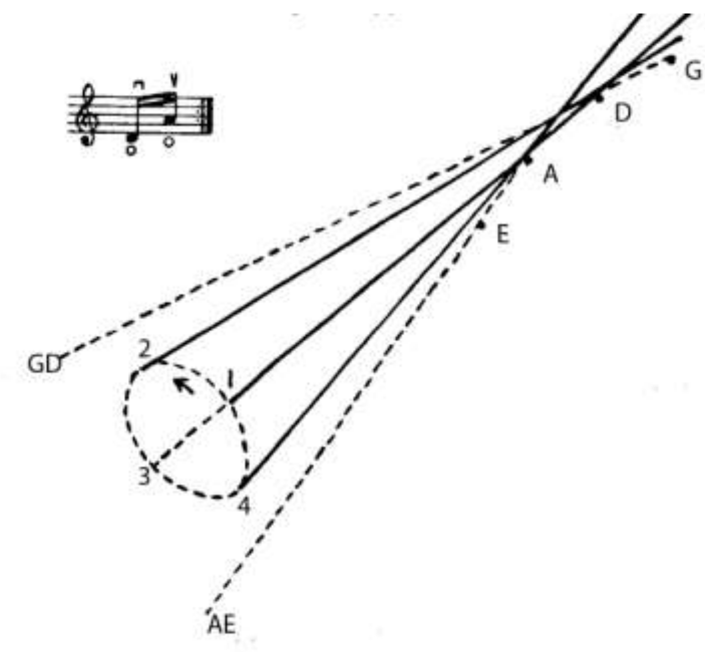

Figure 3: Flipped image of Figure 1 to reflect vantage point shown in Figure 2 [10]

Hodgson found that in string crossings (i.e., bow actions which involve moving the bow across two strings) that do not return to the lower string, the hand moved in a chain of incomplete ellipses (Figure 4).

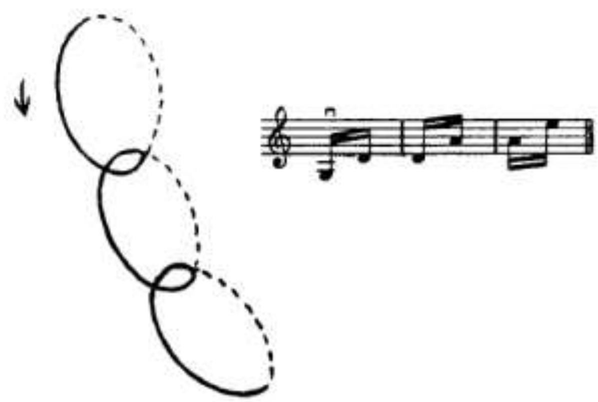

Figure 4: Hodgson's diagram for string crossings without returning to lower string (flipped) [10]

Hodgson found similar loop patterns during the performance of two different arpeggios (Figure 5).

Strokes performed on the same string: Hodgson Findings

Hodgson found that when détaché strokes (i.e., short separate bows played smoothly) are performed repetitively on the same string (in this case the open A string), the bow hand moves in a series of loop patterns (see Figure 6).

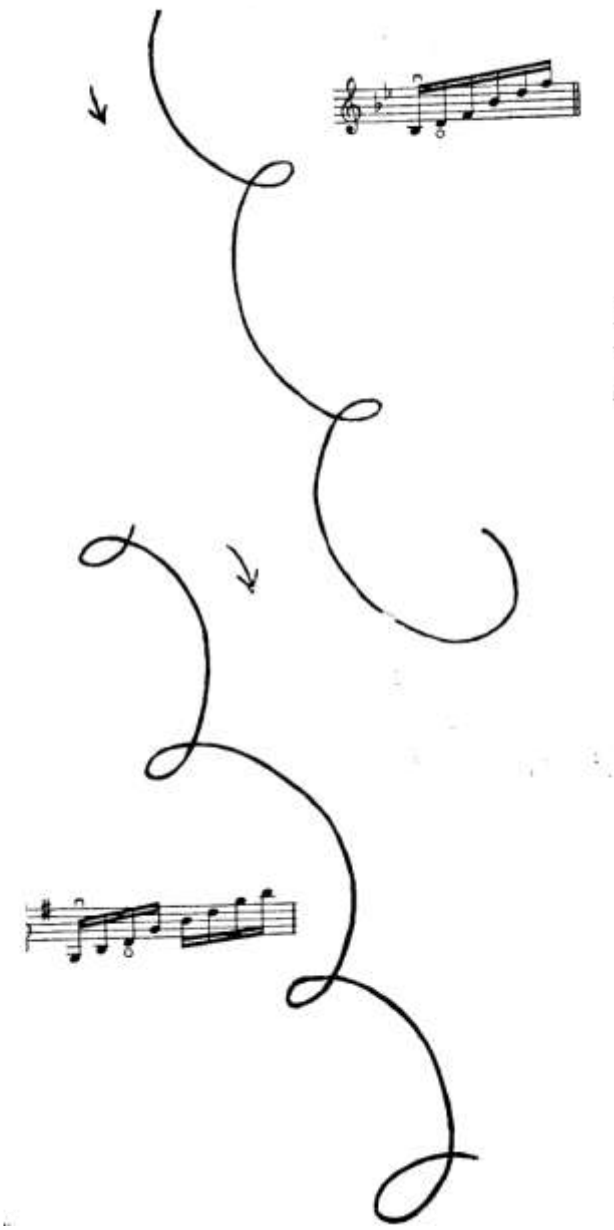

Figure 5: Hodgson's diagrams for the loop patterns found during performance of arpeggios (flipped) [10]

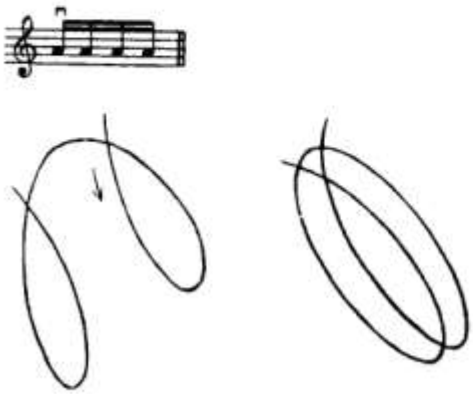

Figure 6: Hodgson’s diagram for détaché strokes performed on the same string (flipped) [10]

Slurred String Crossings: Hodgson Findings

Hodgson found that when string crossings are performed in a slur (the same bow direction), the screw of the bow moves in an arc shape (Figure 7 and 8).

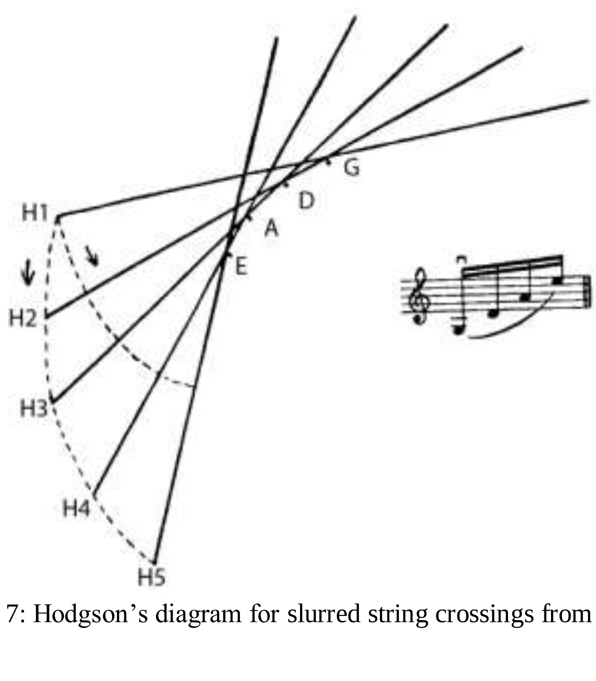

Figure 7: Hodgson’s diagram for slurred string crossings from the G to the E string (flipped)[10]

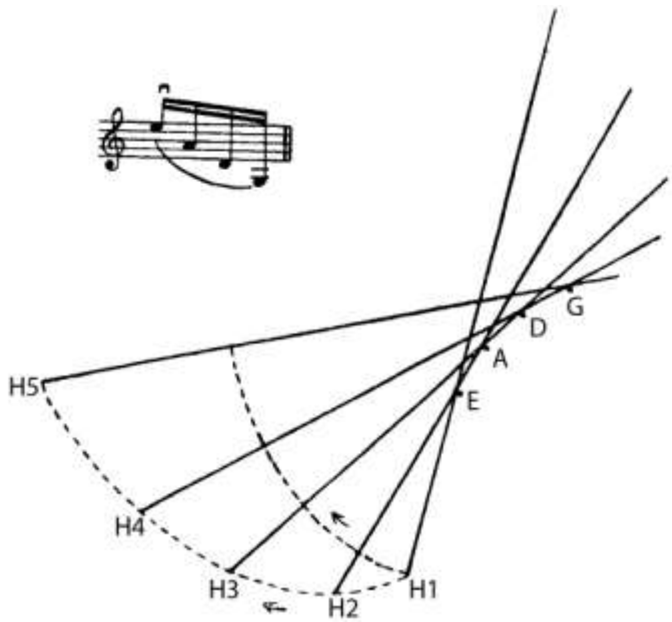

Figure 8: Hodgson's diagram for slurred string crossings from the E to the G string (flipped) [10]

Off-the-String Strokes (Spiccato and Sautillé): Hodgson Findings

Spiccato and sautillé strokes are both characterized as "off-the-string" strokes where the bow drops onto the string and is allowed to rebound off the string utilizing the springy characteristics of the bow itself. The spiccato stroke is often performed at slower tempos than the sautillé stroke and is characterized by the fact that "the bow is thrown down on the strings for every single note and lifted up again" (Galamian 1985). Conversely, the sautillé stroke lacks the lifting and dropping action found in spiccato and instead relies on the "resiliency of the bow stick" and conservation of momentum to fuel the stroke (Galamian 1985). In order to utilize conservation of momentum and resiliency in the bow stick, sautillé strokes are often performed at a faster tempo than spiccato strokes (Pernecky 1998). In Hodgson's study, he found that in spiccato strokes, all parts of the bow move in a figure eight pattern (Figure 9).

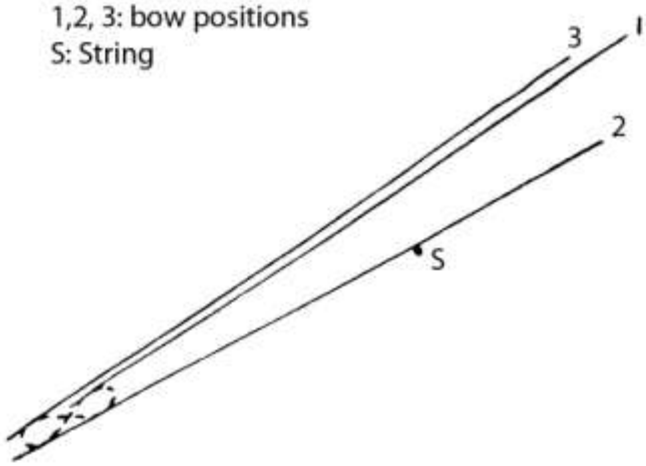

Figure 9: Hodgson's diagram of the spiccato stroke (flipped) [10]

In sautillé strokes, Hodgson found that while the point of impact of the bow with the string continued to move in the figure eight pattern shown in the spiccato stroke, the frog/hand moved in an ellipse (Figure 10).

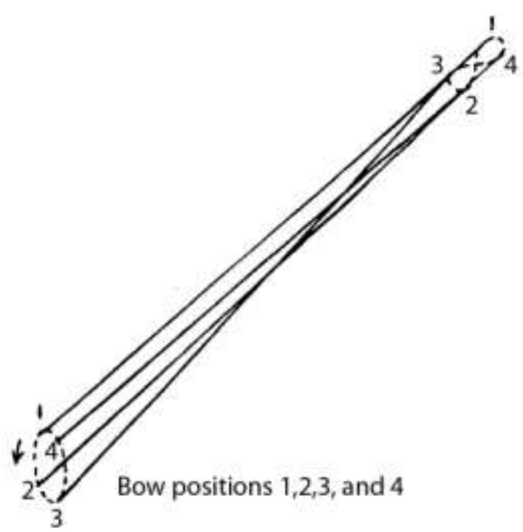

Figure 10: Hodgson's diagram of the sautillé stroke (flipped) [10]

Up Bow Staccato: Hodgson Findings

The up bow staccato stroke can be performed "on" the string or "off" the string. Hodgson refers to the "off" the string stroke as "flying staccato" and found that the frog moves in shallow waves during this stroke (Figure 11). For the "on" the string up bow staccato, Hodgson found that the wave movement of the frog/hand shows "how the motion of the hand is affected by the intermittent pressure of the bow against the strings" (Figure 12).

Figure 11: Hodgson's findings for flying staccato (flipped) [10]

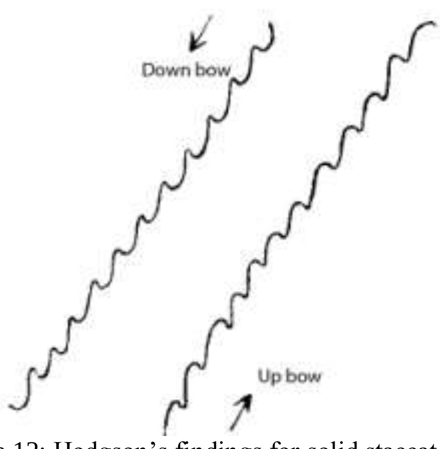

Figure 12: Hodgson's findings for solid staccato (flipped) [10]

Hodgson's study contains useful observations. In order to expand on Hodgson's study, this investigation studied the bow paths of three professional and three student violinists during six selected bow strokes within the violin repertoire. By studying multiple student and professional violinists within the repertoire, this experiment is designed to clarify whether Hodgson's findings hold true for violinists of various skill levels, performing basic bow strokes within the repertoire. In addition, because the technology in 1934 was less advanced, this study was able to examine the bow strokes with present-day video analysis software (TeamPro 4.5.2.0, Dartfish).

Chapter 4: Methods

I. Participant Selection

Three professional violinists (2 male, 1 female) and three student violinists (2 male, 1 female) participated in this study. The professional violinists ranged in age from 25 to 43 years old with a mean age of 36 years old and a median age of 40 years old, and the student violinists ranged in age from 18 to 19 years old with a mean age of 18.7 years old and median age of 19 years old. The professional violinists were active solo, chamber, and/or orchestral musicians who performed on a regular basis. The student violinists were freshmen majoring in music performance at UCLA. Individual differences among the six participants are noted in Table 1. All participants in the study underwent the process of informed consent according to the rules set by the UCLA Institutional Review Board for Human Participants and were free to discontinue participation in the study at any time.

Participant #	Sex	Age	Skill Level	Age started violin	Age started taking lessons
1	Female	25	Professional	4	4
2	Male	40	Professional	7	7
3	Male	43	Professional	7	7
4	Male	19	Student	7	9
5	Female	18	Student	4	4
6	Male	19	Student	5	5

Table 1: Participant Characteristics

II.Task Description:

Each participant was asked to perform five excerpts taken from the Kreisler transcription of the Mozart Rondo. Since each participant had different experience levels with the piece (i.e., some participants had never played the piece, while other participants had performed or practiced the piece at some point in the past), participants were given the excerpts the week before the collection to practice as much as they felt was necessary. Each of the five excerpts is printed below in the same format as given to the participants. For an audio recording of the Mozart Rondo, please reference http://www.youtube.com/watch?v=fwOWKyvPJGY.

