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A case study of scaling multiple parameters by the violin

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Abstract
This article will present a single case study of the acoustic attributes of sound production techniques that are involved in the expansion of performance practice with the violin. In this study, four elements were chosen from the multidimensional network involved in playing a normal tone, and then each was intentionally decoupled from ordinario. These elements (bow speed, bow placement, bow angle, and bow portion) were scaled between minimal and maximal values for any single parameter. Then, between minimal and maximal values, a series of scalar degrees were chosen to more or less uniformly link these extremes. This article will present acoustical attributes of these methods and discuss implications for musical usage. This study found that decoupling of any single parameter will result in perceptible differences that range from timbral to dynamical (sound) class change.

Keywords
acoustics, bow, desynchronization, dynamical systems, multiple parameters, music composition, nonlinear phenomena, scaling, sound production, violin

This article will present a single case study focused on the acoustical attributes of violin sound production when one or more of the elements are intentionally decoupled from idiomatic behavior. Fundamentally different from non-scalable extended techniques (such as using heavy bow pressure to achieve a singular gesture, i.e., “pitchless scraping”), this approach relies on scaling the entire range of any element between minimal and maximal values (such as between

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the fastest to slowest bow speed, regardless of tempo or left-hand behavior). The resultant sounds will have the potential to shift a normal tone to one featuring timbral change, pitches with noise, subharmonics, multiphonics and time-variant multi-tone complexes. In comparison to those discrete extended techniques, scaling allows not only more bioacoustic diversity, but a greater breadth in the treatment of musical material through processes conceptually similar to pitch and rhythmic development. In this study, our aim was to investigate timbral and sound class deviations from ordinary when using scaled parametric change. Ultimately, we wish to examine the notion that scaled manipulation of even a single parameter generates sounds that are appropriate for composition and performance.

Before moving to scaled sound production behaviors, it may be useful to provide examples of compositions that feature non-scaled practices (see Table 1) (Liebman, 2010; Strange & Strange, 2001; Thelin, 2011). Just a small sampling of these methods include:

**Table 1. Compositions featuring extended techniques for string instruments, in non-scalable ways.**

<table>
<thead>
<tr>
<th>Bow placement</th>
<th>Bow above left-hand fingers</th>
<th>Bow in tasto</th>
<th>Specific nodal locations</th>
<th>Bowing under the strings (g &amp; e strings)</th>
<th>Bow in ponticello</th>
<th>Bow ½ on &amp; ½ off bridge</th>
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</thead>
<tbody>
<tr>
<td>Bow on scroll</td>
<td>Helmut Lachenmann</td>
<td>Michael Pisaro</td>
<td>Elvind Buene</td>
<td>Wayne Peterson</td>
<td>Luigi Nono</td>
<td>Allen Strange</td>
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<tr>
<td>Bow below bridge</td>
<td>György Ligeti</td>
<td>Alvin Curran</td>
<td>Salvatore Sciarrino</td>
<td>Richard Wernick</td>
<td>William Sydeman</td>
<td>Philippe Boivin</td>
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<td>Bow on tailpiece</td>
<td>Krzysztof Penderecki</td>
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<td>Lateral bowing</td>
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<tr>
<td>Bow In Shapes or Contours</td>
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<td>Multiphonics</td>
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</tbody>
</table>
| **Table 1. Compositions featuring extended techniques for string instruments, in non-scalable ways.**

<table>
<thead>
<tr>
<th>List of Compositions</th>
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<th>List of Compositions</th>
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<tbody>
<tr>
<td>String Quartet No. 3</td>
<td>Sei Studi</td>
<td>Mind is Moving II</td>
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<tr>
<td>Sei Studi</td>
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<td>Blacklight</td>
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<td>Trialogue</td>
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<td>Varianti</td>
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<td>Star Salon Strikers and</td>
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<td>Slider’s Last Orbit</td>
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<td>Ramifications</td>
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<td>Thursday Afternoon</td>
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<td>String Quartet No. 1</td>
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<td>Six Caprices</td>
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<tr>
<td>Cadences and Variations I &amp; II</td>
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<td>Projections I</td>
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<tr>
<td>String Quartet</td>
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<tr>
<td>Cinq Algorithmes pour</td>
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<tr>
<td>Contrebasse Seule</td>
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<tr>
<td>String Quartet Describing the</td>
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<td>Motions of Large Real Bodies</td>
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<tr>
<td>Sonata for Double Bass</td>
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<td>Luft</td>
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<td>Black Angels</td>
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<td>Glasperlenspiel</td>
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Bow pressure – heavy pressure to produce accents without changing bow direction, heavy pressure to produce a crush tone and hard scrape, light pressure on a node to act as a filter on harmonics.

Many of these techniques when combined have the potential to produce subharmonics and subpartials (bow placement, bow pressure, bow speed, rosin, age of string, and twisting string) (Kimura, 1999), as well as multiphonics (bow pressure, bow speed, bow placement, bow direction, and rosin). Some of the composers and performers who have exploited multidimensionality to a greater degree than normal include Jaap Blonk, Aaron Cassidy, Frank Cox, Michael Edward Edgerton, Julio Estrada, Klaus K. Hüblier, Phil Minton, Giacinto Scelsi, Demetrio Stratos (Blonk, 1997; Cassidy, 2010; Cox, 1994; Edgerton, 2002; Estrada, 1990; Hüblier, 1987; Minton, 2003; Scelsi, 1972; Stratos, 1978).

