The appropriate use of violin vibrato in the performance of baroque, classical, romantic, and even early 20th-century music remains a highly debated and contentious issue. There have recently been a number of detailed studies of vibrato by musicologists investigating the development of late 19th- and 20th-century performance styles, notably by Philip [1], Katz [2], and Milsom [3]. These authors have largely used aural evidence based on early acoustic recordings by distinguished performers whose careers spanned the latter half of the 19th and early part of the 20th centuries.

More recently, Leech-Wilkinson [4] has published a free online book on the development of musical performance styles with a chapter on the violin describing the historical evolution of the use of vibrato. This includes an analysis of some of the same examples illustrated in this study. His analysis used Sonic Visualiser [5], a free software package for musical performance analysis that is widely used in the musicological community. Milsom [3] describes the historical evolution of vibrato, citing several influential 19th-century teachers. These include Louis Spohr in his Violinschule (1832) [6], Charles de Bériot in Méthode de violon (1858) [7], and Joseph Joachim and Andreas Moser in Violinschule (1902-05) [8]. In these pedagogical treatises, the use of vibrato is generally encouraged on longer notes, where the musical, expressive, and emotive content is appropriate.

There are also several older publications describing the use of vibrato as an ornament to the instrument’s sound, notably by Leopold Mozart in his important treatise Gründliche Violinschule (1756) [9]. In chapter 11 of the third edition, Mozart describes vibrato as pressing the finger down on the string, while the hand is rocked backwards and forwards towards and away from the bridge. This is clearly a description of the modern use of vibrato, with the rocking motion of the finger giving rise to cyclic variation in pitch of the bowed note. The widespread use of violin vibrato is therefore not simply a 20th-century development, as has sometimes been claimed. Nevertheless, recordings tend to suggest that vibrato styles have indeed changed over the last 100 years, so that a wider (larger amplitude) vibrato is more commonly used than a century ago.

This paper describes a preliminary study of the use of vibrato from early acoustic and later electric recordings made by a number of distinguished performers. Use is made of custom-designed software to quantify and display both vibrato widths (amplitudes, measured as fractional pitch excursions) and rates (number of vibrato cycles a second).

Much of the previous evidence for the increasing use of vibrato over the 20th century was deduced from listening to recordings,
which lack the quantitative evidence on which conclusions can be confidently established. In contrast, Mellody and Wakefield [10] have made a detailed quantitative study of violin vibrato. However, the emphasis was largely on measurement and analysis, and factors affecting the perception of both real and synthesized vibrato sounds, rather than aspects of historical musical style. In addition, there have been a number of detailed studies investigating the influence of the acoustical properties of the instrument (and performance space) on the perception of violin vibrato sounds. Examples include those of Fletcher and Sanders [11], Matthews and Kohut [12], Meyer [13], and the present author [14]. Wakayama et al. [15] have also measured and compared the use of violin vibrato for selected notes played by four modern virtuosi.

Psychoacoustic studies on the perception of vibrato sounds of the human voice and musical instruments were first pioneered by Seashore [16]. He identified the cyclic fluctuations in pitch, intensity, and timbre arising from the use of vibrato in the singing voice and musical instruments. In this context, we will define timbre as the quality of sound that arises from the relative strengths of the large number of partials (harmonics) excited by the bowed string. Fluctuations in both intensity and timbre are particularly important for violin vibrato tones [14] because of the strongly peaked, multi-resonant response of the violin body. Fritz [17] and a distinguished group of engineers, psycho-acousticians, and musicologists at Cambridge University (UK) have recently conducted what can be claimed to be the first rigorous psychoacoustic investigation of the influence of violin resonances on the perception of vibrato sounds.

In this paper, we first provide a brief introduction to the importance of vibrato in characterizing violin sounds. We then describe the software developed to extract quantitative information on vibrato pitch and amplitude and their variation from note to note from historic recordings. As an illustrative example, we quantify the use of vibrato by six famous violinists spanning the whole of the 20th century, based on its use in the often-recorded Hungarian Dance No. 1 by Brahms (as arranged by Joachim). The early acoustic recordings have been used in previous historical investigations of the use of vibrato [1-4]. In addition, we compare the use of vibrato in the same section of 1912 and 1926 recordings of Liebesleid (“Love’s Sorrow”) played by the violinist/composer Kreisler. The measurements are presented graphically. This allows easy visual comparison of the performance styles of different artists and suggests how such styles have changed over time.