Excerpt #1

Figure 13: Excerpt 1, string crossings and détaché strokes without string crossings, measures 33-40

Excerpt #2

Figure 14: Excerpt 2, slurred strings crossings, cadenza passage at measure 322

Excerpt #3

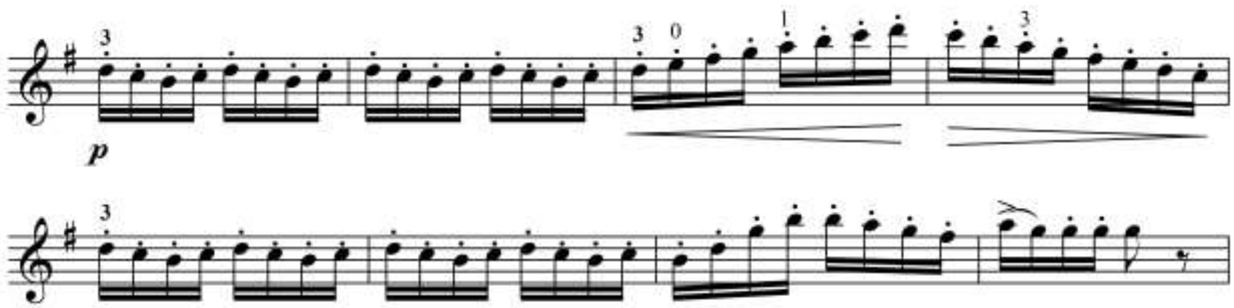

Figure 15: Excerpt 3, Sautillé, measures 1-8

Excerpt #4

Figure 16: Excerpt 4, Up Bow Staccato, measures 84-87

Excerpt #5

Figure 17: Excerpt 5, Hooked Bowings, measures 63-70

Each participant performed fifty-one different trials. Trials included performance of the five excerpts under various playing conditions (Table 2). During the first playing condition, the “preferred way” trials, the participants used their own instruments and bows, played the excerpt at their preferred tempos, and no particular instructions were given as to how to play the excerpt. During the “preferred way: 3x in a row” trials the participants played the excerpt in their “preferred way,” but instead of stopping after playing the excerpt once, they played the excerpt three times in a row, enabling the performer to establish a rhythm that was comfortable to them without having the interruption of having to wait for the “go ahead” from the private investigator. During this condition, performers were not instructed how long to wait between trials, therefore, they could establish a pace comfortable to them. During the “metronome” trials, the participants were asked to perform the excerpts in their “preferred way” with the exception that they must stay with the metronome at half note equals 69 beats per minute. Excerpt 2 was the only excerpt that excluded the metronome trial, since Excerpt 2 is a cadenza passage and is not suited to being played to a metronome. During the “controlled instrument” trials the participants performed the excerpts on a Matsuda 1995 violin and a Nürnberger bow, so that there was no variation in the equipment (i.e., instrument and bow) used among participants. Data was collected over multiple trials in order to choose the best “representative” of the participant’s playing of the excerpt. In addition, trials were collected under these different conditions (i.e., preferred way, metronome, controlled instrument, etc.) so that the condition best suited for analysis could be chosen after the data collection. Any excerpts where a mistake was made in the notes, rhythm, or bowing were not used for analysis.

Experimental Protocol and Analysis:

All participants were given the five excerpts one week ahead of time to practice as much as they felt necessary. The day of collection, participants were given the opportunity to practice between trials to familiarize themselves with the conditions of each trial (i.e., the metronome speed, violin and bow that was new to them). When the participant was ready, two-dimensional kinematics was recorded in the frontal and sagittal planes using two 60 Hz Sony video cameras. In order to analyze the bow path, the video analysis software (TeamPro 4.5.2.0, Dartfish) was used to track the screw of the bow in the sagittal plane. The frontal plane data was used for qualitative analysis only. See Figure 18 for the experimental setup.

The Dartfish software is a user-friendly software used to track the screw of the bow. After the video was imported into the “analyzer” mode, the zoom function was used to focus on the object to be tracked (i.e., the screw of the bow). Then, by selecting the “spline” function and “automatic tracking” option, the screw was tracked as the video was scrolled through frame by frame. The resulting line/curve connected the position of the screw in each frame. It was this line/curve that is represented as the bow path in this paper.

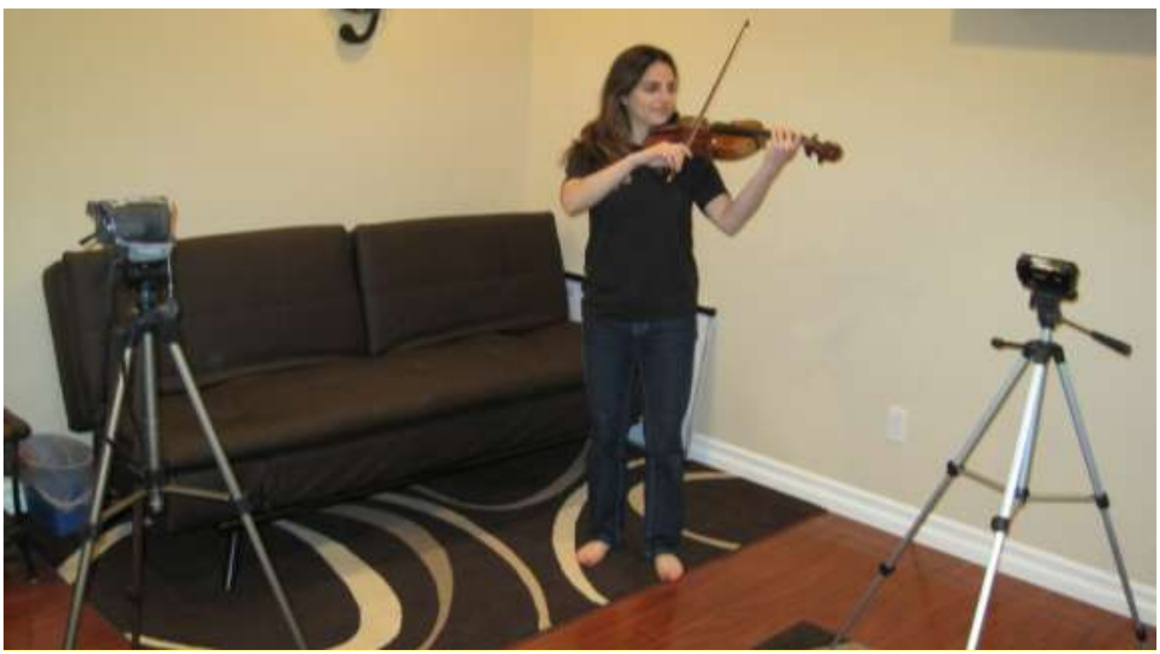

Figure 18: Sample experimental set-up with two cameras capturing video in the frontal and sagittal planes.

Excerpt #	Bowing Studied	Playing Condition	# of Trials Collected
1	String Crossings/ Basic Détaché	Preferred Way	3
1	String Crossings/ Basic Détaché	Preferred Way, 3x in a row	1
1	String Crossings/ Basic Détaché	Metronome = 69	3
1	String Crossings/ Basic Détaché	Metronome = 69, 3x in a row	1
1	String Crossings/ Basic Détaché	Controlled Instrument	3
2	Slurred String Crossings	Preferred Way	3
2	Slurred String Crossings	Preferred Way, 3x in a row	1
2	Slurred String Crossings	Controlled Instrument	3
3	Sautillé	Preferred Way	3
3	Sautillé	Preferred Way, 3x in a row	1
3	Sautillé	Metronome = 69	3
3	Sautillé	Metronome = 69, 3x in a row	1
3	Sautillé	Controlled Instrument	3
4	Up Bow Staccato	Preferred Way	3
4	Up Bow Staccato	Preferred Way, 3x in a row	1
4	Up Bow Staccato	Metronome = 69	3
4	Up Bow Staccato	Metronome = 69, 3x in a row	1
4	Up Bow Staccato	Controlled Instrument	3
5	Hooked Bowing	Preferred Way	3
5	Hooked Bowing	Preferred Way, 3x in a row	1
5	Hooked Bowing	Metronome = 69	3
5	Hooked Bowing	Metronome = 69, 3x in a row	1
5	Hooked Bowing	Controlled Instrument	3

Table 2: Each participant performed a total of 51 trials under various “playing conditions”

Chapter 5: Results and Discussion of Results

After preliminary inspection of the data, the decision was made to analyze only the preferred trials. For Excerpts 1, 3, 4, and 5, the preferred trial played to a metronome was analyzed so that the tempo was uniform among performers. Since Excerpt 2 could not easily be played to a metronome, the best preferred trial for this excerpt was analyzed. Also, because each participant performed three preferred trials per excerpt, the “best” of the three trials was selected to analyze (i.e., the excerpt that contained the least amount of mistakes in notes and bowing, and the excerpt that seemed to represent the performer’s playing style most accurately). The selection of the “best” trial was made by the principal investigator with help from the participant if he/she had a preference. If all trials were similar in accuracy and the participant had no preference, the last of the three trials was analyzed. Consequently, a total of thirty trials (five trials for each of the six participants) were analyzed by tracking the screw of the bow from the beginning to the end of each passage. The term “bow path” describes the digitized path of the screw of the bow at each time point during the performance of the excerpt. “Bow pattern” describes the shape exhibited from the bow path (e.g., curve, wave, loop, etc.). Since the bow paths often overlapped each other, results are displayed below as one representative stroke to clearly show the patterns created by bow path. In order to help the reader understand the results more clearly, a discussion of the results is included within this section instead of discussing the results in a separate chapter. For an audio recording of the Mozart Rondo please reference http://www.youtube.com/watch?v=fwOWKyvPJGY.

Excerpt 1: String Crossings and Basic Détaché Stroke

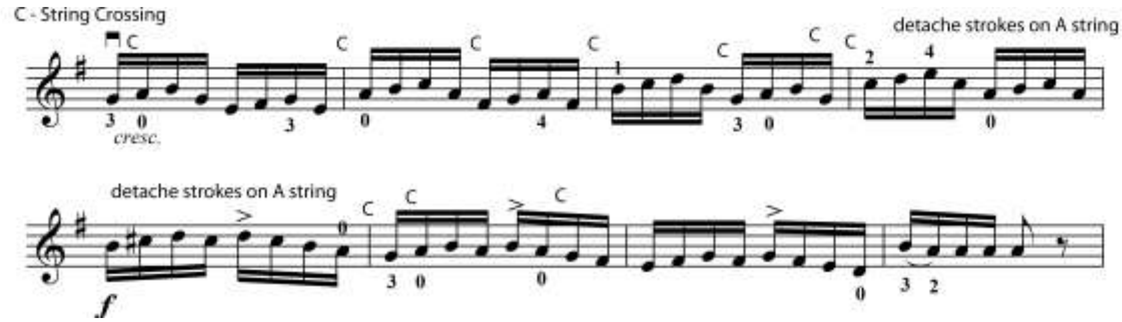

Figure 19: Excerpt 1 with string crossings marked with a “C” and détaché strokes in m. 4-5

For Excerpt 1 (Figure 19), comparisons were made of the bow paths employed by the participants. Excerpt 1 was chosen because the passage includes multiple string crossings (i.e., performance of one note on one string and the next note on a different string – See Figure 19 for all string crossings marked with “C”). In addition, one portion of the passage does not have any string crossings and includes repeated détaché strokes played on the A string (See measures 4-5 in Figure 19). The metronome was set to half note equal to 69 beats per minute to standardize the tempo for all participants. Comparisons of the bow path during the performance of Excerpt 1 demonstrated that all participants employed similar bow paths for the string crossings. However, participants exhibited variation in bow paths when performing the détaché stroke (i.e., short separate bows) repetitively on one string (measures 4-5 in Figure 19). Table 3 summarizes the results.

Pros	String crossings	Détaché Strokes
Participant 1	Curves	Straight lines
Participant 2	Curves	Straight lines
Participant 3	Curves	Loops
Students		
Participant 4	Curves	Loops
Participant 5	Curves	Straight Lines
Participant 6	Curves	Straight Lines

Table 3: Results Summary for Excerpt 1

All of the participants in both professional and student groups performed the string crossings utilizing bow paths in the shape of curves[11] (Figures 20 and 21). The results agreed with the findings from Hodgson's study -- Hodgson also found that when tracking the bow hand, the bow path is in the shape of a curve (Figure 22).

This finding makes sense in terms of the laws of physics. Since one of the primary physical motions involved in a string crossing is flexion and extension of the shoulder joint[12] (which creates an arc-like motion of the hand when holding the bow), the bow should also move in a similar arc shape during string crossings (Figure 23). Thinking

[11] The term "curve" is used in this paper to mean a path that is a continuously bending line that looks like it could form part of a circle or ellipse (i.e., a path that is not a straight line).

[12] If one thinks about the motion of the bow during silent string crossings (i.e., a string crossing without producing any sound), the frog will move in a curved bow pattern (when viewed from the sagittal plane). A performer can achieve the string crossing motion by utilizing a combination of movement from the shoulder (flexion/extension as well as possibly internal and external rotation), wrist (flexion/extension), and/or fingers (flexion/extension). The motions utilized will depend on the distance of the string crossing. For example, if one wants to cross from the G string, the lowest string, to the E string, the highest string, or vice versa, it is impossible to complete this string crossing without flexion/extension of the shoulder joint. In smaller string crossings, for example, going between A and D string (the middle two strings), it is possible to utilize primarily wrist and/or finger motion. In many scenarios, the string crossing motion entails a combination of movements at the shoulder, wrist, and/or fingers.

about the human body and the way the joints are constructed, the most natural way for the body segments to move is in arcs (i.e., circular type motions). Galamian describes this fact in his treatise, originally published in 1962, stating that "… all natural motions of the hand, arm, and fingers as such are circular in character. The motion of bending at any one joint causes an arc to be described by the outer extremity of the section of the arm in motion. Therefore, straight-line motion forms only through a combination of movement which are naturally circular" (Galamian 1985).