In this study, four elements were chosen from multiple parameters involved in playing a normal tone, which were intentionally decoupled from ordinary. These elements (bow speed, aka velocity \([V_b]\); bow placement, aka bow-to-bridge distance \([\beta]\); bow angle, aka skewness; and bow portion) were scaled between minimal and maximal values using a series of steps similar to the tones of a musical scale, based on recognizable differences in kinetic and auditory perception for each parameter.

Numerous authors have previously noted that the production of a normal tone with a desired tone quality and loudness requires balancing multiple parameters, including bow speed, bow pressure, bow to bridge distance, bow tilt, bow direction, bow angle, bow elasticity and inclination, to name only a few. It is this balancing of multiple elements within a highly nonlinear system which are extremely sensitive to small changes in their control settings which make instruments so difficult to play. Such sensitivities are a risk, but when those elements are decoupled from normal performance practice, they become the seeds of musical expression (Antunes, Inácio, & Henrique, 2007; Askenfelt, 1995; Chafe, 1988; Demoucron, Askenfelt, & Caussé, 2009; Guaus, Bonada, Perez, Maestre, & Blaauw, 2007; Guettler, 2003; Guettler, 2006a; Jensen, 1996; McIntyre & Woodhouse, 1978; Schelleng, 1973; Schoonderwaldt & Wanderley, 2007; Woodhouse, 1994). This study will focus on the deliberate unbalancing of each of the four elements listed above in order to produce a change of timbre, envelope or dynamic class (Neubauer, Edgerton, & Herzel, 2004).

In the next section, we will review essential features of bowed string production, in order to better reveal the underlying relations between the numerous parameters involved in contemporary music. This will then lead to the central question whether graded deviations from normal playing will produce corresponding outputs in the acoustic signal.

Science of the bowed string

Pitch on a violin is controlled by the vibrating string length, while amplitude is dependent on bow speed, bow pressure, and bow–bridge distance. In 1973, Schelleng formulated a strong interdependence between the main bowing parameters when producing a normal tone. He found that minimum and maximum bow force decreased with increasing bow–bridge distance, but increased with increasing bow velocity. When the bow force is below a minimum value, multiple slipping (surface noise) occurs; but when the force is higher than a maximum value, it results in an aperiodic string motion featuring a rough, unpitched tone (Schelleng, 1973). Timbre is largely controlled by bow force by shaping the high-frequency content of the string’s spectrum, with secondary contributions from bow velocity and bow–bridge distance. We have already discussed the effect of increased bow pressure on amplitude, and note that while an
increase of bow pressure produces more noise culminating in a crunch tone, a reduction to 
light pressure will produce a bright, flutelike sound (Cremer, 1984; McIntyre, Schumacher, & 
Woodhouse, 1981; Schoonderwaldt, 2009b).

Helmholtz was the first to observe the motion of a bowed string during a sustained, normal 
tone. Generated at the intersection of bow and string, this motion was described as a sharp 
corner traveling up and down a diamond-shaped deformation as the string vibrates. The funda-
mental period of vibration is determined by the time it takes a corner to make a single round 
trip. The generation of sound between string and bow involves a sticking phase and a slipping 
phase. This corner acts as a trigger to release (slip) and capture (stick) the string. For an ideal-
ized normal bowing, this sequence results in one slip and one stick per cycle. This motion is the 
goal for most ordinary bowing techniques. The length of the slipping time is approximately 
equal to the placement of the bowing point, or the distance of the bow to bridge (Guettler, 

However, on a real string, small irregularities are needed to sustain string vibration. These 
irregularities involve energy loss in the string which has the effect of rounding the Helmholtz 
corner. At light bow pressures, the corners are significantly rounded, but become sharper when 
pressure is increased. With increased bow force, the critical static friction is increased, which 
leads to even greater sharpening during release, leading to more energy of the higher partials 
and a brighter sound (Woodhouse & Galluzzo, 2004).

A second consequent of small string irregularities is the creation of secondary waves that 
pass through the bowing point or reflect back from the bow. These waves travel between bow 
and nut, or bow and bridge serving to disturb the ideal movement which has implications for 
many modern techniques, such as with string multiphonics. A third consequent of such irreg-
ularities is to produce a flattening effect. Due to the delay in triggering its release, the period is 
increased, which results in a drop in pitch (Schoonderwalt, 2009a).

Keeping placement and speed constant, the Helmholtz corner can be produced within a 
moderate range of bow force values. To maintain the Helmholtz motion of one stick/slip per 
cycle, two requirements must be met: 1) bow force must be high enough during sticking to 
avoid a premature slip, and; 2) bow force must not be too high so that the corner can trigger 
a release when it passes the bow. The limits of the normal playable region for pressure and 
distance at a fixed bow velocity are such that as the bowing point increases distance from the 
bridge, force must lessen to keep within normal bowing limits. If the bowing point moves 
close to the bridge as force increases, irregular slips superimposed on the fundamental period 
appear, resulting in greater energy at higher frequencies (Schoonderwalt, Guettler, & 
Askenfelt, 2007). Above maximum bow force, a number of phenomena occur that include 
aperiodic, raucous motion, subharmonics (or anomalous low frequencies), and S-motion. 
Below-minimum bow force multiple slips per cycle correspond to surface noise (McIntyre 
et al., 1981).