ROLE OF VIBRATION IN VIOLIN TONE QUALITY

In a recent paper [14], we reviewed previous studies of the complexity of violin vibrato tones arising from the closely spaced, narrow resonances of the violin body. This leads to large-scale fluctuations in the amplitudes of the individual partials and hence timbre of violin vibrato sounds, in addition to the expected pitch fluctuations. Meyer [13] had previously shown that the time delays introduced by reflections from the walls of any performance space greatly increase the complexity and hence projection of the violin played with vibrato.

Another potentially important perceptual factor arises from the highly directional properties of the violin sound at frequencies above around a kilohertz—increasingly so for bowed notes with their fundamental or upper partials (harmonics) on the E-string (Weinreich [18]). The directional properties change very rapidly with frequency, leading to rapid changes in timbre whenever the performer’s body moves or the listener’s head moves in the performance space. Even without any movement of player or listener, the strong directionality of the violin at high frequencies will contribute to frequency-dependent reflections from the surrounding walls and will strongly influence the sound of bowed notes played with vibrato, as originally noted by Meyer [13].

A potential advantage of acoustic recordings in studying the sound produced by individual instruments arises from the absence of any reflected or reverberant sound from the performance space, though resonances of the recording horn can sometimes be important. Acoustic recordings are therefore rather dry and lack any enhancement in quality from reverberant room acoustics. However, the recorded sound is the sound produced by the instrument and player...
alone without any complications from the room acoustics or from artificial reverberation sometimes added in later electric recordings. The disadvantage of acoustic recordings is the additional noise introduced by surface imperfections of the recording medium, which became far less important as recording technology and materials developed throughout the 20th century. Surface imperfections introduce random fluctuations in the measurement of pitch as well as intensity, as illustrated in the examples described below.

The importance of vibrato on perceived violin tone quality is easily demonstrated by listening to the sound of a continuously repeated single-period extracted from a sampled violin vibrato tone. This is indistinguishable from that of a crude electronic synthesizer (Gough [14]). Other features of the violin sound, such as the nature of the initial transient (how the note is first started) and bow noise (McIntyre et al. [19]), are almost certainly important—as, for example, when playing an open string. Interestingly, the sound of a violin remains instantly recognizable, even when the first 50 ms of a long note is artificially removed. Fluctuations of intensity, timbre, and pitch within a note played with vibrato are therefore all likely to be important in defining the violin sound. In this paper, we focus on quantifying fluctuations of pitch, as this is the one factor that is under the control of the player, independent of the quality of the violin or the performance acoustics.

Typical violin vibrato involves a sinusoidal pitch modulation with a width (total frequency swing) that ranges from zero to around a quartertone (50 cents) and occasionally more (100 cents corresponds to a semitone). The cyclic vibrato pitch repetition rate is typically in the range from 5 to 8 cycles per second. Within a given note, a good player has the facility to control the amplitude and the rate of the vibrato used as a function of time. Because of this flexibility and the varied use of vibrato, it makes little sense to refer to vibrato rates and amplitudes for single selected notes alone, as has often been attempted in the past. It only makes musical sense to quantify the use of vibrato over extended musical examples. Even then, one must recognize that any such analysis only provides a snapshot of the player’s style for the specific section of the particular musical example chosen. This fails to take into account any change in a player’s choice of the use of vibrato in response to different emotional and historical contexts, e.g., in playing the music of Bach, Brahms, or Boulez.

**ANALYSIS OF VIBRATO RATES AND WIDTHS**

The automatic analysis of pitch variations from early acoustic recordings presents a number of difficulties arising from the large amount of surface noise and the restricted frequency range, typically extending to only ~3 kHz. In addition, recordings often have piano accompaniments, which “interfere” with automated pitch identification of the solo instrument. To minimize such problems, we first used CoolEdit audio software to filter out wide-band surface noise and to remove almost all the largely transient “clutter” associated with the piano accompaniment. This was achieved by removing all frequencies below 1200 Hz. Although the filtering removes all partials below 1200 Hz, the remaining signal contained all the higher frequency partials (harmonics of the fundamental at the playing pitch), each of which varies in frequency by exactly the same fraction as the fundamental (the note appearing on the printed score). Because the remaining higher partials are exact multiples of the fundamental, the waveform of the filtered sound retains the same periodicity as that of the note being played.