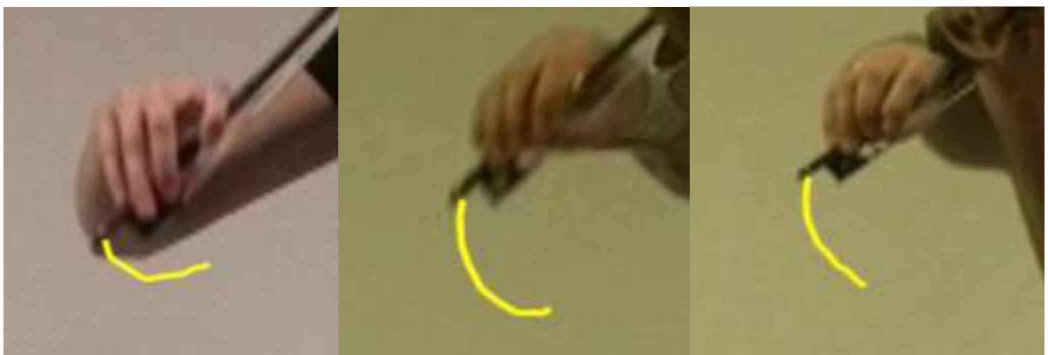

Figure 20: Professional participants' 1, 2, and 3 bow path of the 2nd string crossing of Excerpt 1 (3rd note)

Figure 21: Student participants' 4, 5, and 6 bow path of 2nd string crossing of Excerpt 1 (3rd note)

Figure 22: Hodgson’s findings based on the bow path during performance of string crossings (flipped image) [10]

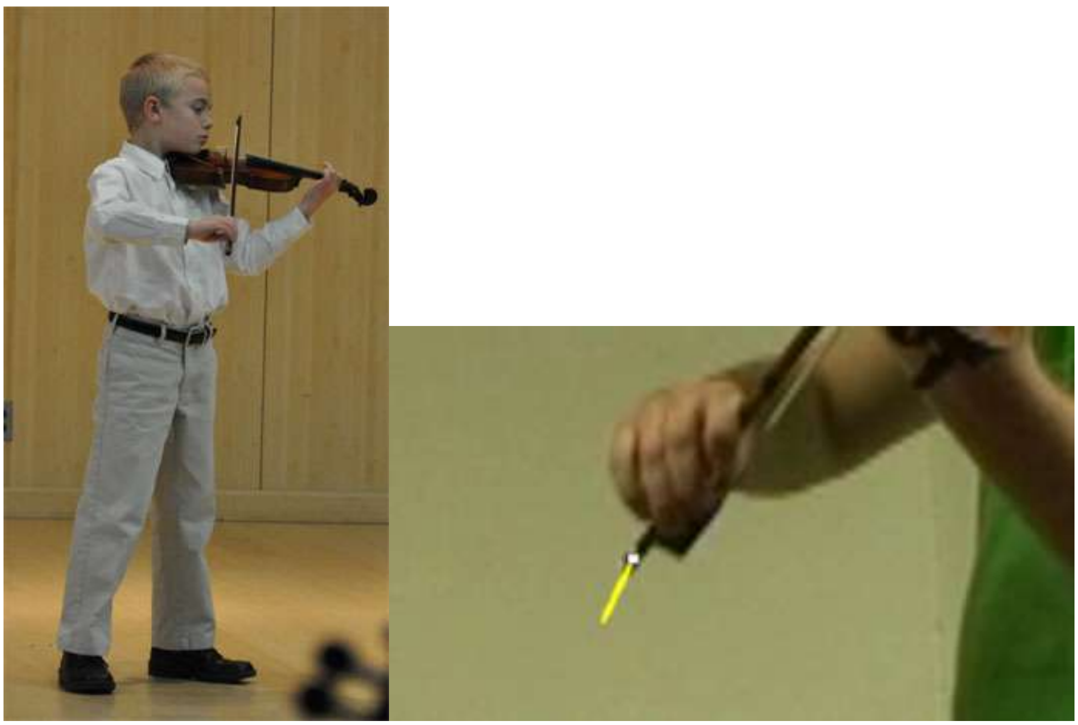

Figure 23: The image on the left illustrates shoulder flexion and extension. Motion of the upper arm in an upward direction is described as shoulder flexion and motion of the upper arm in a downward direction is described as shoulder extension. The image on the right shows the resulting arc-shaped motion of the hand and bow.

All players did not employ identical bowing strategies when performing repeated détaché strokes on the same string. While professional participants 1 and 2, as well as student participants 5 and 6, utilized bow paths in the shape of straight lines (Figure 24), professional participant 3 and student participant 4 utilized bow paths primarily in the shape of loops[13] (Figures 25 & 26). In order to keep the figures uniform, a representative stroke was chosen from the détaché passage (see 5th and 6th notes of m.4, highlighted in blue in Figure 19) so that patterns could be compared among participants. One representative stroke was sufficient to distinguish the “straight line” bow pattern. However, for professional 3 and student 4, it was necessary to show more notes so that the pattern could be distinguished clearly. Student 4 utilized loops that overlapped each other (Figure 25), while professional 3 exhibited loop patterns that did not overlap each other (Figure 26). The Hodgson study found that repetitive strokes on the same string were performed as loops (Figure 27), corresponding with the findings of professional 3 and student 4.

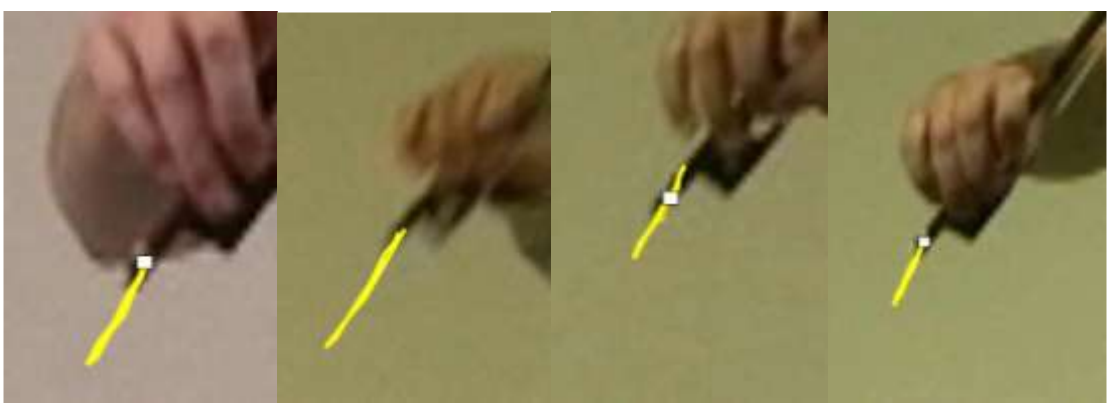

Figure 24: Professional participants 1 & 2 and student participants 5 & 6 utilize bow paths in the shape of a straight line when performing the détaché strokes on the A string in Excerpt 1 (m.4, 5th and 6th notes highlighted in blue in Figure 19)

[13] The term “loop” is used in this paper to mean a path that is similar to a circular or oval shaped line that is curved and overlaps itself.

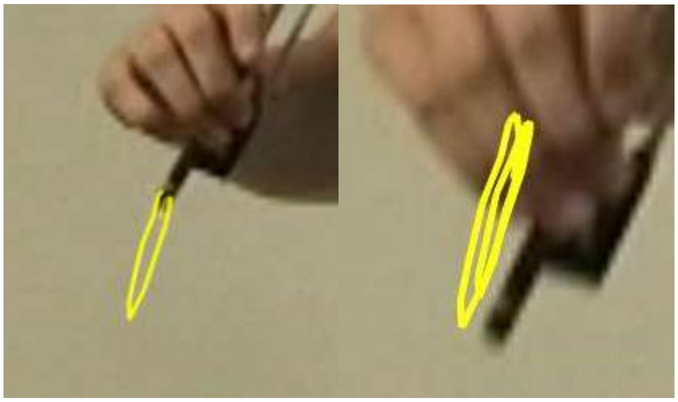

Figure 25: Student participant 4 utilizes bow paths in the shape of loops/ellipses when performing the détaché strokes on the A string in Excerpt 1. The figure on the left shows the almost completed loop formed by performance of the 5th and 6th notes in m. 4 of the excerpt (highlighted in blue in Figure 19). The figure on the right shows the next couple of notes after to show that the pattern does form completed loops.

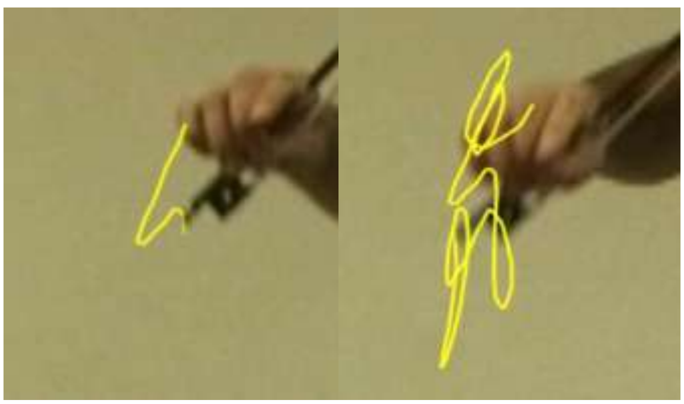

Figure 26: Professional participant 3 utilizes bow paths in the shape of loops/ellipses when performing the détaché strokes on the A string in Excerpt 1. The figure on the left shows an incomplete loop formed by performance of the 5th and 6th notes in m.4 of the excerpt (highlighted in blue in Figure 19). The figure on the right shows the multiple notes following those two notes to show that the pattern does form completed loops.

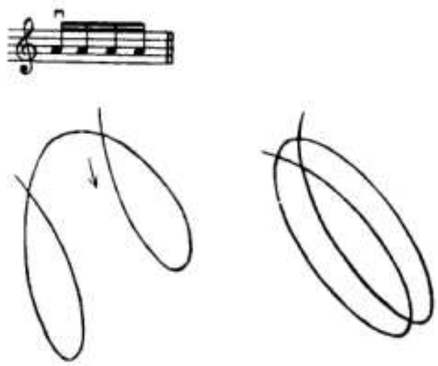

Figure 27: Hodgson found that the bow path of repetitive détaché strokes performed on the same string was in the shape of loops (flipped image) [10]

The results for the détaché stroke suggest that there are at least different two motor control strategies possible to perform the stroke – one strategy exhibits bow patterns in straight lines and the other motor control strategy exhibits bow patterns in loops. Since it was hypothesized that the bow path would be consistent with Hodgson's findings of loops, it was unexpected to find that an additional strategy of straight line patterns was possible. In addition, it was hypothesized that patterns would emerge separating the skill and experience level of the groups. However, the results did not show an association between the preferred control strategy for the détaché stroke and skill level. Since one professional and one student utilized the "loop" strategy whereas two professionals and two students utilized the "straight line" strategy, there was not a clear link between the bow pattern exhibited and the skill level. Because of the limited number of participants in this study, it is unknown whether this is a trend that could be generalized among all professional and student violinists.

Upon observation of the arm segment motions (i.e., upper arm, forearm, hand, and fingers) in the frontal and sagittal planes utilizing Dartfish's slow motion capability, slight differences in segment motion were apparent between participants. All of the participants except professional 1 utilized a pronated forearm position with the little finger not touching the bow. Holding the bow with a more pronated versus supinated forearm position (Figure 28) distributes the weight from the arm more towards the index finger side of the hand versus the little finger side of the hand in supination (Figure 29).

The participants with the more pronated forearm position exhibited a combination of finger motion (flexing and extending the joints in the fingers in a coordinated manner), wrist motion (flexion and extension), and elbow motion (flexion and extension – opening and closing elbow) to help create the length of the stroke on the string. Since professional 1 exhibited a forearm position that was less pronated comparatively, the distribution of the arm weight probably remained more equal across the entire hand compared to the other participants. Instead of utilizing as much wrist and finger motion as the other participants, professional 1 mainly utilized the flexion and extension of the elbow during the détaché stroke.

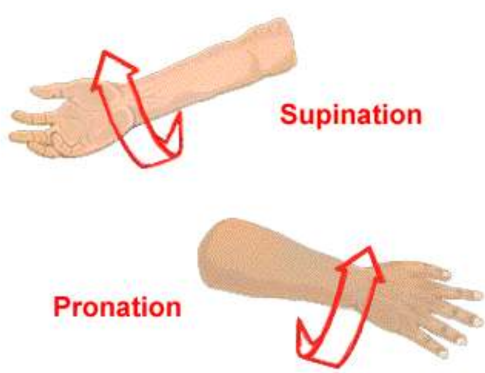

Figure 28: Forearm supination involves rotation of the forearm towards the pinky side of the hand whereas pronation involves rotation of the forearm towards the thumb side of the hand.

Figure 29: Pronation of the forearm while holding the bow distributes the weight of the arm more on the index finger side of the hand while supination distributes the weight of the arm more on the little finger side of the hand

Even though professional 1 varied slightly in the segment motions used to create the détaché stroke, this cannot account for the difference in control strategy of loop patterns vs. straight lines. The only noticeable variation separating student 4 and professional 3 from the rest of the participants was the part of the bow with which they used to play the détaché stroke. While the other participants utilized the middle of the bow or slightly below the middle of the bow, professional 3 and student 4 utilized the middle and upper middle sections of the bow for the détaché stroke. Further research would need to be performed to determine if the location of the bow makes a difference in control strategy used for the détaché stroke.

In addition, professional 3 exhibited a considerable amount of torso movement compared to that of the other players. While the other players primarily performed with little or no torso motion, participant 3 moved his torso constantly throughout the entire excerpt (mostly in the direction of flexion and extension). The body movement most likely explains the reason why participant 3 exhibited a bow path that varied locations (i.e., the bow strokes did not overlap each other and did not remain in the same location from stroke to stroke – see the image on the right in Figure 26), while the other participants exhibited bow paths that overlapped each other with bow strokes in similar locations.

Since Hodgson found that the path of the hand forms loop patterns during the détaché stroke, it was surprising that four of the six participants from the current study employed bow paths of straight lines during the détaché stroke. Considering the possible ways the détaché stroke can be performed, it makes sense that bow patterns in a straight line are possible. Since no string crossings are performed, only a back and forth motion is necessary to create the length of the stroke on the string. When playing on a particular string, the player has some leeway regarding the angle of the bow[14]. It is this freedom that allows the loop strategy to work, since the player is changing the angle of the bow slightly throughout the stroke to form a bow path in the shape of loops. However, just because the freedom to change the angle of the bow exists, does not mean that violinists necessarily utilize this extra space around each string. The four participants who performed bow paths in a "straight line" pattern did not utilize this space around each string. Instead, they maintained a constant angle of the bow throughout the stroke, resulting in the bow pattern of straight lines.

---

[14] Hodgson uses the term of using movements "round the strings" to explain the freedom a player has to change the angle of a bow while remaining on the same string (Hodgson 1958). For example, when playing on the A string, the bow angle can be either almost touching the D string at one extreme or almost touching the E string at the other extreme. This gives the player freedom to play on the A string (without hitting any other strings) with varying bow angles.

Excerpt 2: Slurred String Crossings

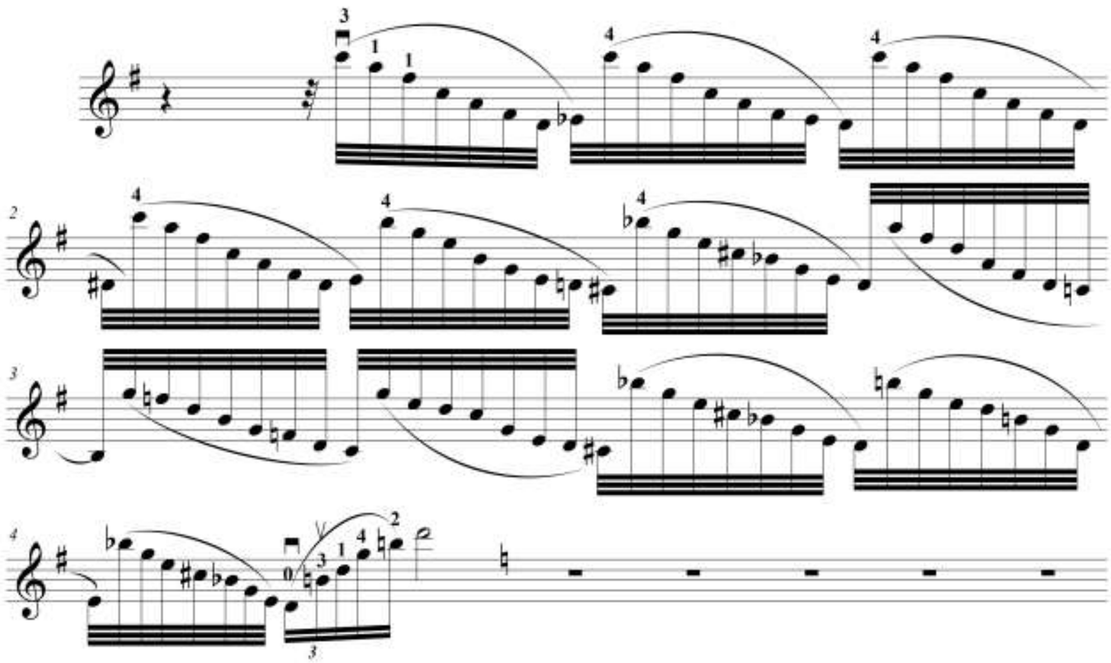

Figure 30: Excerpt 2 with slurred string crossings designated by a "C" highlighted yellow and the big string crossing from D to E string in the transition from the down to the up bow designated by a "C" highlighted blue. The last note of the down bow (E flat) is marked with an arrow.