Subharmonics are caused by the delay of the slip at the first arrival of the Helmholtz corner, 
which is then reflected back towards the nut, and only finally released at the second or third 
return of the kink to the bow. The role of the increased force is to produce a friction force that is 
strong enough to maintain the sticking phase until the corner returns again. The frequencies 
of these subharmonics are dependent on the bow–bridge distance, so that frequency rises as the 
bow-to-bridge distance increases (Guettler, 1994; Hanson, Schneider, & Halgedahl, 1994; 
Schoonderwalt, 2009b). S-motion involves the simultaneous appearance of a Helmholtz period 
with one or more sinusoidal components that appear when bow force exceeds a critical value 
(Lawergren, 1980; Schoonderwalt, 2009a). Additionally, multiphonics occur with careful 
bow–bridge positioning and slight left-hand pressure as robust narrow frequency bands over a 
Helmholtz motion (Guettler & Thelin, 2012; Liebman, 2001; Robert, 1995). These narrow
frequency bands are caused by additional Helmholtz corners, one on each side of the bow when the slip varies in time, amplitude and degree of corner-rounding. (Thelin, 2011).

**Overview of four bowing parameters (angle, placement, portion, speed)**

Bow speed (tightly linked with bow pressure) has a huge effect on the string such that as speed lowers, the tone gets brighter; and as speed rises, the tone loses its brilliance. The relationship of the Helmholtz motion and the fundamental period is that if the string has a fundamental frequency (f₀) of 100 Hz, then each period will equal 1/100 second, which means that for normal playing, the string will slip 100 times per second. Now, if the bow speed increases too much, multiple slips per period may appear. If two slips are produced, the sound will be one octave higher – even sometimes producing a harmonic-like sound. However, if bow speed is too slow, the Helmholtz corners return to the bowing point too soon, which produces a strangled sound, whose pitch will drop slightly (Guettler, 2003, 2004; Schoonderwalt, 2009b; Schoonderwalt et al., 2007; Woodhouse & Galluzzo, 2004).

The bow’s point of contact is important. In general, movement towards the bridge produces tones with increased energy at higher frequencies. Movement over the fingerboard produces tones that are damped and more mellow until approximately mid-string length, at which point continued movement towards the nut produces a nearly symmetrical inversion of the Helmholtz motion that becomes brighter closer to the nut (McIntyre, Schumacher, & Woodhouse, 1983). As the bow moves towards the bridge where the amplitude of vibration is less, the recoil between bow and bridge will be shorter. When placed even nearer to the bridge, a greater percentage of the total vibrating length is involved with giving more energy to the higher partials. To compensate, the bow must be drawn slower in order to retain a constant pitch and to avoid more than a single slip/stick per period (Guettler, 2010b).

Bow placement is linked to loudness, so that placement furthest from the bridge was used for soft tones while loud tones were played closest to the bridge. This is in agreement with Schelleng’s diagram; as distance from the bridge increases, the upper and lower bow-force limits decreased (Askenfelt, 1988; Guettler, 2003, 2004; Guettler & Thelin, 2012; Pitteroff, 1993; Schoonderwalt, 2009b; Schoonderwalt et al., 2007). Regarding bow placement, Guettler reported that a change of bow placement towards the bridge alone does not produce a more brilliant tone, but this is rather due to balancing velocity, force, and placement (Guettler, 2006b).

Slight deviations of bow angle are used by string players in normal playing: a) when changing from up to down bow; b) during crescendi to bring the bow slightly closer to the bridge in order to save length, rather than increase speed or force; c) leads to a drift of the bow–bridge contact point to avoid introducing longitudinal friction that produces noise (Askenfelt, 1988; Guettler, 2003; Hodgson, 1958; Schoonderwalt, 2009a; Schoonderwalt & Wanderley, 2007).

Bow portion, in this study, is identified as 19 different locations and lengths of the bow that may be used for higher level organizational and articulatory procedures by string players, particularly in contemporary music. For normal bowing, active control of bow portions is to facilitate bow gestures and to make certain patterns possible (Askenfelt, 1988).

**Method**

**Parameters and scaling**

Four elements were chosen for this study: bow angle (skewness Sₘ), bow speed (velocity Vₘᵢ), bow placement (bow-to-bridge distance β) and bow portion (Pᵢ). Bow angle is on the horizontal
plane, perpendicular to the fingerboard. Bow speed is a close correlate of bow velocity independent of tempo, left-hand or contextual issues. Bow placement is a close correlate of bow-to-bridge distance but may utilize any location, including those on or above the nut or bridge. Bow portion refers to any length or position on the bow (see Figure 1). Each element was scaled between minimal and maximal values in the following ways:

1) Bow angle moving in symmetric distances from ord (perpendicular to fingerboard) to positions away from and towards body: 11 = 108°; 10 = 90°; 9 = 72°; 8 = 54°; 7 = 36°; 6 = 18°; 5 = 0° (ord); 4 = −18°; 3 = −36°; 2 = −54°; 1 = −72°; 0 = −90°; −1 = −108°.

2) Bow speed is scaled between as slow as possible to as fast as possible without regard for left-hand movement or tempo – the amount of bow used will have an influence on bow speed and was factored into each task. For these tasks, we used seven speeds in total.

3) Bow placement is scaled in 13 steps from high on the fingerboard above the nut to below the bridge in the following way: above nut, on nut, tasto 6, tasto 5, tasto 4, tasto 3, tasto 2, tasto 1, ordinario, ponticello 1, ponticello 2, on bridge, below bridge.

