'Nourishment for the soul' or 'a feast for the ear'? A comparative study of the Stein and Walter fortepiano actions

Stephen Birkett

The *Prellzungenmechanik* (PZM) is a type of piano action mechanism probably devised by Johann Andreas Stein in the 1770s, motivated by his familiarity with Johann Heinrich Silbermann's pianos. In the PZM, instead of being on a fixed rail, the hammer is mounted on the key, so it can rotate freely about a pivot point in the arms of a Y-shaped holder (kapsel) screwed into the keytail. As the key is played the tail of the hammer shank (beak) catches on a hinged hook (prell) behind, and the hammer is 'flipped up' to strike the strings. During the last quarter of the 18th century two distinct versions of the PZM co-existed. Stein's action (Figure 1) continued to be used by his followers Johann David Schiedmayer, Sebastian Lengerer, Johann Louis Dulcken, and others, as well as his daughter Nannette Streicher until 1805. It is characterized by its wooden kapsels, notched prells leaning slightly backwards, and the absence of a backcheck to catch the rebounding hammer.[1] The version attributed to Anton Walter (Figure 2) has brass kapsels, '7'-shaped prells leaning forward, and a continuous backcheck rail.[2] Walter's PZM was continued with little change, other than in the size and weight of the parts, as the so-called Viennese action used in a great many Germanic pianos through the 19th century.

Differences between the pianos of Stein and Walter were described and associated with different playing styles by various historical writers. The 1796 description of von Schönfeld[3] is well known:

> Since we now have two 'original' instrument builders, we also divide our fortepianos in two groups: those of Walter and those of [Nannette] Streicher. Upon careful observation, we can divide our greatest pianists into two groups as well. One of these groups loves a great feast for the ear, that is, it likes enormous noise; consequently it plays very sonorously, extremely quickly, studies the trickiest passages, and the quickest octave leaps. This demands force and strong nerves; in exerting these, one is not capable of achieving a measure of moderation, so one needs a fortepiano whose tone does not jangle ["dessen Schwebung nicht überschnapt"]. For virtuosos of this kind we recommend a fortepiano of Walter's kind. The other group of our great pianists

1 M. Latcham, "Mozart and the pianos of Johann Andreas Stein", *Galpin Soc. J.* 51 (1998), pp. 114–153.

2 M. Latcham, "Mozart and the pianos of Gabriel Anton Walter", *Early Music* 25 (1997), pp. 382–400.

3 Johann Ferdinand von Schönfeld, *Jahrbuch der Tonkunst von Wien und Prag*, Vienna, 1796.

seeks nourishment for the soul, and likes not only precise, but also sweet, melting playing. These players cannot choose a better instrument than one of Streicher's, or the so-called Stein model.[4]

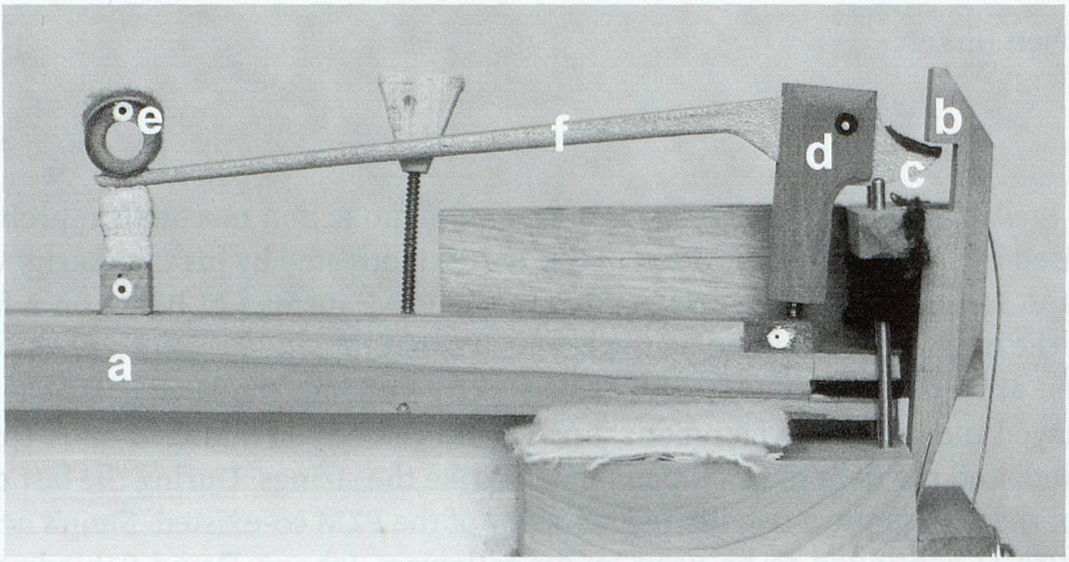


Figure 1: Stein-type PZM action model used for experimental observation, based on a 1794 JD Schiedmayer piano: a) key; b) prell; c) hammer beak; d) kapsel; e) hammer; f) hammer shank. The damper lifter is also seen behind.