For Excerpt 2 (Figure 30), comparisons were made of the bow paths utilized by the participants during the slurred string crossing bow stroke. Excerpt 2 was chosen because there are multiple notes that are slurred (i.e., performed in the same bow direction) that also involve crossing to other strings. Since it is a cadenza passage, performers also have more liberty with the tempo and musical interpretation of the passage, which allows for the investigation of the effects of musical interpretation on the bow path. Therefore, no metronome was used to standardize tempo for this excerpt, giving the participant freedom to take more or less time on certain notes to express his/her own musical interpretation of the passage.

Comparisons revealed that all participants utilized bow paths in the shape of curves for the slurred string crossings throughout the entire excerpt. This result was expected since Hodgson also found that the bow path of the hand during slurred string crossings form curves (Figure 31). It makes sense that slurred string crossings would form curved patterns. As explained in Excerpt 1, motion for string crossings utilize shoulder flexion and extension, which results in an arc-shaped motion for the hand and bow. However, Excerpt 2 is not a simple passage (like the ones studied by Hodgson). Therefore, the added complexity of varied musical interpretations of this cadenza passage required further analysis.

For a more in-depth analysis of Excerpt 2, the first two bow strokes will be analyzed in finer detail. While all participants exhibited curved patterns, the bow path of the participants differed in whether the curves exhibited smooth or jagged edges. Smooth edges are defined as curve-like and round, whereas jagged edges are defined as sharp and pointy lacking the roundness of the edges. See Table 4 for the results summary. For the first two strokes, participants 1, 3, 4, and 6 utilized smooth curved patterns with no jagged edges, while participants 2 and 5 utilized curved patterns with a jagged edge immediately prior to the major string crossing between the down and up bow (Figures 32 and 33).

Pros	Shape during the first two strokes
Participant 1	Curves, no jagged edge
Participant 2	Curves, jagged edge before big string crossings
Participant 3	Curves, no jagged edge
Students	
Participant 4	Curves, no jagged edge
Participant 5	Curves, jagged edge before big string crossing
Participant 6	Curves, no jagged edge

Table 4: Results Summary for Excerpt 2

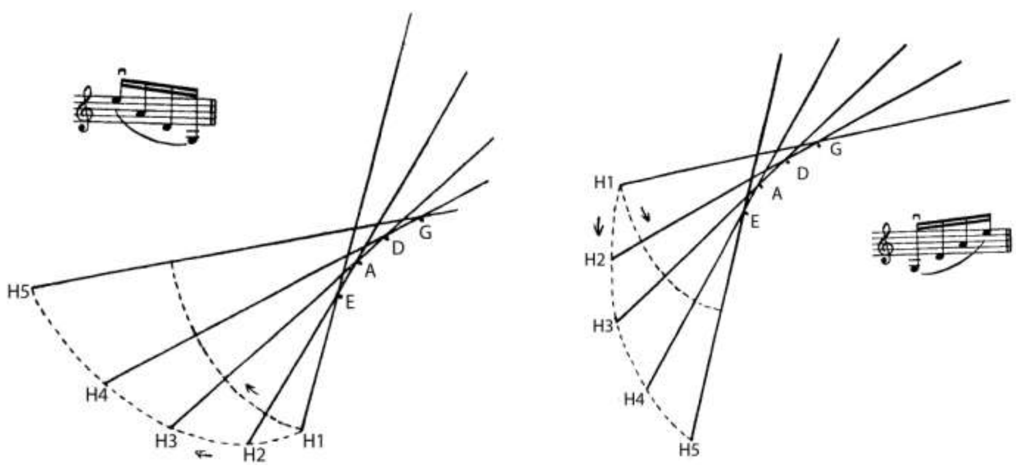

Figure 31: Hodgson found that the bow path during slurred string crossings were in the shape of curves (flipped image) [10]

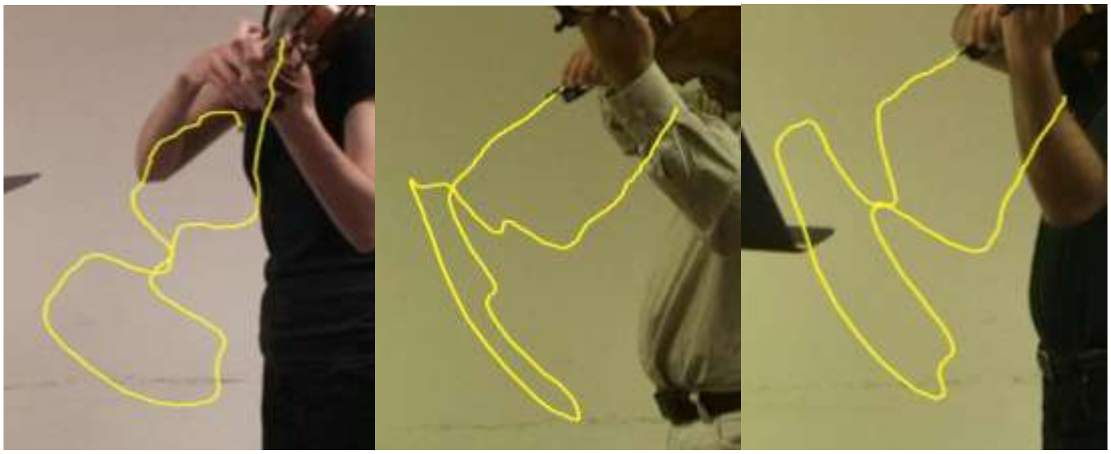

Figure 32: Professional participants 1 & 3 utilize a bow path in a curved pattern with smooth edges in Excerpt 2 (section highlighted in a light blue bow in Figure 30), while professional participant 2 utilizes a bow path in a curved pattern with a jagged edge before the major string crossing from the D to E string ("C" highlighted in blue in Figure 30). Down bows are represented by the arrows in red while up bows are represented by the arrows in yellow. The major string crossing is represented by a blue arrow.

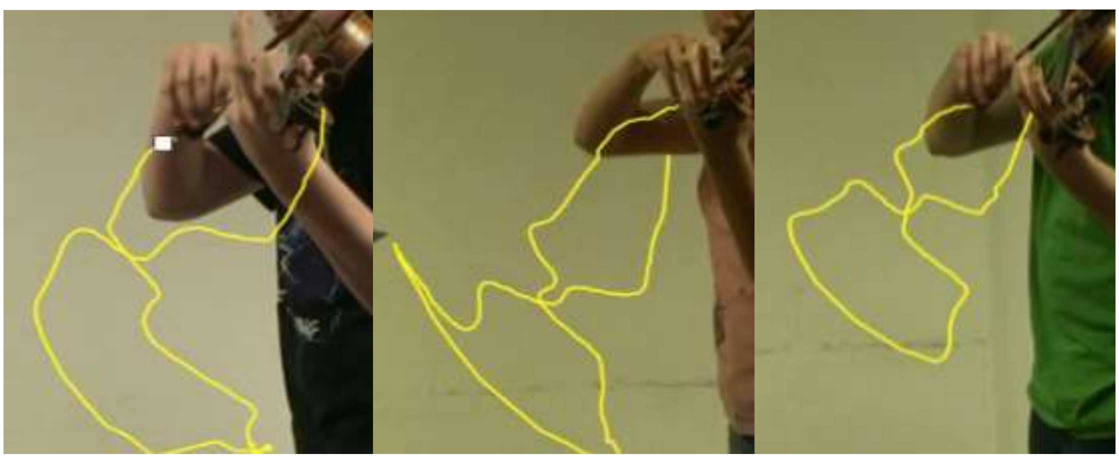

Figure 33: Student participants 4 & 6 utilize a bow path in a curved pattern with smooth edges in Excerpt 2 (section highlighted in a light blue box in Figure 30), while student participant 5 utilizes a bow path in a curved pattern with a jagged edge before the major string crossing from the D to the E string ("C" highlighted in blue in Figure 30). Down bows are represented by the arrows in red while up bows are represented by the arrows in yellow. The major string crossing is represented by a blue arrow.

According to Carl Flesch[15], during string crossings the violinist should "… try to avoid excessive movements and to make those that are necessary almost imperceptible" (Flesch 2000). In the case of Excerpt 2, it is tricky to make the string crossing from D to E string ("C" highlighted in blue in Figure 30) imperceptible because of two complications: 1) The violinist must cross over the A string first before arriving at the final destination of the E string. 2) The violinist performs this large string crossing in the upper half of the bow. String crossings performed in the upper half of the bow require the hand to travel a farther distance than if the same string crossing was performed lower in the bow.

Results showed that the technique used to perform the major string crossing between the down and up bow ("C" highlighted in blue in Figure 29) affected the bow path and whether or not the edge is jagged or smooth. The participants who exhibited smooth edges in the transition from the D to E string started the string crossing motion while they were still playing the last note (E flat) of the down bow (See arrow in Figure 30). Using a similar concept that was developed in Excerpt 1, where different angles of the bow are possible when playing on one string, participants with smooth edges utilized the space they had between the strings when playing on the D string by moving the bow towards the A string while still playing the last note of the down bow on the D string. That way they were closer to their final destination by the time they were ready to play

[15] Carl Flesch (1873-1944), violinist, was a performer and pedagogue. He wrote *Die Kunst des Violin-Spiels* in 1923 based on his experiences as a violin teacher and performer himself. This book was later translated into English, *The Art of Violin Playing*.

on the E string (i.e., their hand had to move a shorter distance to get to the E string). On the other hand, the participants with the jagged edge before the big string crossing finished the down bow motion continuing along the same path used for the previous notes of the down bow before completing a very sharp motion to arrive at the E string for the up bow.

Trying to identify if there was a musical reason behind the “jagged” edge, the principal investigator carefully listened to the audio portion of the research video. It was found that professional 2 tapered the sound at the end of the down bow stroke. As he was making the decrescendo, he held onto the E flat (the last note of the stroke) by rocking the bow more toward the G string as he tapered the note, which contributed to the point of the jagged edge right before the string crossing. Professional 2 was the only participant to decrescendo on the first down bow stroke -- the other participants made either a slight crescendo or remained the same volume. Because of the method professional 2 used to taper the sound, the musical interpretation contributed to the “jagged” edge. The same was not found in student 5. Instead of the jagged edge resulting for musical reasons, the “jagged edge” created by student 5 can be attributed to movement of her torso. Student 5 created the point of the jagged edge by moving her body in an upward motion immediately before the string crossing. It can be hypothesized that she may have created this body movement in an effort to change the angle of the violin, making it technically less difficult to perform the major string crossing.

Student 6 was the only participant to play all of the notes of the slurs evenly without utilizing any rubato (the art of slowing down or speeding up in music for expressive purposes). One can see that his bow path for the down bow looks like a mirror image of the bow path for the up bow. Professional 1 utilized bow paths that were most similar to those used by student 6. Musically, professional 1 lengthened the first few notes of the down bow. Then, once she achieved the tempo she desired, she played the rest of the down bow and next up bow fairly evenly. Tempo and rubato impacted the bow path exhibited by professional 2 as well. He started the down bow slowly and then sped up until he paused slightly before the string crossing. Then, on the up bow he played very quickly, using very little bows for the first several notes of the up bow. This explains why the up bow path was so close to the down bow path – the tempo that he played the first part of the up bow was almost the same speed as that of the string crossing from D to A. Because this cadenza passage allowed the participant much freedom for expression, individuality can be seen in the musical choices[16] and the effects of those choices on the bow paths.

[16] There are a myriad of factors that affect the musical choices of the performer. While this paper only addresses some of these factors, there are numerous additional reasons that could account for differences in the bow path including style, articulation, dynamics, acoustics, instrument and bow differences, variations in the thickness of the string (E string is thinner than G string), and variations in choice of contact point.

III. Excerpt 3: Sautillé

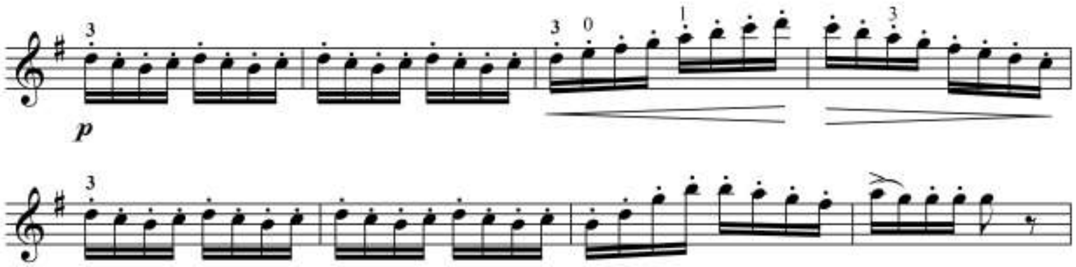

Figure 34: Excerpt 3, sautillé stroke with string crossings marked with a “C” highlighted in yellow

For Excerpt 3 (Figure 34), comparisons were made of the bow paths employed by the participants during the sautillé bow stroke. Use of the metronome (set at half note equal to 69 beats per minute) required all participants to perform the excerpt with either the sautillé stroke (versus spiccato, the other “off” the string stroke) or an “on” the string détaché stroke. The use of the spiccato versus the sautillé bow stroke can often be dependent on the speed of the passage being played. While both strokes are defined as “off” the string strokes (i.e., the bow bounces), sautillé utilizes the momentum and the inherent flexibility of the bow to perform the stroke (Galamian 1985). This often happens at faster tempi (Pernecky 1998). Spiccato, on the other hand, requires more control from the player’s arm in lifting and dropping the bow to and from the string (Galamian 1985), which often occurs at slower tempi. All participants performed this excerpt at the same tempo, in an attempt to force players to perform the sautillé stroke. It was noted that all participants used an “off” the string sautillé stroke to perform the passage with the exception of student 6. Student 6 performed the excerpt at the lower ¼ of the bow (other participants utilized a portion of the bow closer to the middle), which inhibited any rebound of the bow at this speed, resulting in an “on” the string détaché stroke.

Therefore, since participant 6 was the only participant to use a détaché stroke rather than a sautillé stroke, his data was eliminated for the sake of study of the sautillé stroke.

Comparisons of the bow path during performance of Excerpt 3 revealed that participants employed bow paths either in the shape of a straight line or in the shape of a loop (Table 5). Participants 1, 2, and 5 share commonalities and exhibited bow patterns in the shape of straight lines (Figure 35), while participants 3 and 4 seem to share commonalities and exhibited bow patterns in the shape of loops (Figure 36). Hodgson reported that in sautillé strokes the bow path of the hand forms a loop/ellipse pattern (Figure 37), which concurs with the results from participants 3 and 4.