4) Bow portion features 19 divisions of the bow that include: 1/3 at tip, 1/3 at middle, 1/3 at frog, nine equal divisions from tip to frog, 2/3 at tip and mid, 2/3 at mid and frog, 2/3 from middle of tip to middle of frog, full bow, 1/27 at tip, 1/27 at mid, 1/27 at frog.

Stimuli

One professional violinist (E.K.) with over 20 years’ experience was recruited to take part in this study. The tasks were composed by the second author, M.E.E., and involved playing the full scalable range for each element in contexts that isolated the change of a single parametric setting on the pitch A3 for four beats, followed by a rest of four beats, then performing the next scale degree for four beats, then resting for four beats, repeat as necessary. The violinist had two training sessions with M.E.E. to learn and refine the specified task. These sessions focused on identifying min/max values for each parameter as well as each intermediate step by balancing kinetic activity with sonic result. The values for each step were chosen when a change was perceived by the performer. Additionally, with some behaviors, the performer needed to utilize radical physical maneuvers to perform extremes of a task, such as with bow angle at 90 degrees (#0, 10), in which the violinist will change the position of the instrument, by moving the scroll towards the dorsal plane of the body. In each sequence, the player attempted to manipulate only one parameter, while keeping all other variables constant. Figure 2 shows the correspondence of notation and scaling for angle and speed.

The stimuli were recorded by E.K. in the Concert Hall at the Institute of Music, Martin-Luther-University Halle-Wittenberg, under the supervision of the third author, W.A. The environmental noise of the hall was very low. The recordings were made at a distance of two meters in front and 50 cm above the violin with two microphones in an ORTF setup. The direction of the violin was facing the microphones. Even when bowing at extreme angles, the position of the violin to the microphone changed only to a small extent, as the violinist was instructed to keep the position constant. The microphones consisted of two cardioid studio microphones (Neumann UM 57) with a power supply (Neumann UN61V). The signals were recorded on a SONY DAT TCD – D100. Before recording, E.K. tuned to A4 = 442 Hz. Acoustic analyses were conducted using PRAAT (Boersma, 2001), TF32 (Milenkovich, 2000) and Sonic Visualizer (Cannam, 2012). The spectrograms used narrowband analyses (43 Hz, 0.03s) in a Gaussian window. The time-slice (FFT) analyses were chosen from the most stable portion of each signal (window length, 0.03s). The calculations for Jitter, shimmer and signal-to-noise ratio were
made using a least mean square approach (Milenkovich, 1987) using 100 msec tokens. Spectral centroid used window size of 1024 Hz at increments of 512 Hz with a Gaussian window. The analysed samples were chosen as representing the best fit from multiple recordings of each procedure. The criteria, by which they were chosen, included the mechanical sound production characteristic (i.e., correct place and degree of skewness for bow angle, appropriate speed, pressure, rotation, etc.) and uniformity of output.

Results

Attributes of bow angle

Figure 3 shows 13 narrow-band spectrograms, each .5/s in length featuring all bow angles, arranged from extreme angle −1 (towards the body) to angle 11 (away from the body) – each paired with its corresponding musical notation which represent a single time slice (0.03/s) selected from a relatively stable portion of each sequence. Angles at, or nearly perpendicular (#4, 5, 6) produce a single f0 with a harmonic spectrum, whose second harmonic carries the most energy. Then, continuing skewness with the frog moving towards the scroll, angles #7 and #8 features a second harmonic that dominates the texture, along with an amplitude increase of harmonics four to nine. This is accompanied by a general sense of noise, though each angle has a different distribution of high energy bands coloring the composite sonorities.
Taken together, the increased energy in higher harmonics and noise produced a more trebly-like sound. As skewness approaches parallel (#9), all harmonic material related to the f0 on a3 is lost and noise dominates to an even greater degree. As might be expected, skewness in the opposite direction mirrors that towards the scroll. Significantly, at angles parallel to (0, 10) or crossing over parallel (−1, 11) there is no possibility to produce the Helmholtz corner, so no

**Figure 3.** Thirteen tightly cropped narrow-band spectrograms of scaled bow angle productions, paired with their waveforms and corresponding musical notation. The musical notation represents a single time slice selected from a relatively stable portion of the segment. Note how the perception of the f0 is dominant for degrees closely related to ordinary, while movement away begins to feature a reduction of the f0, an increased emphasis of harmonic two along with nonharmonic partials, as well as noise components.
harmonic components related to a3 are seen, rather stable spectral peaks appearing at 2 kHz supported by a noise floor are produced (see Figure 3).

**Attributes of bow placement**

Figure 4 shows 13 narrow-band spectrograms. While attempting to keep bow pressure constant, movement towards the bridge reduced overall amplitudes while increasing noise. By pizzicato 2, the f0 was nearly obscured and whose spectral peak occurred at harmonic 8, while a high amplitude broadband sonority extends from approximately harmonic 16 to 40. Going in the opposite direction towards the nut, it was previously mentioned that symmetry exists relative to bowing at the mid-portion of the string (McIntyre et al., 1983). In this experiment, we consider taste 3 to be the approximate half-way point on the string. Note how taste 1 and 5 carry similar properties – see especially the musical notation (harmonics 2 and 6 dominant). Similarly, taste 2 and 4 are similar (harmonic 2 dominant), while taste 3 seems to have its own unique properties (harmonics 2 and 4 dominant). However, our study shows that taste 3 to 5 carries a significant amount of high amplitude noise that stretches approximately 1.5 octaves, while taste 1 and 2 do not. When bowing on the bridge or nut, noise dominated the pitch content. Above the nut, or below the bridge, bowing on the short string section produced strong sine-wave like tones featuring a clear spectral peak appeared above a noise floor.