The resulting waveform was then analyzed using Praat software [20], which uses autocorrelation techniques to follow the periodicity of the waveform and hence the pitch of the note being played. The pitch data file was then manually “corrected” for the small number of missing or mistaken values. Such “mistakes” (usually of an octave up or down) arise from the presence of noise and the very large changes in amplitude, shape, and spectral content of the vibrato waveform within each vibrato cycle. A Mathcad™ [21] software program was then written to extract the pitch of the note being played, i.e., the note appearing on the printed score. This enabled us to plot the fluctuations in pitch of each note as deviations from the notes on the printed score, assuming the notes were centered on the pitches of an equal-tempered chromatic scale, i.e., the semitones of a piano keyboard.
tuned to the overall tuning of the extract being played. Fluctuations about the pitch of the note, and any intentional or uncontrolled changes in intonation within a single note, can then be displayed as a single continuous plot, as illustrated in Fig. 1.

The above analysis is illustrated for the first 12 bars of Brahms’s Hungarian Dance No. 1 recorded by Joachim in 1903. The curly lines under specific notes of the music illustrate the use of vibrato identified by Katz [2] from listening tests. The upper trace shows the computed pitches of the recorded sound derived using the Praat software. The superimposed step-wise lines show the output from the automated musical note identification software corresponding to the semitones of an equal-tempered scale, with the overall pitch tuned to that of the instrument. The software assumes that the fluctuations from vibrato are less than a quartertone. The target pitch can always be identified to the accuracy of a semitone. If the pitch excursion within a note occasionally exceeds a quartertone, a correction is automatically applied to keep the target pitch unchanged. On an expanded scale, the lower trace shows the time variation of the pitch fluctuations ΔHz about the notes of the equally tempered scale. The two dashed lines represent pitch variations of ±50 cents from the semitone-scale (a total width of a semitone = 100 cents).

Despite the rather large random fluctuations in measured pitch, even on the open G-string, our analytic measurements provide much more detailed information than could ever be deduced from listening tests alone. Indeed, Katz [2] failed to detect the relatively large amplitude of vibrato of almost a quartertone swing on the very first note.

Once vibrato has been established, the pitch variations within single notes can often be fitted to pure sine waves, after making a small correction for any underlying slow variations in intonation. This enables us to quantify both vibrato rates and amplitudes and their variation with time within each note (provided the notes are not too short). Such fits are illustrated in Fig. 2 for the first note of the Hungarian Dance, once vibrato was established by the four violinists illustrated. Note the fluctuations in pitch superimposed on the sinusoidal vibrato traces,

Figure 1. Pitch variations of the first 12 bars of Brahms’s Hungarian Dance No. 1 in G-minor recorded by Joachim in 1903. The upper curve indicates the pitch (f) derived using the Praat software and the superimposed step-wise variation in pitch given by the automated note-recognition software assuming an equal temperament chromatic scale. The lower trace, on an expanded scale, shows the fluctuating differences in pitch (Δf) between the recorded pitch and the notes of the equally tempered scale. The dashed lines indicate a total pitch swing of a semitone (100 cents).
which arise from intrinsic noise from the recording medium rather than the player. Such fluctuations became less important over the century, as the recording medium and electronic recording techniques improved in quality. Note also the significant amount of vibrato used by Joachim and the increase in both vibrato amplitude and vibrato rate used by the later violinists. However, it would be dangerous to use evidence from an isolated note, in one particular piece of music, by only four players, to deduce that such increases illustrate a universal changing style of violin playing over the first half of the 20th century. To address such issues, it is important to analyze longer musical examples and many more players and musical examples.