Pros	Shape of Sautillé Stroke
Participant 1	Straight Lines, Same Location
Participant 2	Straight Lines, Similar Location
Participant 3	Loops, Not in same location
Students	
Participant 4	Loops, same location
Participant 5	Straight Lines, same location

Table 5: Results Summary for Excerpt 3

Figure 35: Professionals 1 & 2 and student 5 utilize bow paths in the shape of a straight line when performing the sautillé stroke in Excerpt 3 (5th and 6th note of Excerpt 3, highlighted in blue in Figure 34)

Figure 36: Professional participant 3 and student participant 4 utilize bow paths in the shape of loops when performing the sautillé stroke in Excerpt 3 (5^{th} and 6^{th} note of Excerpt 3 highlighted in blue in Figure 34)

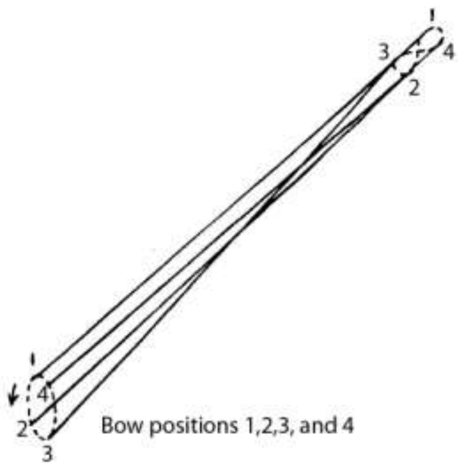

Figure 37: Hodgson found that the bow path when tracking the hand during the sautillé stroke are ellipses/loops (flipped image) [10]

The results for the sautillé stroke suggest that there are at least two different motor control strategies possible to perform the stroke – one strategy exhibits bow patterns in straight lines and the other strategy exhibits bow patterns in loops. However, the results did not show an association between the control strategy used for the sautillé stroke and skill level. Since there was one professional and one student who utilized the “loop” strategy and two professionals and two students who utilized the “straight line” strategy, there does not seem to be a link between the strategy employed and the skill level.

Because of the limited number of participants in this study, it is unknown whether this is a trend that could be generalized among all professional and student violinists.

Upon observation of the arm segment motions (i.e., upper arm, forearm, hand, fingers) in the frontal and sagittal planes utilizing Dartfish's slow motion capability, some differences in segment motion were apparent among participants. While the professional participants utilized a large degree of finger motion (flexing and extending the joints in the fingers in a coordinated motion) to perform the sautillé stroke, the student participants used varying degrees of finger motion. For example, student 5 used a large degree of finger motion whereas student 4 utilized no observable finger motion. Instead, participant 4 utilized a circular motion of the hand/wrist to move the bow. This is most likely what accounted for the loops in participant 4. It was more difficult to identify the reason behind the loop pattern created by the bow path of participant 3. However, one major observable difference between participant 3 and the other participants was the bow grip. Participant 3 exhibited a higher wrist (relative to the elbow level) than the other participants (Figures 38 and 39). The bow grip affects the arm mechanics considerably (Galamian 1985), and therefore, it is a reasonable hypothesis that the loop stroke may be a result of the bow grip. Because his wrist is higher, participant 3 contacts the bow almost underneath the stick with the tips of his index and middle fingers while the other participants maintain a flat contact with the side of the bow with the middle finger and a contact on the top and side of the bow with the index finger (Figure 38 – image on the left). Since participant 3 is able to produce force underneath the bow stick (because his fingers have contact underneath the stick), it suggests that he also would have more ability to generate force away from the string (the lifting action of the bow). Looking back at the bow grip of the other participant who exhibited loop patterns, student 4 utilized a bow grip with the 1st finger extremely close in distance to the rest of the fingers which affects the contact of the index finger on the bow. While the participants 1, 2, and 5 contact the bow with 2nd joint of the index finger on top of the stick (Figure 39), participant 4 contacts the side of the bow with the tip of his index finger (Figure 38 – image on the right). This pulls the balance of his hand more towards the little finger (i.e. supination – Figure 28 and 29), which is the finger responsible for the lifting action of the bow away from the string. This could also explain the lack of finger motion in observed in student 4 with the hand motion dominating the movement of the bow, since the hand was not in a position where the fingers help create the length of the stroke (as observed with the other participants).

Figure 38: The image on the left shows the bow grip of professional 3 exhibiting a high wrist with the index and middle finger contacting the bow almost underneath the stick. The image on the right shows the bow grip of student 4 with tip of the index finger contacting the bow on the side of the stick.

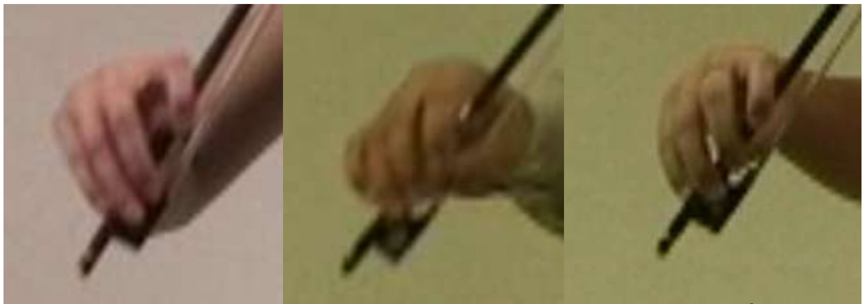
Figure 39: Bow grips of Participants 1, 2, and 5 with contact of the 2nd joint of the index finger on top of the bow stick

In addition, professional 3 exhibited a considerable amount of torso movement compared to the other players. While the other players primarily performed with little or no torso motion, professional 3 moved his torso throughout the excerpt (mostly in the direction of flexion and extension). The body movement most likely explains the reason why participant 3 exhibited a bow path that varied locations (i.e., the bow strokes did not overlap each other and did not remain in the same location from stroke to stroke – see Figure 41), while the other participants exhibited bow paths that overlapped each other with bow strokes in similar locations (Figure 40). Since body movement affects the bow path as measured in this study, analysis must take this added variable into account. In professional 3, the motor control strategy can be a result of the arm movements, the body movement, or a combination. Further research is needed to try to separate out the effects of each variable on the motor control strategy.

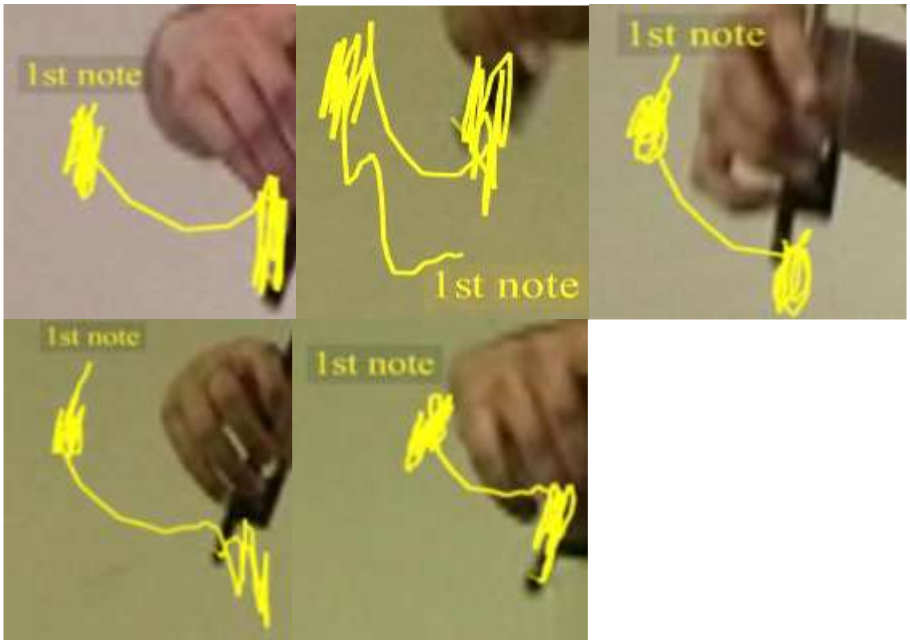

Figure 40: In Excerpt 3, Professionals 1 & 2 and Students 4, 5, & 6 utilize bow strokes that remain in a similar location, overlapping previous strokes

Figure 41: In Excerpt 3, Professional 3 utilizes bow strokes in different locations (the bow strokes do not overlap)

The most surprising result was that four participants employed bow paths of straight lines during the sautillé stroke. This result was unexpected, since Hodgson found that the hand moved in circular patterns during the sautillé stroke. Considering the possible ways the sautillé stroke can be performed, it makes sense that bow patterns in a straight line are possible.

Bouncing the bow can be compared to bouncing a basketball. In order for the basketball to bounce up from the floor, one must first push the basketball downward into the floor. Similarly, a force toward the string is necessary for the bow to bounce off of the string; however, since the bow stick is long, there are two methods to create this bouncing motion. The first method entails keeping the frog/hand stationery and creating a rotation of the bow tip around the frog. Motion of the forearm in pronation and supination or a "see-saw" action of the bow fingers will create this bouncing motion (at this point there is no motion creating the length of the stroke) where the bow hair contacts the string and then springs back. The other possibility entails motion of the entire bow including the frog and tip of the bow going towards and away from the string in a bouncing motion together. Of the two methods, it is the first method of bouncing the bow which will allow the frog to remain in a "straight line" path. As explained in the previous example, this straight line pattern would utilize the frog as the point about which the rest of the bow rotates to create the springing action where the bow hair contacts the string. Movement of the fingers (flexing and extending the joints of the fingers in an oblique direction to mimic the direction the bow is moving), hand (flexion and extension of the wrist), slight opening of the elbow (flexion and extension), and slight swinging at the shoulder joint (abduction and adduction) creates the motion in the direction of the stroke (which is what creates the length of the stroke and the resulting straight line formed by the bow path), while the rebound/springing action (as described above) creates motion at the tip away and towards the string. Therefore, the movement of the tip is not dependent on the movement of the frog moving towards or away from the string.

Although this investigation did not intend to study the bow path tracked at the tip, in order to see if this hypothesis was valid, the tip motion was examined for some participants[17]. Results of the bow path (tracked at the tip) employed by participants 2 and 5 confirm the hypothesis that even though the frog may move in a straight line, the tip can move in curves (Figure 42). In fact, although professional 2 and student 5 both exhibited straight line bow patterns at the frog, each of them exhibited different patterns at the tip (Figure 42). While professional 2 exhibited figure eight patterns, student 5 exhibited arc-like curved patterns at the tip. The results of professional 2 agree with the findings of Hodgson's study that the bow path at the tip created figure eight patterns (Figure 37).

Figure 42: Professional Participant 2 and Student Participant 5 exhibit a figure eight and curved/arc-like pattern when the bow path is tracked at the tip

[17] The bow path was tracked at the tip for those subjects whose tip was in the camera view. Unfortunately, the tip was not captured in the video for participants 1 and 4.

While results of the six participants revealed that two patterns of bow paths (at the frog) were employed (i.e. straight lines and loops), all participants performed a loop stroke on the note directly prior to a string crossing (Figure 43). The only exception was professional participant 2 (Figure 44) because he performed a loop stroke only on the note prior to the 2nd string crossing of the excerpt (crossing from E to A string) and continued the straight line strokes on all notes prior to the 1st string crossing of the excerpt (crossing from A to E string). One possible reason a player might employ a loop stroke prior to the string crossing is to create momentum that will carry the bow to the next string smoothly prior to the performance of the string crossing. Because the bow pattern of a string crossing exhibits a curved pattern, it makes sense to utilize a loop pattern (circular motion) to take advantage of the physics of circular motion versus linear motion. This concept is similar to motion found in daily life. For example, when running to a desired location, in order to change directions and still maintain a linear path, one must slow down, stop, turn around and then continue running in the opposite direction. It is impossible to maintain constant speed during a linear change of direction. However, if one wanted to change directions while maintaining constant speed, one could utilize a circular path (similar to a circular driveway). The second method of changing directions would possibly be smoother, since a constant speed could be maintained during the change of direction.

Therefore, perhaps the loop pattern of the stroke before the string crossing helps conserve momentum similar to that in the running example above, which possibly helps to create a smoother motion of the string crossing and smoother sound. Otherwise, participants would need to create a greater force at the instant of the string crossing to change direction of the bow in order to perform the string crossing, which might create inconsistencies in the sound.

Utilizing an alternative method to the loop stroke on the note before the string crossing, professional 2 inched closer to the E string (gradually moved closer to the E string on each successive stroke) during the several notes prior to the string crossing. This strategy probably created a similar result to the loop strategy – the string crossing would probably be smoother to the E string if the distance traveled in the same amount time is decreased. Another factor that could explain why professional 2 employed a loop pattern before the 2nd string crossing and a straight line pattern before the 1st string crossing is that the 1st string crossing goes to E string on an up bow, while the 2nd string crossing goes to the A string on a down bow. Therefore, the 1st string crossing allows professional 2 to create part of the curve of the string crossing at the same time he is playing the last down bow on A string before the string crossing. While this strategy is logically possible on the 2nd string crossing (the up bow could form part of the arc of the string crossing), professional 2 employed the loop strategy instead.

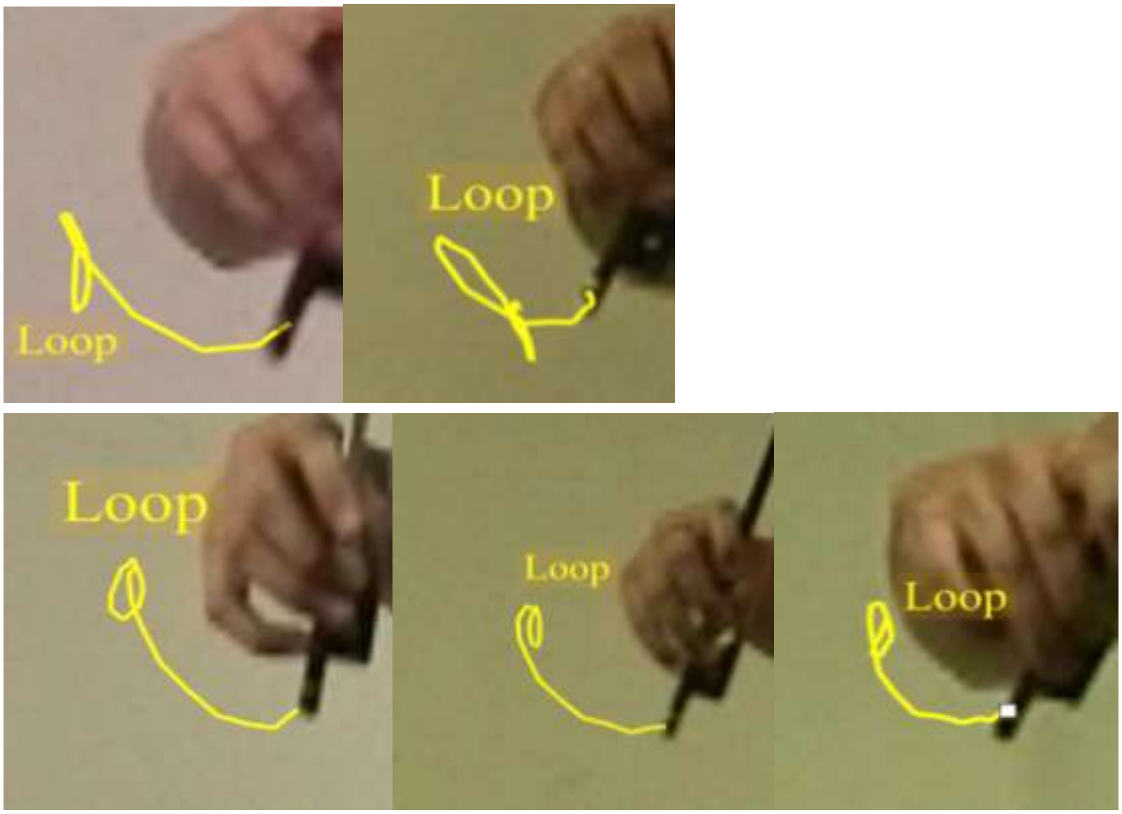

Figure 43: Professional participants 1 & 3 and student participants 4, 5, & 6 perform a loop on the stroke before the first string crossing ("C" in figure 34) of Excerpt 3

Figure 44: Professional 2 does not perform a loop on the stroke before the first string crossing, but does perform a loop on the stroke before the 2nd string crossing to the E string ("C" in figure 34)

IV. Excerpt 4: Up bow staccato

Figure 45: Excerpt 4 Up bow staccato

For Excerpt 4 (Figure 45), comparisons were made of the bow paths employed by the participants during the up bow staccato stroke. In the up bow staccato stroke, participants can perform the up bows either “on” the string, or they can perform the up bows “off” the string. In the case of the “on” the string stroke, participants perform each successive pitch (i.e., up bow stroke) in the same position on the bow that they ended the previous pitch/stroke, without leaving the string between each stroke. Executing the “off” the string stroke (i.e., the bow leaves the string in between successive up bow strokes) requires the performer to choose among three different approaches to using the bow. Performers may 1) overlap/use the same portion of the bow for multiple up bow strokes by recovering/retracting the amount of bow they used on the stroke during the lift, 2) continue in the bow where they left off the previous stroke, utilizing similar bow placement as they would in playing the excerpt “on” the string, or 3) utilize more bow during the lift and continue the next up bow further down the bow from where they finished the last up bow. Use of the metronome (set to half note equals 69 beats per minute) standardized the tempo. However, participants were free to utilize whichever technique they wished when performing the excerpt.