**Attributes of bow portion**

Figure 5 shows 19 narrow-band spectrograms. With the violinist keeping all other parameters constant (speed, pressure, etc.), note how the samples feature minimal spectral deviation from ord (see Figure 5). The use of different bow lengths and locations on the bow has many implications: one is that variations of bow portion may be used to organize bowing within the up to down bow cycle (Askenfelt, 1988; Schoonderwalt, 2009b); another is to coordinate onset and offset as a generative tool to decouple left and right hand gestures; a third is to decouple the amount of bow movement from time (implying variations of bow speed); a fourth is to decouple the place on bow from habitual accentuation (implying non-habitual variations of pressure).

**Attributes of bow speed**

Figure 6 shows seven narrow-band spectrograms. For all bow speeds, a clear harmonic structure was always present, with harmonic 2 being the spectral peak. A trend at the lowest and highest speeds includes greater amplitudes at h02 and an increase of noise, with less of the f0. At the lowest and highest bow speeds, the signal excited by the frictional force becomes increasingly noisy, erratic and are severely nonlinear (McIntyre & Woodhouse, 1978). As shown in Figure 6, the two fastest bow speeds feature temporal instability, while moderate speeds have stable spectra. Slower speeds feature less amplitude, temporal inconsistency and more noise compared to ordinary (Müller & Lauterborn, 1996) (see Figure 6).

**Jitter and shimmer**

Jitter is a measure of the cycle-to-cycle variation in the pitch period, while shimmer is a measure of the fluctuation in amplitude between waveform cycles (Milenkovich, 2000). Regarding shimmer, bow angles adjacent to ordinary (#4 & 6) had low shimmer values while angles distantly removed carried higher shimmer values. With bow speed, only the fastest speeds carried
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With bow placement, only those positions near the bridge carried moderately high shimmer values. With bow placement, only those positions near the bridge carried moderately high shimmer values.

The distribution of jitter is less straightforward. Extreme angles had both high (trebly 1, 0, 10, 11) and moderate (1, 8, 9) jitter values. Moderate angles (3, 7) encompassed both moderate

Figure 4. Thirteen tightly cropped narrow-band spectrograms of scaled bow placement productions, paired with their corresponding musical notation. The musical notation represents a single time slice selected from a relatively stable portion of the segment. Note how movement towards the bridge begins to emphasize greater energy at higher frequencies. By ponticello 2, the f0 is nearly lost while noise becomes more prominent – as discussed in the text, this may be due to greater bow pressure. Movement away from the bridge over the fingerboard tends to reduce the f0 until approximately midway, at which point symmetry of string vibration appears – compare tasto 1 and 5, and tasto 2 and 4.
and low jitter values, while angles at/close-to ordinary had low jitter values. For bow placement, those positions above-the-nut and above-the-left-hand stop had high jitter values, while on-the-bridge had moderate jitter values, with all others carrying low jitter values. Interestingly, all bow speeds carried relatively low jitter values (see Figure 7).

**Spectral centroid**

Spectral centroid is a measure used to characterize where the centre of mass of the spectrum is located. Perceptually, it has a robust connection with the impression of the “brightness” of a sound (Grey & Gordon, 1978). Our findings show that spectral centroid is strongly affected by bow angle, such that as the bow is skewed away from ordinary, the centre of mass increases linearly. Bow placement similarly showed a clear trend – as the bow moved towards the bridge, spectral centroid rose; and as the bow moved over the fingerboard from tast 1 to 5, spectral
Since the string is mirrored symmetrically from termination to midpoint, it appears that bow force may have lessened from tast 3 to 5. Surprisingly, there were huge differences between bowing on the bridge and nut, with much higher values at the nut. For bow speed, centroid measures were mostly uniform, though with the fastest bow speeds having the lowest center of mass and the slowest speed having the highest center of mass (see Figure 8).
The finding that bow movement away from the bridge produced lower centroid values are in disagreement with a previous study which found that centroid lowered when moving towards the bridge (Schoonderwaldt, 2009b). This may be explained by the contribution of bow force, which was neither precisely controlled nor monitored in this study.

**Figure 7.** Comparisons of jitter versus shimmer. Note how those bow angle variations that exceed a close relationship to ordinary feature both high jitter and shimmer values. For bow placement, note the relative uniformity of jitter and the nearly linear increase of shimmer when moving bowing point from nut to bridge. Bow speed seemed to feature symmetry of shimmer until mid-speed point as both speeds 1 and 7 had high values that decreased towards moderate speeds.

**Figure 8.** Spectral centroid shows the center of mass of a spectrum and is connected with the brightness of a sound. Note how bow angle is symmetric when moving away from ordinary. For bow placement, the expected symmetry between T1 and T5, T2 and T4 did not occur. This may be due to differences of bow pressure. As a group, bow speed carried the lowest values.