As a preliminary study, we have chosen to extend our examples using recordings of the first few bars of Hungarian Dance No. 1 by Brahms. This has been chosen because it has been recorded by a large number of individual players over the last century and has been used in several previous studies of the historical evolution of violin vibrato [1-4]. The examples used here were extracted from The Recorded Violin [22]—a treasure-trove of recordings of many distinguished violinists over the century—or were available as free downloads from the internet. As we are only interested here in pitch variations, the quality of the recordings resulting from any re-mastering of the originals is not a serious issue.

COMPARISON OF PERFORMANCE STYLES

Figure 3 illustrates the vibrato-induced pitch deviations from an equal-temperament scale.
for six distinguished violinists spanning 100 years of violin playing. Such plots highlight the general increase in vibrato width over the last century. Both Joachim and Leopold Auer used only a third to half of the vibrato widths of modern players, though accurate measurement of smaller amplitudes is difficult because of the large amount of surface noise.

Contrary to what has often been claimed, the measurements reveal only a slight evolution of vibrato rates with time, though the rocking hand movements will indeed be faster because of the larger amplitudes involved. A faster vibrato movement, as opposed to an increased vibrato rate, may well have led to some confusion amongst pedagogues and musicologists in describing and commenting on the evolution of a “faster vibrato” over the centuries. In the above example, many of the note lengths are relatively short, with vibrato generally only used on the longer notes, as advocated by Leopold Mozart and subsequent 19th-century teaching texts (see Milsom [3]).

Figure 4 makes use of the above data to derive the spectrum of vibrato-induced pitch fluctuations. The spectra were obtained by taking the Fourier spectrum of the individual traces shown in Fig. 3. The traces show the average pitch fluctuations as a function of frequency, with significant increases above the background
noise level, typically of between 5 and 8 Hz. The frequency of the overall increases indicates the vibrato rates used by the player; the widths and the variation in height of the peaks arise from variations in vibrato rates both within notes and from note to note. The measurements indicate overall vibrato rates for Joachim and Auer that are very similar, in the range 5½–7½ Hz, and ~½ Hz faster for Heifetz. Toscha Seidel uses a still faster and wider vibrato in the range 6–8 Hz, while Kogan’s is typically ~½ Hz slower and similar to that used by Heifetz. Anne-Sophie Mutter, a great colorist of tone quality, provides an extreme example of a very wide vibrato, often slow with a rate changing significantly within a note from around 5–7 Hz, presumably reflecting an intended Gypsy quality to the playing style. The absence of any significant increase in spectral weight at two (or three) times the main peak indicates that, to within the accuracy determined by the presence of surface noise, the vibrato fluctuations are largely symmetric about the mean pitch and are sinusoidal in character, as already illustrated in Fig. 2.

EMERGENCE OF THE MODERN “CONTINUOUS” VIBRATO

Acoustic recordings at the turn of the 20th century tend to confirm that violinists used vibrato more sparingly than is common today, with vibrato generally restricted to longer notes, allowing the completion of several vibrato cycles. This follows the guidance on the use of vibrato given in several influential tutorial texts, such as those previously mentioned by Spohr.
(1832) [6], de Bériot (1858) [7] and Joachim-Moser (1902-05) [8]. Milsom [3] provides several musical examples of the recommended use of vibrato taken from the original texts. Such advice is consistent with modern psychoacoustic observations summarized by Brown and Vaughn [23]. These authors showed that, for vibrato rates of greater than ~5 Hz, the ear cannot follow pitch changes, though it produces a change in perceived timbre. Conversely, the slowly varying pitch of players using a slower wide vibrato can be very unpleasant. Brown and Vaughn found that, for notes with at least one or more vibrato cycles, a sufficiently fast vibrato is perceived as a change in timbre at the time-averaged pitch. In contrast, for shorter vibrato tones, the perceived pitch is weighted towards the last pitch sounded. It is interesting to note that, as early as 1900, music critics were disparaging the increased use of vibrato—even on short notes and “technical passages.”