Comparisons of the bow path revealed that all participants exhibited wave patterns and employed an "off" the string stroke (Table 6). The term "wave" is used in this paper to mean a path resembling an undulating curve deviating from a straight path (Figure 46). Only one undulation is necessary to be defined as a "wave" pattern. In addition, participants 1 and 2 also utilized loops for some strokes, as well as waves for other strokes (Figure 47). All three professionals overlapped at least two of the up bows (i.e., utilized the same portion of the bow for multiple strokes). The student participants did not utilize the overlapping technique, and instead performed each successive stroke closer to the frog (Figure 48). Hodgson found that up bow staccato strokes exhibit wave patterns when the bow paths do not overlap (Figure 49), which agrees with the results from this study during performance of the "non-overlapping" up bow staccato strokes. Although Hodgson does not include a diagram for the "overlapping" staccato, he describes this as "a series of forward loops, with the place of contact almost stationery" (Hodgson 1985), which concurs with the results from professionals 1 and 2 in this study.

Pros	Shape	Overlapping on the up bows?	On or Off the String?
Participant 1	Wave and loops	Yes	Off
Participant 2	Waves and loops	Yes	Off
Participant 3	Waves	Yes	Off
Students			
Participant 4	Waves	No	Off
Participant 5	Waves	No	Off
Participant 6	Waves	No	Off

Table 6: Results Summary for Excerpt 4

Figure 46: Example of an undulating wave pattern

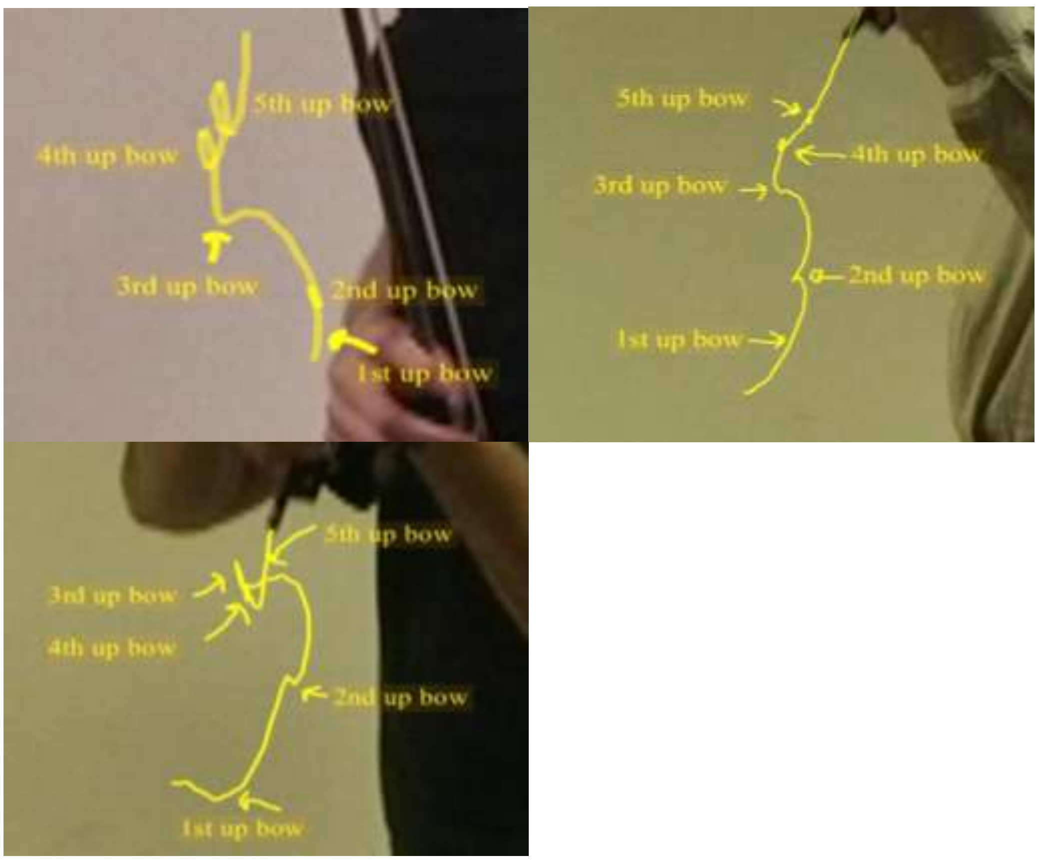

Figure 47: Professional participants 1, 2, & 3 utilize overlapping up bow staccato strokes. The red arrow represents the starting direction of the stroke.

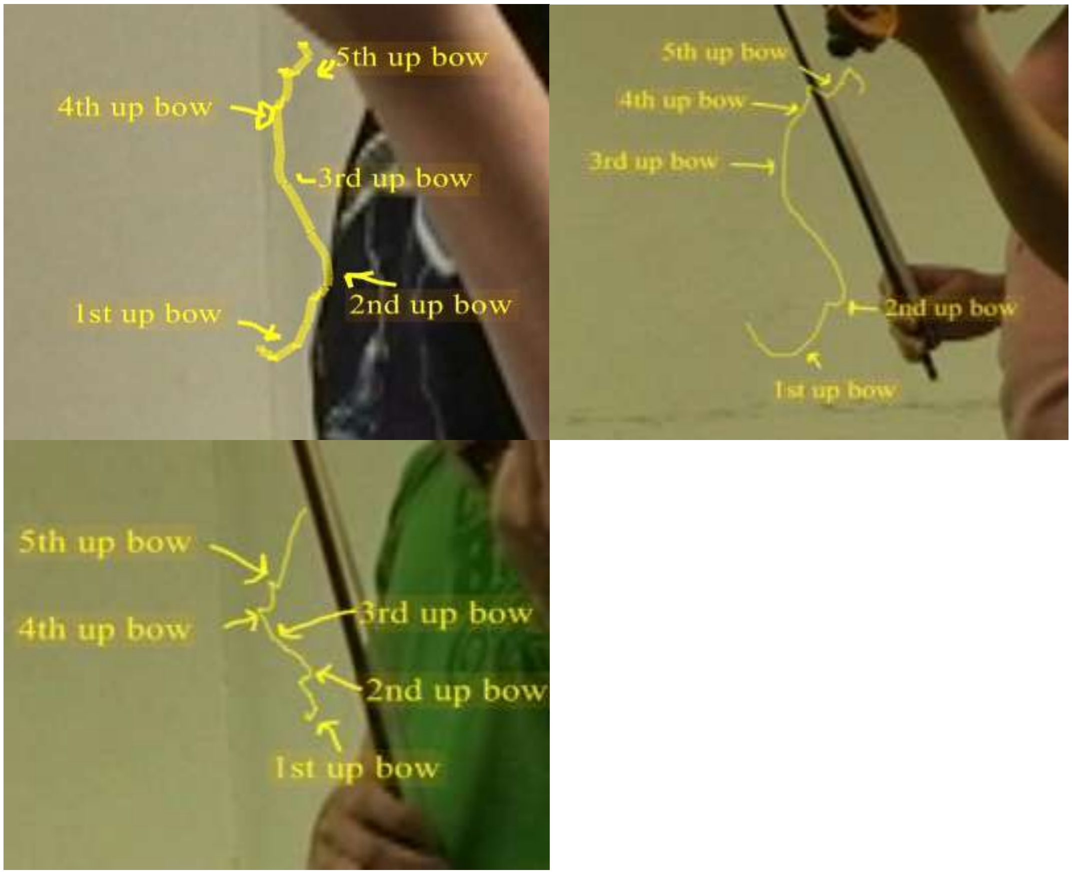

Figure 48: Student participants 4, 5, & 6 do not utilize overlapping up bow staccato strokes. The red arrow represents the starting direction of the stroke.

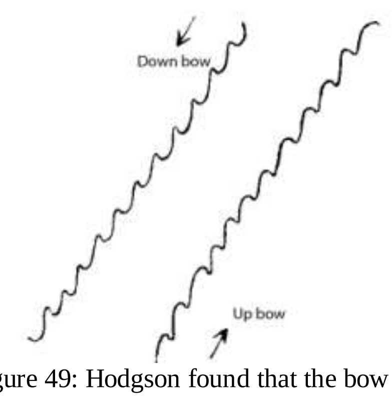

Figure 49: Hodgson found that the bow path during performance of the up bow staccato is in the shape of a wave when there is no overlap of the bow strokes (flipped image) [10]

Comparisons of the up bow staccato bow patterns showed that all participants exhibited bow paths in wave patterns. In Simon Fischer's[18] exercise book, *The Basics*, he explains that the up bow staccato bow stroke is formed by "curves." He states, "Rapid, anticlockwise[19] forearm rotation is an important arm movement in the staccato. The bow stroke that plays each staccato note is curved, and is played around the string[20], not as a straight line along the string. The angle of the pressure for each note curves into the string rather than pushing down vertically" (Fischer 1997). He provides an exercise that forces the student to use the pivoting motion around the strings while playing the up bow staccato (Figure 50) – the exercise has the student pivot to the D string and play a short grace note before pivoting the bow back to the A string to create the staccato note (which is the string the intended staccato note was to be played on). In requiring the student to pivot to the D string in this exercise, the student must exaggerate the pivoting motion that Fischer suggests one should use in playing up bow staccatos on the A string. Results showed that the participants did utilize the space "around the strings" in Excerpt 4 by changing the angle of the bow on the string during performance of the up bow staccato stroke, which was exhibited by a bow path in a "wave" pattern.

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[18] Simon Fischer is a pedagogue who studied with the world renowned teacher Dorothy Delay. He is a well-respected performer and teacher, who has given pedagogy masterclasses around the world. His book, *The Basics*, gives students exercises to explore Fischer's pedagogical techniques and develop the foundational elements in violin playing.

[19] The anti-clockwise rotation that Fischer is referring to is the pronation of the forearm used to rock the bow closer to the lower string before completing the clockwise rotation (supination) of the forearm necessary to perform the up bow staccato stroke.

[20] The concept of playing "around the string" was explained in previous sections of this paper as the "leeway" the player has in the angle of the bow. For example, when playing on the A string, the bow angle can be either almost touching the D string at one extreme or almost touching the E string at the other extreme.

Figure 50: Exercise from Simon Fischer's book, *The Basics,* to help students exaggerate the "curved" motion of the up bow staccato stroke. Copyright © 1997 by C.F. Peters Corporation. Used by Permission. All Rights Reserved.

While all participants employed wave patterns during the up bow staccato stroke, professionals 1 and 2 also employed loop patterns on the 4th and 5th up bow strokes (Figure 18). Part of the explanation for the change to a loop pattern is that professionals 1 and 2 overlapped those particular strokes exhibiting the looped shape, whereas they did not overlap the strokes exhibiting the wave shape. In order to overlap the bow on those strokes, professionals 1 and 2 took the bow off the string after performing the up bow and looped back to a lower part in the bow before starting the next up bow stroke on the string. Interestingly, even though professional 3 also used overlapping strokes on the 3rd and 4th up bows, his overlapping strokes did not form a loop pattern. This can be explained by the increased motion of his instrument as he performed the overlapping strokes compared to participants 1 and 2 who had little or no movement of the instrument. Professional participants 1 and 2 implemented the overlapping stroke by forming loop shaped paths with the bow hand (and kept their violins in the same place throughout the stroke). In contrast, professional 3 overlapped his 3rd and 4th up bows by recovering/retracting the bow (i.e., moving it closer to the tip in order to utilize the same place on the bow to perform the next stroke) utilizing a linear downward hand motion only. However, usually a linear motion like this would create sound as one moved the bow downward on the string. Professional 3 solved this problem by moving his violin away from the bow in a downward motion and then brought the violin back up to the bow once the retracting motion was finished and he was ready to play the next up bow on the string. This movement of the instrument away from the bow achieved the same effect as lifting the bow off the string. Since none of the student players overlapped the bow strokes, it is hypothesized that this "overlapping" technique is more difficult to perform and requires deliberate practice[21] to perfect the technique.

[21] Deliberate practice is a term utilized by researchers in the field of skill acquisition, Ericsson and Anders, to describe practice in which there is a clear goal of improving one or more aspects of performance. See the following section on Excerpt 5 for more discussion on deliberate practice and skill acquisition.

Excerpt 5: Hooked Bowings

Figure 51: Excerpt 5 Hooked Bowings, hooked bows are marked with an "H" highlighted in yellow

Bow paths were compared for the hooked bow stroke in Excerpt 5 (Figure 51). A "hooked bow" entails two successive bow strokes played in the same direction usually followed by a third stroke in the opposite direction. In Excerpt 5, for example, the first two notes are down bows that are "hooked" together followed by an up bow. In hooked bowings, the player stops the bow in between the two notes that are performed in the same bow direction, making the 2nd note a staccato (or detached) articulation. In the case of Excerpt 5, the performer stops the bow in between the dotted eighth note and the sixteenth note. Excerpt 5 contains four hooked bow strokes (the hooked bowings studied are marked with an "H" in Figure 51). The tempo was standardized by the use of the metronome set to half note equal to 69 beats per minute.

Comparing bow paths during the performance of Excerpt 5 revealed that three strategies were utilized by the participants (see Table 7). For the first hooked bow stroke of the excerpt, professional participants 1 and 2 performed a loop in the time period where the bow stopped after the dotted eighth note and before the sixteenth note. Although professional participant 3 also performed a loop, instead of performing the loop between the eighth and sixteenth notes, he performed a loop pattern during the performance of the sixteenth note (Figure 52). Students 4, 5, and 6 employed wave bow patterns in between the dotted eighth and sixteenth note (Figure 53). However, the waves of students 4 and 5 were larger than the shallow wave created by student 6. Since Hodgson did not study this exact bowing, results from this study cannot be compared to his findings.