The finding that bow movement away from the bridge produced lower centroid values are in disagreement with a previous study which found that centroid lowered when moving towards the bridge (Schoonderwaldt, 2009b). This may be explained by the contribution of bow force, which was neither precisely controlled nor monitored in this study. Although the performer
attempted to keep pressure constant, it is natural for players to increase force when playing closer to the bridge, so most likely it was bow force that caused an increase of centroid, and not placement alone. Regarding bow speed, our findings are in agreement with the previous study which showed centroid lowered with increasing velocity, i.e., the tone becomes duller at faster bow speeds (Schoonderwaldt, 2009b).

**Harmonics to noise ratio**

Harmonics to noise ratio (HNR) is a measure of the degree of acoustic periodicity where high values represent a signal whose energy is periodic and low values represent tones with significant noise (Boersma, 2001). Our findings show clear results, with tones at, or closely related to, ordinary having the highest values. For bow angle, movement away from ordinary to extreme angles had increasingly low HNR values (more noise – see Figure 3).

When bowing at extreme angles, the bow features two dimensions of movement and a greater area of contact that interferes with the Helmholtz motion. At such angles, bow hair shifts from nearly perpendicular and strongly uniform against lateral displacement to nearly parallel and highly vulnerable to lateral displacement. This displacement generates micro-slippage of bow hair in two dimensions which contributes to noise. With differential slippage, bow hair release is not uniform as differences exist between the inner and outer edges of bow hair – then at extreme angles these temporal differences will be magnified to an even greater degree, as one side of the bow will be significantly further from the bridge than another (Askenfelt, 1988; Chafe, 1988; McIntyre et al., 1981). An alternative interpretation of noise production at extreme angles is that, by keeping the bow placement constant, the player opposes the natural drift of the bow that occurs under influence of the stick-slip interaction with the string, and by this interferes with the Helmholtz motion (Guettler, 2003; Schoonderwaldt, 2010). For bow placement, movement from tasto 1 to tasto 3 produced tones with progressively lower HNR values, however, from tasto 3 to tasto 5, we find a mirror effect with rising HNR values. This is because bowing on the string is symmetric, so that bowing close to the bridge or nut are essentially the same, except for an inversion of the Helmholtz motion (McIntyre et al., 1983). Boersma reported that tones with a lower center of energy will have higher HNR values due to a lower sensitivity of HNR to jitter (Boersma, 2001). As shown in Figure 8, bow speed variations as a group had the lowest centroid measures, and as we see in Figure 9, higher HNR values (see Figure 9).

**Intensity and spectral weight**

Intensity measures were highest for ordinary. For bow angle, movement away from normal followed a linearly decreasing curve. For bow placement, ponticello 1 and 2 featured decreased intensity values. Going in the opposite direction, tasto 1, 2, and 3 featured slightly lower intensity values, while tasto 4 and 5 featured higher intensity values, which may be explained by the aforementioned string symmetry. Regarding bow speed, intensity was nearly 10 dB greater in comparison to angle and placement, implying that perhaps greater bow force was used by the player (see Figure 10).

Spectral weight is a novel measure developed by the authors to summarize the distribution of energy in a spectrum that features harmonic, inharmonic and noise components, such as is common with contemporary music. This measure consists of noting the spectral components found in specific bins relative to the peak amplitude in the following categories: at peak; within −0.1 to −3 dB; within −3.1 to −6 dB; within −6.1 to −12 dB; within −12.1 to −24 dB from the
peak over its entire spectrum. After collating the components within each category, we then
determined spectral weight according to the sum of all components across all bins. We found
that tones that were harmonic or nearly harmonic featured values around 10 components per
composite, while tones with significant noise had values of 20 components or higher (see
Figure 11).

Figure 9. Harmonic to noise ratio is a measure of the relations between tone and noise. A high value
means less noise, a low value means more noise. For bow angle, the symmetry is mostly inverted with
small differences at or near parallel. For bow placement, movement towards the bridge produced more
noise; movement over the fingerboard produced more noise to midway point, then less noise towards the
nut, thus confirming symmetry of string vibration. Bow speed was also symmetrical with low and high bow
speeds featuring more noise; as bow speeds went towards moderate, noise decreased.

Figure 10. Across all three procedures, those closely-related to ordinary had the highest intensity values.
Figure 12A presents a comparison of spectral weight versus jitter; Figure 12B a comparison of spectral weight versus shimmer. Ordinary tones carried small weight values, as did those tones resulting from angles that were closely related to ordinary (4 and 6). Angles 1 and 3 had moderate weight values, while those angles parallel or crossing over had higher weight values. Placement at tasto 6, and above the nut had weight flux values, while on the bridge was moderate, with all others low (see Figure 12). Changes of speed carried low values. Note that high weight values did not equal high jitter – more often high weight correlated with high shimmer.

**Bow force**

Bow force was not systematically controlled nor monitored in this study; rather the performer was instructed to keep bow pressure constant. The reason for not including bow pressure is that this study was intended to focus on the scaling of decoupled performance techniques by the violin in live performance settings. This focus on scaling relies on developing consistent degrees of parametric change within minimal and maximal values, similar to scales of pitch or time. Three of the chosen parameters (angle, placement, portion) feature visual/spatial movements which make discrimination of scaling relatively straight-forward. Likewise bow speed involves kinaesthetic properties which allow for intuitive discrimination of scaling. Further, each parameter may be more or less isolated from each other parameter. However, the isolation of bow force is extremely difficult due to its tight coordination with many other parameters involved in sound production, such as bow position, skewness, tilt, speed, etc.; and although extreme overpressure and light bowing are often seen in contemporary composition and performance, we felt that attempting to physically monitor any internal scaling of force...
would inhibit the larger intent of examining decoupled string production. Therefore, due to the necessary limitations of the methodological design, controlled measures of bow force were not included and are recognized as a deficiency, which we hope to address in future studies. Relevant research involving measurements of bow force in live performance include Guaus et al. (2007), Paradiso & Gershenfeld (1997), Young (2003), Rasamimanana (2003), and Demoucron et al. (2009).
**Discussion**