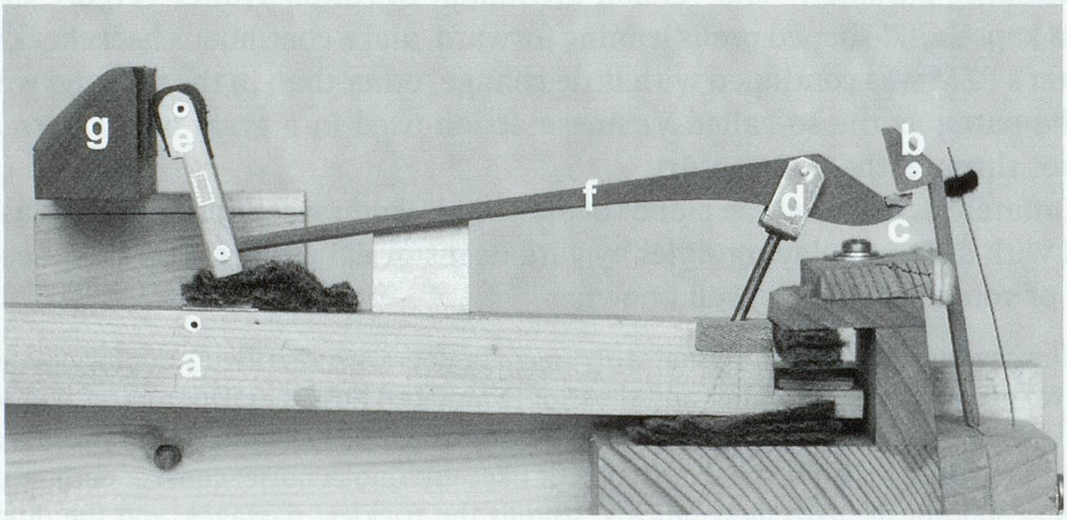


Figure 2: Walter-type (Viennese) PZM action mechanism used for experimental observation, based on a ca. 1795 Anton Walter piano: a) key; b) prell; c) hammer beak; d) kapsel; e) hammer; f) hammer shank; g) backcheck rail.

The writer says that, without moderation an unpleasant tone can be produced on a Stein, while the sound of the Walter is comparatively safe even with robust

4 Transl. T. Skowroneck, *Beethoven the Pianist*. Cambridge: Cambridge University Press, 2010, p. 76.

playing. It is often assumed[5] that the "jangling tone" (as translated by Skowroneck) is the effect of a rebounding hammer double-striking the string because there is no backcheck in the Stein. However, von Schönfeld may have been describing the compromised response of stringing, soundboard, and so on, when robust playing exceeds the design capabilities of the instrument. Andreas Streicher, in his 1801 booklet,[6] is quite clear about this:

> *Striking [the keys] too hard* (which will ruin every fortepiano) produces far less sound than you would normally believe, for every string can only yield a limited degree of loudness. If one were to try increasing that still further through a heavy stroke, the string would be set into an unnatural vibration.[7]

The safety derived from a backcheck by avoiding double-striking will not prevent the "jangling tone" of von Schönfeld if the piano itself is pushed past the limit as described by Streicher. Jurgenson[8] puts this bluntly: "The backcheck only makes it possible to violate the instrument and good taste, while improving nothing."

To be fair, though, this is a matter of degree, and one could argue that both Stein and Walter properly matched the action and instrument capabilities. The absence of a backcheck would not be a limitation if double-striking only occurs when the tone has otherwise already been compromised by too forceful playing. The present paper examines the backcheck question in a larger context, by comparing the dynamic response of the Stein and Walter PZM in terms of their overall design differences.

The PZM key stroke is usually described by three phases: (i) *Lost motion*, in which the hammer moves with the key until the beak comes into contact with the prell hook; (ii) *Working key travel*, as the key continues to drive the beak into the prell and the hammer is flipped upwards rotating on its axle, until the point of let off (or 'escapement') when it loses contact; and (iii) *Aftertouch*, subsequent motion of the components after let off until they come to rest with the key held down. A final phase, the *key release*, can also be included in a complete key stroke.

A scant 0.5 mm of lost motion as measured at the key front with a slow key press is typical and considered necessary for consistent reset of the beak under the prell hook when not playing softly. Working key travel is largely fixed by action geometry and the requirement that the hammer needs to be actively controlled by the key for soft playing until it is quite close to the string. About 3 or 4 mm of front key motion is typical of 18th century PZMs. The amount of aftertouch is an historically uncertain aspect of PZM regulation and can be quite variable. Current

5 M. Latcham, "The check in some early pianos and the development of piano technique around the turn of the 18th century", *Early Music* 21 (1993): pp. 28–42.

6 *Kurze Bemerkungen über das Spielen, Stimmen und Erhalten der Fortepiano welche von Nannette Streicher geborne Stein in Wien verfertigt werden*, Wien, 1801.

7 Transl. P. de Silva, *The Fortepiano Writings of Streicher, Dieudonné, and the Schiedmayers*. Lewiston NY: Edwin Mellen Press, 2008, p. 49. Italics are Streicher's.

8 W. J. Jurgenson, "The structure of the classical piano", paper read at Antverpiano, 1989.

practice is to set this up with anything from almost none to a few mm of key front motion before the key reaches the stop rail after escapement in pianissimo playing.