Pros	Hooked Bowing 1	Hooked Bowing 2	Hooked Bowing 3	Hooked Bowing 4
Participant 1	*Loop*	Wave	Wave	Wave
Participant 2	Loop	Loop	Loop	Loop
Participant 3	Loop	Loop	Loop	*No loop*
Students				
Participant 4	Wave	Wave	Wave	Wave
Participant 5	Wave	Wave	Wave	*Loop*
Participant 6	Wave	Wave	Wave	*Very Small Wave*

Table 7: Results Summary for Excerpt 5

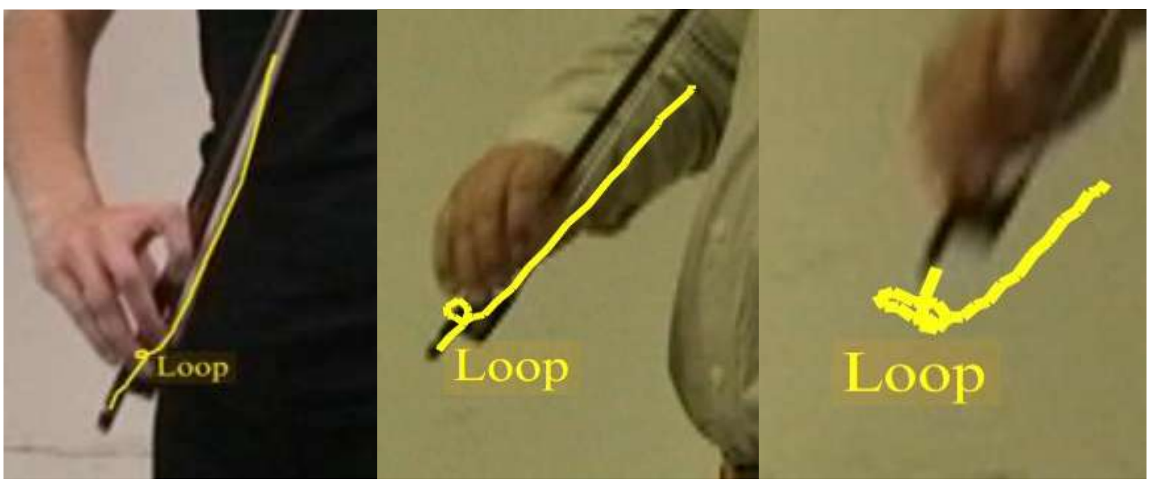

Figure 52: Professional participants' 1, 2, & 3 utilize bow paths in the shape of loops during performance of Excerpt 5 (Bow path of the first hooked bow, the first two down bows, of Excerpt 5). The yellow arrow shows the direction of the stroke and the red arrow shows where the rest occurs between the dotted eight and the sixteenth note.

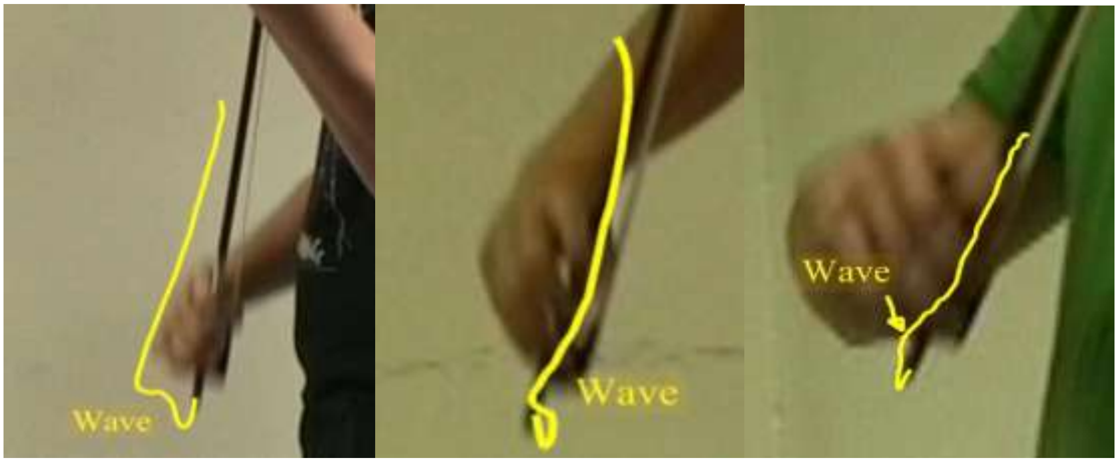

Figure 53: Student participants' 4, 5, & 6 utilize bow paths in the shape of waves during performance of Excerpt 5 (Bow path of the first hooked bow, the first two down bows, of Excerpt 5). The yellow arrow shows the direction of the stroke and the red arrow shows where the rest occurs between the dotted eight and the sixteenth note.

When comparing the bow path of only the 1^{st} hooked bow stroke of the passage, a clear difference is observable between the students and the professionals. All three professionals employed the loop pattern, while all three students exhibited a wave pattern. The appearance of a loop pattern in all three professionals suggests that a loop pattern begins to appear after years of refining the stroke. Thinking analytically about the appearance of the loop pattern in the professionals and how it is created, one could hypothesize that the creation of the loop comes from a relaxation of the bow arm at the exact millisecond that the bow is stopped (during the release of the bow between the dotted eighth note and sixteenth note). During this moment, the performer possibly changes angle of the bow (rocking the bow closer to, but not hitting, the A string) and creates a circular motion that allows the performer to re-grip the E string and perform the 16^{th} note with a clear articulation. The loop strategy allows the up bow following the hooked bow to be at the same angle as the down bow during the hooked bow. This allows for consistency of sound without having to change the angles of the arm segments or changing pressure exerted by the hand from the down to the up bow. This motion requires very fine coordination of the arm and the bow hand. In addition, the movement in the direction of the length of the stroke (the pulling motion of the bow on the string) must be coordinated and timed with the weighting/unweighting of the bow. Because this stroke requires the player to move efficiently in an extremely refined manner, the loop pattern results from years of deliberate practice. According to Ericsson, an authority in the field of skill acquisition, experts achieve consistency and reliability in their performance through years of deliberate practice in which there are specific goals of improving one or more aspects of technique (Ericsson 1993). Similar to sports, expertise in violin playing is associated with efficient physical movements (Flesch 2000).

Interestingly, the bow pattern exhibited by each participant during the performance of the first hooked bowing of Excerpt 5 was not necessarily the bow pattern the participant exhibited on the subsequent hooked bowings of the same passage. For example, while professional participant 1 displayed a bow path in the shape of a loop in the 1st hooked bowing of the passage, she utilized a bow path in the shape of a wave for the following three hooked bows (Figure 54). Similarly, participant 3 utilized loops for the first three hooked bows, but did not quite loop the last hooked bow, forming a bow path with a jagged (sideways “V”) shape to it. Correspondingly, in the student violinists, the bow patterns used for subsequent hooked bows were not necessarily the same pattern used on the first hooked bow of the passage. Student participant 5 utilized bow paths in the shape of waves for the first three hooked bows, while she used a loop shaped stroke for the last hooked bow (Figure 56). In addition, student participant 6 utilized bow paths in the shape of waves for the first three strokes, and although there was a slight wave pattern on the last stroke, the shape was almost a straight line.

Returning to the hypothesis of the “loop” stroke being a result of years of practice to gain the motor efficiency required to perform the stroke in a consistent manner, professional 1 was the youngest (15 years younger than the median age of the three professional participants) of all the professionals and was the only one to change to a wave bow path on the 2nd through 4th bow strokes. In addition, professional 1 and student 5 are capable of performing the stroke utilizing two different control strategies, which may give them more flexibility in performance to utilize whichever method comes easiest to them at that particular moment. More research would be needed to test out these possible hypotheses.

Consistency refers to the repeatability of performance and is often attributed to those of “expert” skill (Deeny 2004). Examining the consistency in the performance of the four hooked bowings within each participant (Figure 55), the results show that professional participant 2 and student participant 4 exhibited the most consistency (i.e., all four hooked bowings were performed with the same bow pattern by the participant, Figure 55). In addition, student participant 6 showed consistency in the bow pattern employed (i.e., a wave pattern was used for all four hooked bows); however, the fourth hooked bowing exhibited a smaller wave than the previous hooked bows (Figure 57). Therefore, although the bow pattern exhibited was consistent, there was a slight difference observed within the wave bow pattern. Similarly, professional participant 3 showed consistency in the bow pattern employed (i.e., a loop pattern was attempted for all four hooked bows), however, he did not complete the loop on the fourth hooked bowing (Figure 57). Therefore, although the basic intentions of the motor patterns were consistent (an unweighting and re-weighting of the bow), there were observable differences in the pattern of the last hooked bow. So, the results of this study do not show that the professional players, or "experts," exhibited a greater degree of consistency than student participants for the hooked bowing. However, because of the limitation of a small sample size, it is unknown whether this would be seen as a general trend among violinists. It is also unknown whether or not "consistency" is more desirable than "flexibility" in bowing technique. Perhaps traits of both "consistency" and "flexibility" can coexist – one can have a set of "possible" motor patterns that are available in one's "toolbox" of strokes which are very consistent within themselves, but also have the "flexibility" to switch from one pattern to another as necessary.

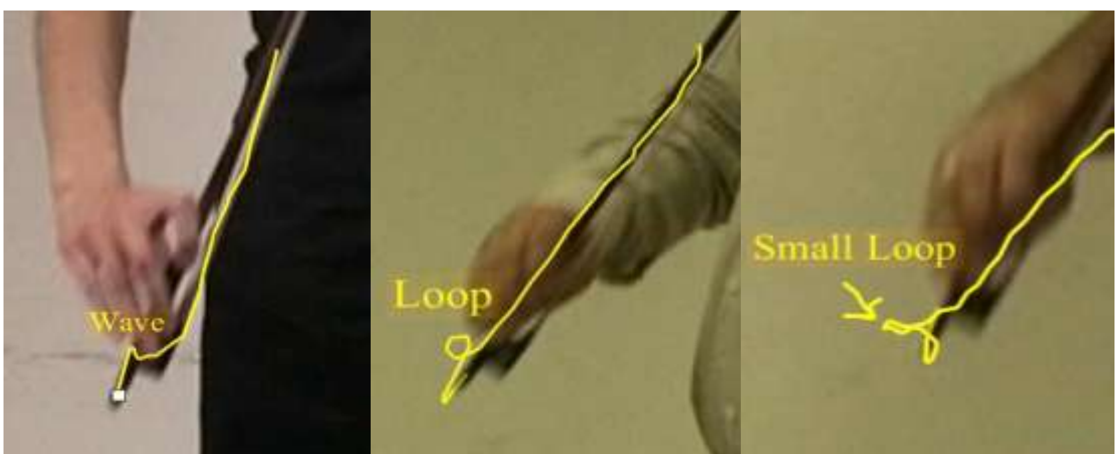

Figure 54: In the 2nd hooked bow of Excerpt 5, professionals 2 & 3 utilize similarly shaped bow paths (loops) as they did for the 1st hooked bow while participant 1 switches to a wave pattern. The yellow arrow shows the direction of the stroke and the red arrow shows where the rest occurs between the dotted eight and the sixteenth note.

Figure 55: In the 2nd hooked bow of Excerpt 5, students 4, 5, & 6 utilize similar bow paths (wave) to those in the 1st hooked bow of the excerpt. The yellow arrow shows the direction of the stroke and the red arrow shows where the rest occurs between the dotted eight and the sixteenth note.

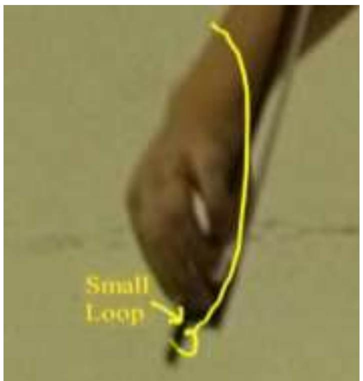

Figure 56: In the 4th hooked bow of Excerpt 5, participant 5 changes to a loop pattern. The yellow arrow shows the direction of the stroke and the red arrow shows where the rest occurs between the dotted eight and the sixteenth note.

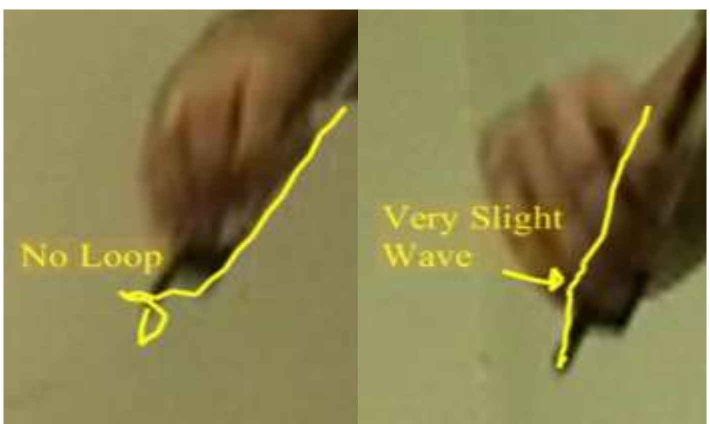

Figure 57: In the 4th hooked bow of Excerpt 5, participants 3 & 6 utilize the same motor control strategy as the other hooked bows, but there was a slight inconsistency in how the pattern was exhibited compared to the other strokes. The yellow arrow shows the direction of the stroke and the red arrow shows where the rest occurs between the dotted eight and the sixteenth note.

One hypothesis for developing “expert” level performance could be the interrelation of two concepts of skill acquisition – deliberate practice and automaticity. While some researchers have found that expert performances exhibit a high degree of automaticity (Deeny 2004), other researchers explain the individual’s struggle against automaticity for fear that performance will reach a peak level that cannot be improved upon once the skill becomes automatic (Ericsson 2004). In research of marksmen, Deeny found EEG activity of the brain differed between skilled and expert performers. The expert marksmen exhibited less communication between the left hemisphere (the side of the brain involved in analytical processing) and the premotor area (the part of the brain involved in motor control) compared to the skilled marksmen. As a result, the experts were able to access the parts of the brain necessary for performing the skill (i.e. premotor area, motor cortex, and subcortical regions) with minimal interference from the left hemisphere (Deeny 2004). Then, according to Ericsson’s research on deliberate practice, the ability to analytically process during deliberate practice is what separates expert performers from skilled or amateur performers (Ericsson 1993).

While these two findings may seem contradictory, there is a way for them to work together, which may be a key to expert performance. The balance between automaticity and conscious control during skill execution is extremely interesting because in order for performers to reach a high enough skill level to be considered experts, they must undertake hours of deliberate practice during which they consciously analyze and re-organize their movement patterns. This process of practicing with conscious examination eventually facilitates performance of the skill with automaticity, allowing experts to perform without interference from the left hemisphere or more analytical side of the brain. The ultimate goal is for the expert to alternate between the “conscious control mode” and the “automatic performance mode.” An expert must have the ability to analyze and improve his/her skills during practice and then enter a state absent from critical thoughts during performance – a state that sport psychologist Timothy Gallwey refers to as performing “in the zone” (Gallwey 1977). This concept of alternating between the practice mode and performance mode can work regardless of how many control strategies the performer has in his/her “toolbox.” For example, during a performance, the player might use different strategies for similar bow strokes in various parts of the piece without consciously choosing one strategy over another. Instead, the mind/body system simply chooses a strategy that fits well with the preceding segment of the piece and its associated motor pattern.

Another possible explanation for the absence of consistency of bow patterns within participants 1, 3, 5, and 6 is that the demands on the performer are slightly different for each of the four hooked bowings. The music that comes before and after each hooked bowing is different. The 1^{st} hooked bowing is the first note played by the participant in that particular trial of the study, whereas the 2^{nd} and 4^{th} hooked bowings follow the up bow in between the 1^{st} and 3^{rd} hooked bowings, and the 3^{rd} hooked bowing starts following a lift. This may account for the difference in bow path employed by professional participant 1 on the 1^{st} hooked bow versus the rest of the passage. This may also explain why participants 3, 5, and 6 exhibited different bow paths on the 4^{th} hooked bowing, since the 4^{th} hooked bowing follows a difficult trill and shift down to 1^{st} position.

The difficulty in the fingering hand may have disrupted the “automaticity” of the bow for those participants, since cognitive resources may have been disproportionately directed to the fingering hand at that moment.

Chapter 6: Concluding Discussion

This study investigated the path of the bow, when tracked at the screw, during six basic bow strokes (détaché strokes with string crossings, détaché strokes without string crossings, slurred string crossings, sautillé, up bow staccato, and hooked bow strokes) performed in excerpts of the Kreisler transcription of the Mozart Rondo by performers of different experience and skill levels. See Table 8 for a summary of the results and how the results compared to Hodgson's findings.