**Music relevance**

We suggest that composition and performance based on the decoupling of multiple parameters is fundamentally different than one featuring discrete (nonscaled) extended techniques. As is shown in this case study, the scaling of three prominent elements (angle, placement, speed) produce demonstrable change in sound quality and/or acoustic class (from *ordinario*: to subharmonics or related; to two independent frequency contours; to spectral emphasis; to mix of pitch and noise; to noise) (Neubauer et al., 2004). These changes may be classified into four categories of relatedness based on their acoustical attributes in the following way:

- **Closely-related**: same pitch as *ordinario* with only slight timbre change  
  *example*: bow angles 4 and 6

- **Moderately-related**: same pitch as *ordinario* with large timbre change; sound class change retaining *f0* within new sonority  
  *example*: bow angles 3 and 7

- **Distantly-related**: sound class change with no or very little retention of *f0*, though retaining some other aspect related to the gestural contour  
  *example*: angles 1, 2 and 8, 9

- **Not-related**: no aspect of *ordinario* production is retained  
  *example*: angles 0, −1 and 10, 11

These notions of relatedness are crucial to the rationale for scaling parameters. As opposed to the discrete extended technique which presents a singular quality with little transferability, and thus limited evolutionary potential; even a limited manipulation of any single parameter begins to exhibit a developmental potential similar to pitch and rhythmic elaboration of the sort that extends a motive to a phrase and then to larger groups. Crucially, each elaboration of pitch or rhythm will feature treatments that are more closely or distantly related – likewise with scaled parameterization.

Next, scaling even a single parameter has the potential to change sound quality. However, once parametric variation exceeds closely-related values, a fundamental property of all mechanical instruments and voices begins to impose itself. This property, central to all dynamical systems, reveals that nonlinearity is an inherent property amongst all the components of the acoustic system (power, source, resonator, and articulation). What this briefly means is that any input to the total system has a mismatch with another part of the system, and if the control mechanism is not within certain limited thresholds, then nonlinear effects begin to happen, such as above and below certain bow force limits for ordinary tones (Berry, Herzel, Titze, & Story, 1996). For composers and performers, the resulting nonlinear phenomenon can be useful tools in creative contexts. Therefore, it is due to the inherent nonlinear aspects of instruments and voices that it is not possible to accurately predict one sound that results from parametric decoupling, but, in some cases, there are multiple and equally valid sound outputs (Edgerton, Neubauer, & Herzel, 2003). This is also why different performers will produce different outputs using nearly identical production characteristics. Certainly, there is some overlap between the discrete product and a scaled approach. Our view is that an output of the discrete approach is simply a subset of the more comprehensive scaled approach – similar to a point on a continuum.

With scaled multiparametric contexts, the relationship of composer to performer is altered. In some cases, the intended sounds may be indicated in the score, while others may feature a
tablature notation. In every case, the performer is invited to collaborate by personally defining the min/max values and where the steps between these extremes lie. It is not realistic for the composer to completely define the extremes or intermediate steps since each performer and instrument will carry different tendencies. This means that performers have to conceptualize how decoupling affects sound production and imagine its sonic output. This approach does not suggest a lack of composer imagination, but rather a realistic acceptance of nonlinearity and its stimulating potential for use in musical performance.

**Multiple parameters explicitly identified**

During the production of normal tones by voices and instruments, multiple parameters each exhibiting minute fluctuations, combine to form the composite timbral output. However, past a certain threshold, even at moderate degrees from ordinary, these minute fluctuations may affect the sound in larger, more obvious ways by producing timbral change, or an increase of articulatory behavior, or even changing from one acoustic class to another (Edgerton et al., 2003).

The following example presents an excerpt of the composition *Recoil* by Franklin Cox (Cox, 1994). This composition attempts to raise those multiple parameters involved in sound production from a supporting role to one on par with the normally dominant pitch/rhythmic axis. The methods Cox used involved: 1) raising the complexity of individual parameters involved in producing sound from a normal to heightened state; 2) to develop a plausible syntax that would allow for a differentiation of those multiple parameters; and 3) that this syntax would allow individual parameters to retain their identity while undergoing morphological procedures.

Specifically, the composer focused on the temporal aspects of left hand pitch gestures, right hand bow gestures and right hand vertical bow movement. Each element was organized into distinct contours and organized according to a hierarchical model. These elements featured shifts in playing from normal to less normal, and normal to more extreme. Of the 13 or so elements that are involved in producing sound on the violin, *Recoil* used bow placement (circular bowing, towards *sul ponticello* [SP], towards *sul tasto* [ST], jagged motion ending ST, jagged motion ending SP), bow speed (normal, faster than usual for a given dynamic, slower than usual for a given dynamic, *molto flautando*), and bow rotation (*col legno*). The effect of this non-scalable behavior is to produce a counterpoint of overlapping layers based on a polyrhythmic organization between the left and right hands (Cox, 2008) (see Figure 13).