The mechanical behaviour of a piano action is usually visualized by extrapolating from the geometric relationships between the parts as determined by their configuration.[9] This approach is based implicitly on the assumption that these relationships do not change significantly under playing conditions. It is expected that the 'dynamic response' should be more or less a faster version of what is observed 'statically' when the key is moved slowly, as in very soft playing or for adjustment during action set up. In reality this is not so.

Compliance due to flexibility of the components and compression of felts, cloths, and leather at contact locations between them, can cause the dynamic response to be very different from the static response. As will be demonstrated, the PZM key stroke scenario described above is at best only a very rough approximation of what actually occurs for stronger playing, as the forces generated deform components and compress contact materials. These dynamic effects are complex and inter-related, and they are dependent on material properties. Recreating the builder's original intentions with some confidence can be difficult. In particular, the properties of ephemera in an ancient extant instrument will have changed over time, or it may be missing or have been replaced. To illustrate these points, the nature and extent of aftertouch depends strongly on the softness and thickness of the stop rail cloth and its location with respect to the key tail, as well as the style of playing; this uncertainty complicates understanding of other aspects of the dynamic behaviour, such as the correct and efficient function of the Walter backcheck, or the rebound of the Stein hammer from the key, which are affected by aftertouch characteristics.

In a previous paper[10] techniques were described for investigating the dynamic response of piano action mechanisms using high-speed imaging. This work began the comparative study of the Stein and Walter PZM by examining response to pianissimo and forte playing. Detailed motion of the components was presented and the nature and timing of their interactions analyzed. The significant deformation of the hammer shank was directly observed, and its implications explored, particularly as this affects the backcheck position and function, and beak-prell relationship. With forte playing the flexing hammer shank was shown to be responsible for reduction and loss of contact between beak and prell prior to the escapement event determined by action geometry. Comparison of the Stein and Walter PZMs is continued in the present paper with an analysis of the direct

9 For example, see the analyses in: M. Cole, *The Pianoforte in the Classical Era*. Oxford: Clarendon Press, 1998, pp. 292–310; M. Latcham, "The check in some early pianos"; K. Mobbs, "A performer's comparative study of touchweight, key-dip, keyboard design and repetition in early grand pianos, c. 1770 to 1850", *Galpin Soc. J.* 54 (2001), pp. 16–44.

10 S. Birkett, "Observing the 18th century *Prellzungenmechanik* through high-speed imaging – Pianissimo and forte response compared", in: T. Steiner (Ed.), *Cordes et claviers au temps de Mozart, Actes des Rencontres Internationales harmoniques, Lausanne 2006*. Bern: Peter Lang, 2010, pp. 305–326.

relationship between the action components, including the key front, at various playing levels. Some well-established, though apparently incorrect, speculations about PZM function are critically examined using the understanding of dynamic response obtained here.

Methods

Single-key benchtop models were constructed for the experimental study. The Stein model (Figure 1) is based on a 1794 Johann David Schiedmayer (DS) piano;[11] the Walter (AW) model (Figure 2) is based on a ca. 1795 Anton Walter piano.[12] These actions were accurately aligned with an appropriate bichord string box so the arrangement is representative of the original piano in all respects. DS has a 584 mm speaking length (c^1 note) with 0.46 mm iron wire, strike point 51 mm from the nut, and hammer throw 31 mm; AW has slightly thicker 0.52 mm iron wire and speaking length 590 mm (b^0 note) with a 51 mm strike point and hammer throw of 31 mm. An adjustable slap rail was placed behind the AW prell according to the original piano design configuration; DS has no slap and the bellyrail is about 4 mm behind the prell at rest. As can be seen in the complete setup shown in Figure 3 the arrangement provides an unimpeded view from the side for observations. Dampers were not present in the portion of the study reported here.