Bowing	**Bow Patterns Exhibited in this Study**	**Hodgson Findings**
Détaché strokes with string crossings	Curves	Curves
Détaché strokes without string crossings	Loops and Straight Lines	Loops
Slurred string crossings	Curves	Curves
Sautillé	Loops and Straight Lines	Loops
Up bow staccato	Waves and Loops	Waves and Loops
Hooked bow strokes	Loops and Waves	Not Studied

Table 8: Results Summary

Although some of the results of this investigation are similar to and support Hodgson's earlier work, a major difference emerged. In this study, more than one bow pattern was often exhibited for each bow stroke. In contrast, Hodgson reported only one possible bow pattern for each bow stroke. There are several potential reasons for this difference. First of all, Hodgson did not indicate how many violinists partook in his investigation. If only one violinist was studied, it makes sense that only one strategy was found per bow stroke. Additionally, Hodgson studied the bow strokes utilizing very simple passages (often 2 or 4 notes long) that were not contained within actual repertoire. When studying the bow strokes within the repertoire, many complexities are added to the investigation. Bowing in the repertoire is complicated because usually different techniques are combined within a passage, making the isolation of any one technique virtually impossible. For example, Excerpt 4 utilizes up bow staccato as well as string crossings, making it harder to isolate the bow path created from just the up bow staccato stroke. Hodgson's study, on the other hand, isolated the techniques. In addition, Hodgson's work did not include the complexity of "musical interpretation" for a passage. Since his study used small excerpts usually on open strings, the goal of the performance was solely to perform the technique with no thought about dynamics or other expressive musical qualities.

Even with the limitations of the small sample size (6 participants total), the results demonstrate that there is more than one possible control strategy for some of the basic bow strokes. For example, in the performance of détaché strokes without string crossings, some participants exhibited bow patterns in the shape of loops, while other participants exhibited bow patterns in the shape of straight lines. Similar findings occurred for the sautillé stroke – some participants utilized a "loop" strategy while others utilized a "straight line" strategy. In addition, for the up bow staccato stroke, some participants employed patterns in the shape of waves only, while other participants demonstrated patterns in the shape of waves and loops. The difference in control strategy for this bow stroke, however, was due to whether or not the participant utilized overlapping bow strokes (i.e., utilized the same portion of the bow). Finally, in the hooked bow stroke, which is the only bowing from this study that Hodgson did not study, both “loop” and “wave” strategies were utilized. Similar to the up bow staccato stroke, the participants did not necessarily utilize the same strategy to perform all four hooked bows in the passage. Some participants utilized the “loop” strategy for one hooked bow stroke while utilizing a “wave” strategy for the other hooked bow strokes of the passage (or vice versa).

The same participants (participants 3 and 4) that employed the “loop” strategy for the détaché strokes without string crossings also employed the “loop” strategy for the sautillé stroke. Similarly, the same participants (participants 1, 2, 5, and 6) that employed the “straight line” strategy for the détaché strokes without string crossings also employed the “straight line” strategy for the sautillé stroke. This result is not too surprising, since pedagogues including Flesch and Galamian agree that the sautillé stroke is derived from the basic détaché stroke (Galamian 1985, Flesch 2000). Therefore, it would make sense that the motor control strategy would be the consistent in the same player for both strokes.

Based on the results of this study, the motor control strategy implemented for any particular stroke is not necessarily associated with skill level. For both the détaché and sautillé strokes, the “loop” strategy was employed by one professional and one student player while the “straight line” strategy was employed by two professional and two student players. The détaché stroke is the most fundamental stroke in violin playing. Therefore, the finding that there is more than one control strategy possible for this stroke (when studying performers of the highest skill and experience levels) implies that there is more than one “valid” way of controlling the fundamental physical movements on the violin. Because of the limitations of the small sample size, it is unknown whether there are only two control strategies possible or whether there are other possibilities as well. More investigation would need to be completed to determine this.

The finding that there is more than one valid control strategy in violin bowing has numerous pedagogical implications. If there is not just "one" correct way of performing a bow stroke, how can teachers help students find motor control patterns that will fit their body the best? Should an instructor teach the way he/she thinks about the motion so that the student can experiment with that way and then come up with his/her own conclusions from this experimentation? If this is the case, should students study with multiple teachers so that they can be introduced to different methods of controlling the movement? Should an instructor try to figure out what strategy fits the particular student best? Or, should the instructor try to figure out what course that student is already on and guide them in a similar direction? These are a few of the many questions that should be considered.

Most learners have experienced different instructional styles. Extreme differences in teaching styles can be exemplified by two contrasting approaches in which teachers either adapt their teaching to the needs of the learner or expect the student to adapt to his/her teaching. The former implies that the teacher has a deep understanding of the subject matter enabling him/her to develop solutions to problems in different settings and scenarios, even those that may be unfamiliar to him/her. This type of teacher has the flexibility to adapt his/her teaching to students with different styles, and approaches teaching with a mind toward what approach will work best for each individual. The latter implies that the teacher has a pre-scripted approach to teaching and follows a strict methodology that he/she believes in strongly and would like to impart upon the learner. For this type of teacher, every student is taught the same thing in an identical manner. Perhaps this type of teacher feels that there is only one "correct" way of playing. Given the findings of this study, this approach of teaching may be worth re-evaluating. In the book *A Teacher is Many Things,* Earl Pullias explains that one of the many roles of a teacher[22] is to be a "learner." He writes, "The wise teacher learns from his students and learns with his students" (Pullias 1977).

Based on the results of this study that show there is more than one approach for creating basic strokes in violin playing, it would be beneficial for a teacher to understand the mechanics of violin playing so well that he/she could figure out the best way to guide each individual student to achieve his/her potential. In this type of teaching, it is not essential that the student performs in the same way as the teacher. Instead, it is more important for the teacher to be able to develop exercises in which the student can increase his/her understanding of possible performance strategies until the student gradually finds

[22] Earl Pullias explains that the role of a teacher is comprised of so many parts that are often contradictory to each other. He writes, "Teaching is many things. The teacher is many persons. Teaching is sometimes instructing, explaining or telling, yet very little can be 'taught' in this sense. Teaching is waiting, but there is a time for action. Teaching involves demands that externally imposed standards be met, yet the best standards are self-made. The teacher is 'learned' – he should know more than his students – but he is aware of deep ignorance and is in essence a learner. The teacher is, in the nature of the teaching/learning process, an example, yet he is stumblingly faulty; he has feet of clay. A teacher should be objective and detached, but probably the best of teaching is very like a love affair" (Pullias1977). In his book, he describes twenty-two roles of a teacher: 1) a guide, 2) a teacher, 3) a modernizer: a bridge between generations, 4) a model: an example, 5) a searcher: one who does not know, 6) a counselor: a confidant and friend, 7) a creator: a stimulator of creativity, 8) an authority: one who knows, 9) an inspirer of vision, 10) a doer of routine, 11) a breaker of camp, 12) a storyteller, 13) an actor, 14) a scene designer, 15) a builder of community, 16) a learner, 17) a facer of reality, 18) an emancipator, 19) an evaluator, 20) a conserver: one who redeems or saves, 21) a culminator, and 22) a person.

a method that works best for him/her. In pedagogy, there are already many exercises that teachers may give students to facilitate the student in finding his/her own path. For example, Simon Fischer's book, *The Basics*, provides exercises which allow the student to experiment with different types of motions through explorative learning methods (Fischer 1997). One example of such an exercise is his "hand balance" exercise where he has the student explore how the balance of the hand changes throughout the length of the bow. In this exercise, found on page 6 of Fischer's book, the student lifts certain fingers off the bow so that he/she can begin to understand and feel which fingers play an important role at certain parts of the bow. In exercises such as this one, the teacher does not have to tell the students exactly how to perform the stroke nor give the student "the answer." In fact, the entire point of the exercise is for the student to figure this out on his/her own as his/her bow hand may need slightly different balance than the teacher's bow hand or his/her bow grip may cause the balance to be slightly different than that of the teacher. This type of exercise puts the teacher in more of a guiding role rather than that of an authoritarian figure.

Maryellen Weimer discusses the importance of "learner-centered" education in her book *Learner-Centered Teaching*. She feels that the present-day education system based upon lecturing and teaching from a pre-established curriculum "makes students dependent learners (Weimer 2002)." However, she hopes that the education system can change towards a learner-centered approach. She writes, "If the goal of teaching is to promote learning, then the role the teacher takes to accomplish that goal changes considerably. Teachers no longer function as exclusive content experts or authoritarian classroom managers and no longer work to improve teaching by developing sophisticated presentation skills. They will lecture less and be much more around the classroom than in front of it (Weimer 2002)."

This idea is similar to teaching other disciplines. While some instructors teach the students the "process" of doing a math problem, others teach the students to "memorize" the steps of how to do the problem. While memorization has a place in learning, the ultimate goal is for the student to have enough understanding of the process to think through problems that are different from the ones they are used to solving. A violin teacher only has limited time during the lesson, often only one hour per week. If the student is unable to self-teach, they are wasting the practice hours of the week in which they could be solving problems on their own. Therefore students who can self-teach will be better players in the long run. The role of the teacher is to prepare the students to "think" about how to solve different problems and how to come up with solutions that work for the individual. This will help guide the student in their practice sessions at home. Sometimes this process is as simple as the teacher working through enough problems with the student at the lesson until he/she understands the method of how to do this on his/her own. Other times it may require more creativity and effort on the teacher's part to get students to the point where they can "think" on their own.

Finally, just as it is helpful in math to be able to solve a problem using multiple methods, the same may be true in violin playing. Being able to perform a bowing motion in different ways may give the student flexibility to choose the easiest or best method when he/she encounters it within the repertoire. Could it be useful for students to learn as many different ways as possible of completing a stroke so that their bodies are adept at utilizing multiple strategies? With this approach, depending on what is presented in the music, the body should be able to adopt automatically the motor pattern that is best suited for that particular situation. Or, would this be confusing for the body and the performer to practice different methods of motor control? Alternatively, it may work best for the teacher to guide the student towards solutions that work best for each particular individual. More study of the instructional process and motor control strategies would be needed to understand the advantages or disadvantages of these learning strategies.

In addition to providing evidence that more than one control strategy is possible in bowing basic strokes, the results also provoked interesting questions as to “why” the results turned out the way they did. In chapter 5, multiple hypotheses were proposed to provide possible answers to those questions. Many of the answers to these hypotheses, unfortunately, cannot be answered utilizing simple motion analysis software such as Dartfish. The analysis performed in this study deliberately used equipment that is easily accessible to the general public and could be used in a teaching studio or home practice setting. However, a drawback to utilizing relatively inexpensive equipment for this study was that in order to test the multiple hypotheses presented as to “why” the results turned out the way they did, one would need to perform more studies requiring equipment that can make measurements such as electromyography to identify the muscles activated, advanced motion tracking equipment utilizing automated motion sensors placed on the bow or arm segments to gain a three dimensional picture of the motion, equipment to measure the pressure of different fingers on the bow, or equipment tracking the angular velocity and acceleration of the bow and arm segments to obtain bow speed or segment velocities and accelerations. If we can begin to understand the correlations between bow path and the physical motions that created the bow path seen in the results, motion analysis software could be a tool used to give an indication about the motor control strategies being used during violin playing.

A similar approach takes place when a doctor is trying to diagnose a patient who presents with an illness. In order to diagnose the patient, the doctor will try to utilize the least invasive methods to try to locate the cause of the symptoms. If someone presents with chest pain, the doctor does not immediately perform open heart surgery, but instead he will look at risk factors (e.g., cholesterol levels, blood pressure, age) along with performing minimally invasive tests such as an EKG or stress test. If those tests point to heart disease, the doctor may perform a more invasive test such as an angiogram to check for blocked arteries. Only then, if results point to a coronary blockage will the doctor perform open heart surgery to restore blood flow.

In the case of a doctor, proper diagnosis of symptoms often means life or death, whereas in violin playing, the consequences of improperly developed motor control strategies may result in poor tone and possibly, at the very worst, injury to the performer. However, the methods for diagnosing issues can be similar. At the moment, teachers and students rely on visual and auditory feedback happening in real time to diagnose problems. Perhaps, live motion analysis software can provide another tool that will allow teachers and students to reap more information in a relatively simple and non-invasive way. Live motion analysis technology allows students and teachers to analyze many aspects of performance. In addition to tracking the bow path, the technology is capable of playing back video in slow motion (at ¼ normal speed or ½ normal speed), comparing performances side by side (up to four videos at one time) or overlaid on top of each other (up to 2 videos at one time), and comparing a student's video to that of a professional to determine similarities and differences. These visual comparisons enhance the abilities of the teacher to utilize his/her knowledge in a way that will be helpful to the student. Usually a teacher must analyze and identify problems in a student's playing in real-time. He/she relies on words and demonstration to help a student understand the problems and methods of fixing them. Video analysis technology will give the teacher the additional tool of being able to make comparisons and replay videos in slow motion to show the student exactly what he/she sees. If both the student and teacher obtain a clearer view of what is actually happening during performance, problems can potentially be pinpointed and solved more efficiently. In addition, use of this type of software can be very useful in helping the student to become more independent in identifying his/her own technical problems and directing practice sessions in between lessons to address those issues. Even just a few sessions with this type of software could prove useful for a student who benefits from this type of visual learning tool[23]. In fact, similar live motion analysis technology is already being used in sports to give immediate feedback to players.

While this paper has focused mainly on the physical motions during bowing, one cannot stress enough the importance of training the student's ear to guide him/her to

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[23] The amount and type of in-depth analysis that is beneficial for a particular student will vary depending on the individual student, his/her learning style, and his/her personality. It is important that the teacher and student are careful not to overanalyze to the extent that the student experiences a complete breakdown of skill.

favorable motor patterns. The purpose of this paper was to explore the various motor patterns that will enable a good sound. However, just because the motor patterns are developed in an appropriate way does not ensure that the resulting performance will have musical value. In addition, the method the teacher utilizes in order to develop students' motor patterns will vary depending on the student and the teacher. Just as there are multiple motor patterns possible for basic bow strokes, there are also multiple paths towards teaching a student how to achieve a musically satisfying performance. While some students will have more success focusing on the physical motions that will enable them to carry out their musical intentions, other students will have more success focusing on the aural concept and letting the body figure out how to create that result without too much motion analysis. The end goal is the same – be able to perform artistically, with the freedom from technique to express the music exactly how we feel it.

Chapter 7: Implications and Future Research

One of the primary goals of this study was to encourage performers and teachers to explore the possibilities of acquiring an understanding of the mechanics involved in violin bowing. The finding that there is more than one valid strategy for performing a bow stroke has numerous implications for pedagogy. This study gives support to teaching methods that utilize a learner-centered approach where the teacher assumes a guiding rather than an authoritarian role, helping the student to find the best movements for his/her unique physical make-up. In addition, this study has displayed some of the capabilities of motion analysis software of violin playing. This technology can possibly be an additional tool to be utilized by students and teachers in the future of pedagogy. Future research can aim to clarify and confirm the findings of this study as well as answer some of the questions that were raised. Possible studies include: 1) repeating a similar study adding use of three dimensional automatic motion tracking equipment with capabilities to measure speed and acceleration parameters in order to gain a more complete picture of the biomechanics involved; 2) researching how technology of this nature can be implemented into pedagogical settings; 3) studying a greater number of violinists to see if the trends in this study can be generalized among all professionally and student violinists; and 4) studying violinists at the very beginning stages of learning to see how the motor patterns develop over time. Hopefully, through combined efforts of researchers, pedagogues, and students, we can continually increase the information available to aid in the understanding and the pedagogy of bowing technique.

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