**Multiple parameters explicitly identified and scaled**

All parameters may be varied between minimal and maximal values, for example with bow pressure or vocal fold tension (extremely lax to hyper-pressed). An example of multidimensional scaling was reported by Berry and colleagues in an excised laryngeal experiment (Berry et al., 1996). In this study, two elements, asymmetrical vocal fold tension and subglottal pressure were experimentally scaled. The authors found that variations of asymmetrical vocal fold tension and subglottal pressure produced chest-like vibrations, falsetto-like vibrations, vortex-induced vibrations (whistle-like), and instabilities that were shown in bifurcation diagrams. The authors found that an increase in subglottal pressure with low to medium vocal fold asymmetries did not result in instabilities but remained in chest-like vibrations. However, as micrometer asymmetry and subglottal pressure increased, bifurcations involving falsetto-like and whistle-like vibrations and instabilities began to appear. The results provide experimental evidence that even small parametric change may result in qualitative variation. In music composition, perhaps the first explicit use of multiple parameters was identified by Hübler (1984).
In Figure 14, an excerpt of the composition, *Adjusting to Beams Falling*, for flute and cello by Edgerton is presented (Edgerton, 2006). The title originates from the chapter “G in the Air” from the book *The Maltese Falcon* by Dashiell Hammett (Hammett, 2010). This composition is a continuation of work designed to elevate the structural importance of those musical elements that are normally seen as appendages to pitch and rhythm. This is achieved by scaling the multidimensional phase spaces of both instruments. As early as 1911, Schönberg suggested that

> If it is possible to create structures out of Klangfarben that are differentiated according to tone height (pitch) . . ., then it must be possible to make such progressions out of the Klangfarben of the other dimension out of that which we call Klangfarbe. (Schönberg, 1922)

Specifically, this piece examines ratios of redundancy/novelty, tension/release, fission/fusion, consonance/dissonance across multiple dimensions. This is accomplished by 1) selecting robust elements involved in sound production, 2) scaling each parameter between minimal...
and maximal values, in order to 3) compose across multiple dimensions utilizing methods of similarity, contrast, development and variation as found within the pitch/rhythm domain; this leads potentially to 4) an increase of procedural redundancy/novelty, which may be achieved either within a single or across multiple dimensions via 5) modulation within the same dimension, or via transference of procedural contour from one dimension to another; such procedures add to 6) notions of relatedness, similar conceptually to tonal music, but here implies that transposition/modulation within a single dimension will retain correspondence when transferred to another dimension; this may 7) heighten the inherent nonlinearity of a system by shifting a value into a certain robust range, or by decoupling the elements from one another into certain ratios; the result of such procedures often 8) produce a) nonlinear phenomena, b) changes of timbre, or c) nonharmonic source/resonant multiplicities. In this composition, the multiple parameters that were scaled include: bow rotation, bow portion, bow angle, bow pressure, bow speed, bow placement, onset and offset characteristic, and left hand depression (see Figure 14).

**Conclusion**

The open question of whether graded deviations from normal playing produce corresponding outputs in the acoustic signal has been answered affirmatively in this study. As numerous authors have discussed, manipulations to the way sounds are produced often result in changes to sound’s quality (Dempster, 1979; Edgerton, 2004; Rehfeld, 1978; Spaarnay, 2012; Strange & Strange, 2001; Turetsky, 1989). However, we wish to dig deeper by examining whether the breadth of parametric selection and scaling has any further effect on quality.

This article shows clear results. Three of the parameters showed significant timbral or acoustic class change when decoupling exceeded movement of two scale degrees (bow angle, bow placement, and bow speed), while the fourth had less to do with timbre and more with bow stroke organization and articulation (bow portion). For bow angle, movement away from ordinary produced spectral emphases, inharmonic components and noise. For bow placement, movement away from ordinary in the tasto region produced noise, spectral emphasis, and reduction of the f0 up to the string midpoint, where an inversion of the Helmholtz motion produces symmetry of outputs towards the nut. Movement towards the bridge produced increased energy with higher harmonics, along with noise at ponticello 2. Then going into non-normal bow positions, placement on or beyond the termination point produced sonorities unrelated to the f0 (A3 or 220 Hz). Manipulations of bow speed featured slight timbral change at each scale degree, with significant noise appearing at slower than ordinary speeds; however, in no case did we find acoustical class change for bow speed.

As can be seen in the musical transcriptions in Figures 3, 4, and 6, scaling beyond closely-related degrees may produce sonorities involving single pitches with timbral change, multiple pitches, mixtures of pitch and noise, and noise. Obviously, more detailed analyses are needed to understand how such fine-tuned manipulations affect Helmholtz motion (multiple slips, frictional force, etc).

We found that decoupling multiple parameters does increase diversity of sound output related to production characteristics. This correspondence is dependent on the full extent of any single parameter: for example, the slowest bow speed lasting 70 seconds on a single bow, while the fastest bow speeds will challenge the player to move the right arm as quickly as possible, no matter how conventionally unmusical the tones may seem at first – of course we do presume that proficiency of production still to be an important issue as with all performance practice. Secondly, between these extremes, the number and ratio of scale degrees are ideally best coupled with a corresponding perceptual change, or some intuitive spatial/kinetic
property. For composers and performers, this case study is the first step to demonstrating that, while modernist compositional activity presumed to have reached the limits of timbral and multiphonic production, a significant corpus, exploiting the psycho-acoustic limits of sounds by instruments and voices, awaits those who systematically investigate the decoupling of prominent elements involved in sound production.

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**References**