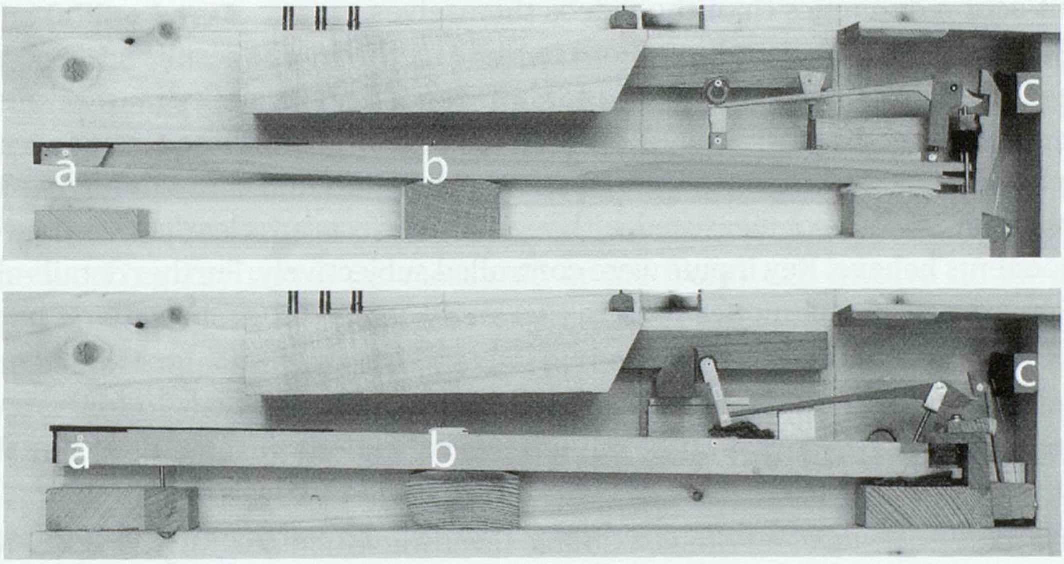


Figure 3: Bichord string model shown with DS (top) and AW (bottom) action model in correct configuration for observing experimental key strikes: a) key front; b) balance point; c) slap rail.

11 Germanisches Nationalmuseum Nürnberg, MIR 1102. Data obtained from a technical drawing and supplementary information by W.J. Jurgenson, 1987.

12 Germanisches Nationalmuseum Nürnberg, MINe 109. Data obtained from a technical drawing by S. Wittmayer, 1974.

The key was played in the normal way and subjective judgement used to obtain the desired 'dynamic level', defined as follows: (i) *pianissimo* is very soft controlled playing for which dynamic effects do not occur and the action behaves as one would imagine from geometric considerations and static regulation; (ii) *fortissimo* is the strongest playing that can effectively be used without compromising tone or action response; and (iii) *mezzo* refers to one or more intermediate levels used in various tests. The appropriate fortissimo dynamic level for AW produced a larger volume of sound from the string model, as can also be confirmed by the greater string excursion obtained.

Two synchronized digital cameras recording 8,000 frames per second[13] were used to observe action response. In all tests one camera viewed the hammer tip and rear segment of the key (at the point underneath the at-rest hammer head). The second camera viewed either the beak-prell area, or the key front. The high-speed videos show interesting qualitative observations of events and interactions, and deformations of parts, but can also provide quantitative information. Automated motion tracking of small markers attached to the components, visible in Figs. 1–3, was used to obtain the position of the action components, expressed as their vertical and horizontal displacements (mm) with respect to the initial (at rest) location. Positive reference directions were chosen as backwards (away from the key) for horizontal and upwards for vertical. Graphical presentation of these results, either in terms of time (history), or by relating the motions of components to each other, as in the present paper, is much more informative about action dynamics than the videos themselves.

There are some obvious limitations to these methods. The results are, of course, gained from these specific models, and their general applicability must be viewed with some caution. Consistency is difficult to maintain with these types of actions, which are subject to changes from ambient conditions and through having been played. Forces were not measured, although their effects are clearly evident in how components behave. Key inputs were controlled subjectively. Further details about the experimental techniques used in this study can be found in the first paper.[14]

From key to hammer

At the most basic level a PZM is a double lever for which one might expect to be able to define a combined leverage ratio, for instance the vertical displacement of the hammer vs that of the key front. For a simple double lever these would be proportional and we can speak of a constant ratio. However, in the PZM the hammer lever is mounted on the key, so its pivot moves toward the key front as the key rotates. The short arm of the hammer lever (from axle to prell hook)

13 Frame intervals are therefore 0.125 ms or 1/8000 second.
14 S. Birkett, "Observing the 18th century *Prellzungenmechanik*".

will gradually increase during the key stroke, so it can be expected that the overall leverage ratio will diminish. In other words, the PZM can be described as a decelerating action.

The relationship between the vertical position of hammer and key front[15] is shown for a range of dynamic levels in Figure 4. The key front marker provides the motion of the key at the normal playing location (180 mm to the balance point in both actions). The key stroke begins in the lower right with lost motion, during which the key moves about 0.5 mm before the hammer shows any significant motion. Thereafter, at pianissimo level the hammer moves toward the string as anticipated by static regulation, and, indeed, the deceleration effect predicted by action geometry can be seen in the gradually diminishing slope of the hammer vs key position 'line'. Considering the local slope of this curve as the effective ratio, DS diminishes from about 12 to 9 and AW somewhat less, from beginning to end of the key stroke.

For a given action configuration the smallest amount of aftertouch that is possible by playing very lightly at key bottom, so the key just meets the stop rail cloth and settles, can be called the static aftertouch. The pianissimo plots of Figure 4 show this to be about 0.6 mm for DS, and 1.1 mm for AW.[16] After striking the string the hammer drops down to the key and settles on the key rest cloth for DS, falling with the key on its release; with AW the hammer is caught on the check, and held there on release until the key has fallen to about the position of static escapement, after which the hammer drops again and bounces slightly on the falling key.[17]