Figure 5 illustrates the vibrato used by the 16-year-old Heifetz in a remarkable 1917 recording of a transcription of Schubert’s *Ave Maria*, and by Kreisler in 1912 and 1926 in two recordings of his composition *Liebesleid*. (The two Kreisler examples are also illustrated and discussed by Leech-Wilkinson in paragraphs 11-13 of his online book [4].) Kreisler is often cited as the originator of the modern “continuous” vibrato, though he was not alone in using it in the early years of the 20th century. This is shown by the very similar continuous use of vibrato in the Heifetz recording with a very similar amplitude and range of vibrato rates to those of Kreisler and to those used in his later 1926 recording illustrated in Fig. 5. A computer fit to a sinusoidal pitch variation, for the 3-sec-long note ~4 seconds after the start of the illustrated section of Kreisler’s 1912 recording, demonstrates a remarkable constancy within the note of both vibrato amplitude (±20 ± 1 cents) and rate (7.05 ± 0.05 Hz), after an initial “start-up” vibrato cycle. Interestingly, there is some evidence for the vibrato on all notes starting from the central pitch with an initial downward vibrato half-cycle, as advocated by modern teachers such as Ivan Galamian [24]. Although the advice to vibrate under the pitch of the note would make it sound flat, the advice is probably a way of compensating for the natural rocking action of the hand being easier towards than away from the bridge.

The use of vibrato by Kreisler in the later 1926 recording is almost identical to that of the earlier recording, though somewhat less regular. The longest note is played with the same vibrato width (±20 ± 1 cents), but at a slightly faster rate of 7.5 Hz for the first half of the note, slowing to ~6.95 Hz for the second part. Figure 5 also illustrates the way that Kreisler starts and stops the vibrato at the start and end of each note—and at each time the bow direction is changed as the same note is repeated, indicated by the vertical arrows. In this sense, the vibrato is used on all the longer notes played, rather than being used continuously, i.e., without stopping. Indeed, the way that a player starts, stops, and shapes vibrato within a note is a very important characteristic of a player’s individual style. To paraphrase Flesch: without vibrato, it is impossible to recognise individual players, but using vibrato each player is easily and surely distinguished (cited in full by Milsom [3, p. 122]). Note also the use of portamento (continuous pitch changes between notes) in both the Heifetz and Kreisler examples, which for slow portamento often triggers spurious note changes in our automatic note-changing detection software, illustrated by the vertical lines in Fig. 5.

**CONCLUSIONS**

We have developed software and graphical outputs that facilitate a critical comparative analysis of the use of vibrato in historic and modern recordings of the violin—and of any other instrument. Comparison is made of the use of vibrato by six famous violinists playing the same section of Brahms’s Hungarian Dance No.1 and of Kreisler and Heifetz playing sections of more lyrical examples. The measurements quantify the increasing amplitude of vibrato widths over the 20th century and illustrate the emergence of the modern form of “continuous” vibrato. In addition, the software allows the automated analysis of note lengths and the use of portamento (sliding in pitch) between notes, which are other important factors involved in the development of violin-playing styles over the last century.

It would be interesting to extend this study to many more violinists and musical examples,
Figure 5. Examples of the “continuous” vibrato used by Heifetz and Kreisler, with insets showing the spectrum of vibrato rates obtained from somewhat longer sections than the 12 seconds illustrated. The expanded-frequency lower traces show the fluctuations in pitch around the notes of the equal-temperament chromatic scale. The dashed horizontal lines correspond to a fluctuation in pitch of ±50 cents (a total swing of a semitone). The vertical arrows indicate bow changes on the same note.
particularly to players in the first half of the 20th century, when there was much more variation in the use of vibrato than is common today. It is interesting to note that Joachim used somewhat more vibrato on longer notes than has sometimes been recognized, though accurate measurements of small amounts of vibrato tend to be masked in acoustic recordings by surface noise. This presumably has an influence on listening tests as well, which would be an interesting avenue to explore.

Despite Auer’s acerbic strictures on the frequent abuse of the use of vibrato [25, Ch. 4, sec. 9], he uses vibrato throughout the Brahms sample at a very similar rate to modern performers, but with typically only a third to half the width. However, other contemporary recordings show some players using a wider and some a narrower vibrato. It is therefore important to recognize that, although the examples examined here are consistent with a continuous increase in vibrato widths over the century, the present study simply quantifies the vibrato rates and amplitudes used by a relatively small number of prominent violinists. In reality, the evolution of vibrato over the last century would almost certainly have shown much more variation amongst individual performers and schools of violin playing than we have been able to illustrate, in what is effectively only a preliminary study.

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