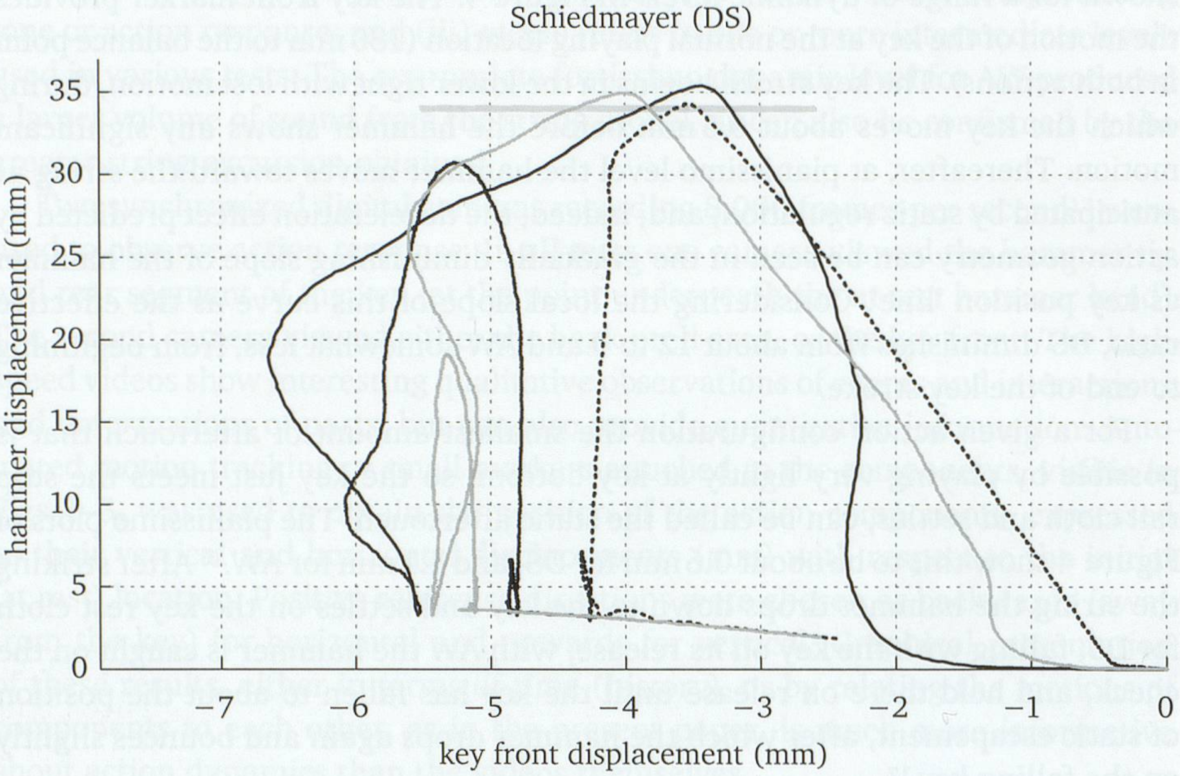
As can be seen in Figure 4, at all but the softest controlled pianissimo playing, the dynamic relationship between key and hammer motion is more complex. A pianist will be aware of these effects. Even though they happen too quickly to be actively perceived while they are occurring they become integrated with playing technique and the overall approach to the keyboard. As much as half of the working key travel (as measured at the front) can involve no hammer motion at all. Various factors can be responsible for this, including compression of the balance punching or cloth, flexing of the key, flexing of the hammer shank, compression of the beak leather, and changes in the relation between hammer beak and prell. During the key stroke the flexed or compressed parts relax, so the hammer mostly catches up with the key. The position of the key front at the moment of hammerstring contact varies with dynamic level, but unpredictably as it depends on the timing of relaxation and vibration of deformed components.

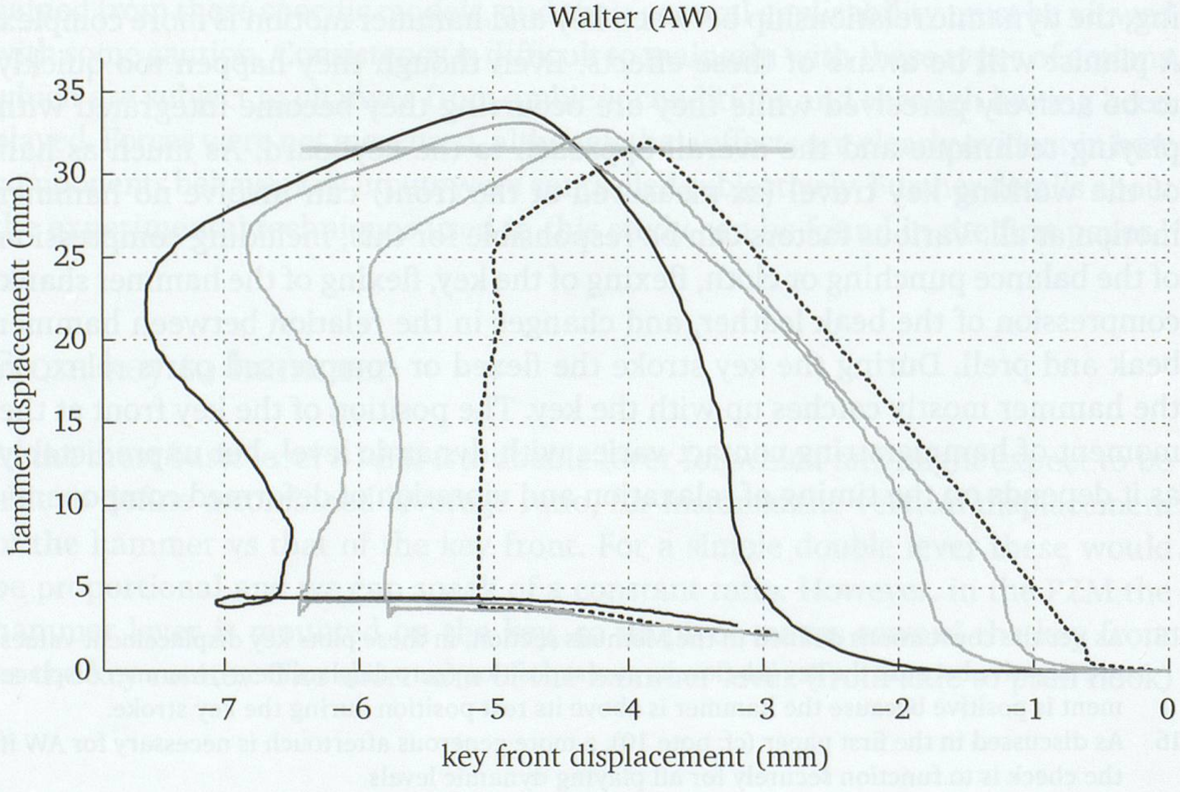
15 As per the conventions defined in the Methods section, in these plots key displacement values are negative because the key is below its at-rest position (zero displacement); hammer displacement is positive because the hammer is above its rest position during the key stroke.

16 As discussed in the first paper (cf. note 10), a more generous aftertouch is necessary for AW if the check is to function securely for all playing dynamic levels.

17 As noted in the figure caption, the final part of the key release is not shown in the plots to avoid confusion by overlapping the initial phase of key motion.

Figure 4: Hammer vertical displacement related to key front vertical displacement for DS and AW as indicated at dynamic levels pianissimo (dashed), fortissimo (black), and intermediate level(s) (grey). Location of string at-rest is shown by the horizontal line. Key release is partially omitted to avoid confusion.





Any consideration of decelerating key leverage for all but the softest playing is clearly meaningless, as the final approach to the string is governed primarily by dynamic factors and the state of the key and hammer as determined earlier in the keystroke, rather than the current motion of the key front.

In both actions, stronger playing to obtain a louder dynamic resulted in more aftertouch, regardless of conscious attempts not to 'play into the key bottom'. The overall range of aftertouch increased by up to 2 mm compared to static (minimum) aftertouch. With stronger playing, oscillation of the key on the stop rail cloth can also be seen in the plots. In both actions and for all dynamic levels the key has already reached the stop rail before the hammer returns from the string. In AW the backcheck captures the hammer securely, but sometimes on the rebound after it bounces back up off the key rest cloth;[18] the DS hammer rebounds freely after contacting the key, with only a single significant bounce that almost, but not quite, reaches the string at fortissimo.

Key flexing

Key flexing can be evaluated by monitoring the position of points on either side of the balance rail. The motion of the rear key segment tracking marker underneath the at-rest hammer head (140 mm and 137 mm behind the balance point on DS and AW respectively) was compared to that of the key front marker. For a rigid key these would move together, so their displacements are proportional, as governed by the ratio of their respective distances to the balance point. This 'rigid' leverage line is provided in Figure 5 which shows the relationship between the two key displacements with fortissimo and mezzo dynamic levels for DS and AW.

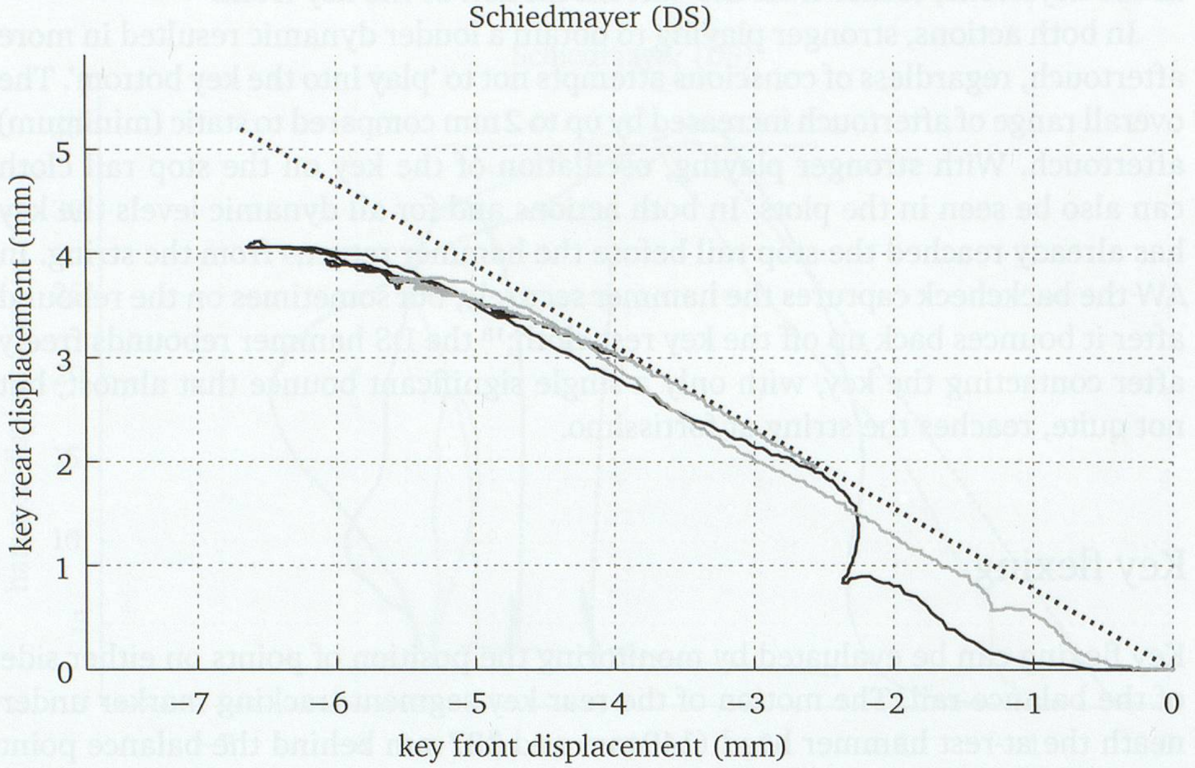
With pianissimo playing the trajectory follows the leverage line except for a slight deviation while held on the stop rail. The substantial deviation for stronger playing includes the effects of key flexing, as well as any compression of the balance punching.[19] This effectively extends the period of lost motion as seen at the key front, because the hammer moves with the rear of the key. This effect is associated with the lengthy period of working key travel when the hammer remains stationary (see Figure 4). As the rear of the key 'catches up' with the leverage position, the hammer is also rapidly accelerated, while the front of the key stops moving, and even moves upwards slightly in DS.

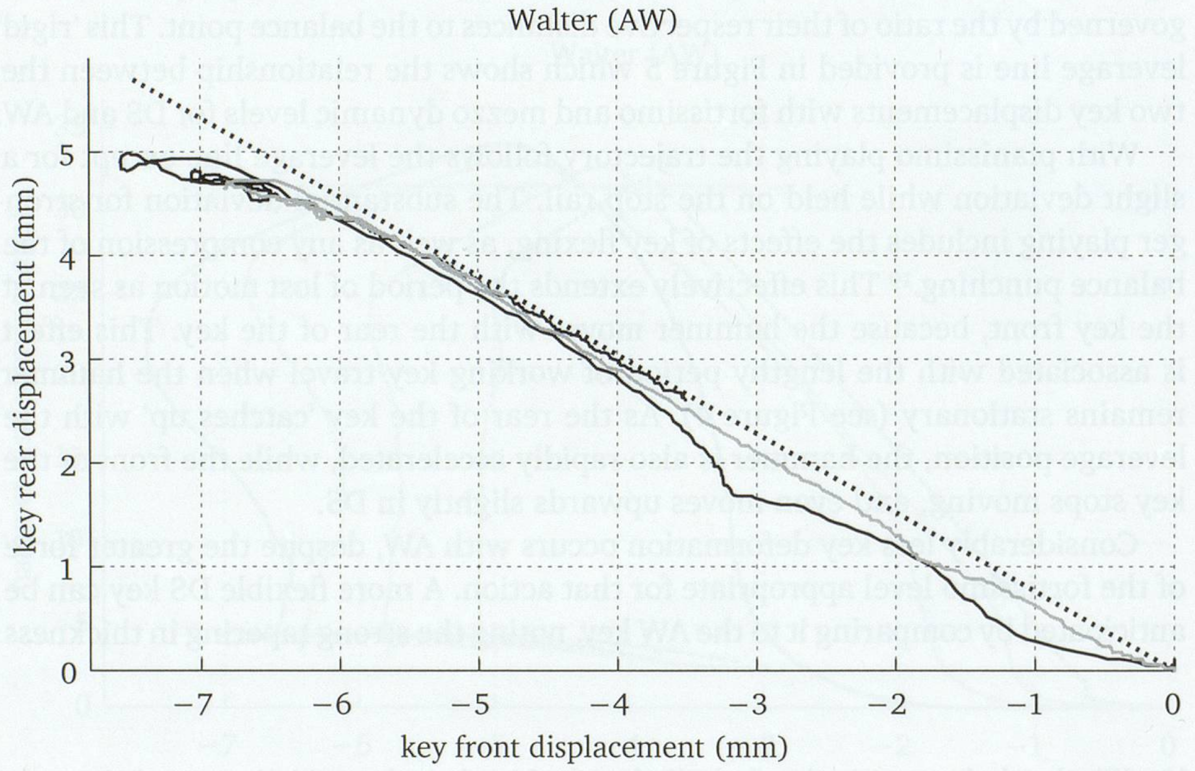
Considerably less key deformation occurs with AW, despite the greater force of the fortissimo level appropriate for that action. A more flexible DS key can be anticipated by comparing it to the AW key, noting the strong tapering in thickness

18 Whether the hammer reaches the key before checking depends sensitively on regulation, especially the nature and position of the backcheck leather surface.

19 Balance punching compression cannot be separated from key flex unless a third point on the key at the balance rail is monitored, which was not possible with the present camera set up.

Figure 5: Deviation of key from rigid leverage (dotted line) at dynamic levels mezzo (grey) and fortissimo (black). Displacement of key rear segment vs front shown. Return of released key to rest is omitted for clarity after it begins to follow the leverage line.





toward the front of the DS key. Measuring at rear, balance, and front positions these dimensions are: AW key – 19, 18, 18 mm; DS key – 16, 16, 11 mm. The stiffness of a beam in bending is related to the cube of its thickness, so the effect of tapering on key deformation during strong playing can be quite significant.

Key-prell relationship

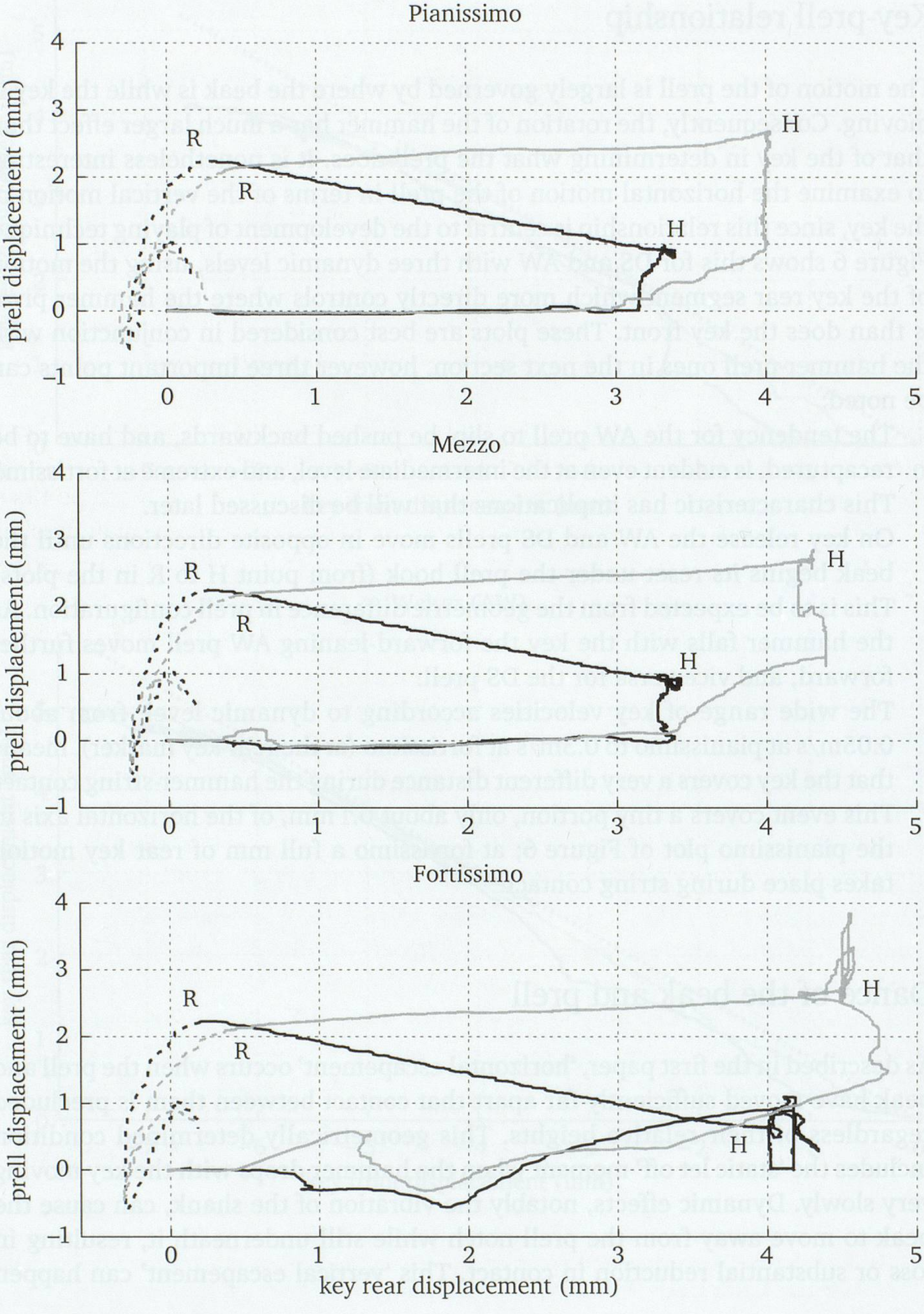
The motion of the prell is largely governed by where the beak is while the key is moving. Consequently, the rotation of the hammer has a much larger effect than that of the key in determining what the prell does. It is nonetheless interesting to examine the horizontal motion of the prell in terms of the vertical motion of the key, since this relationship is central to the development of playing technique. Figure 6 shows this for DS and AW with three dynamic levels, using the motion of the key rear segment which more directly controls where the hammer pivot is than does the key front. These plots are best considered in conjunction with the hammer-prell ones in the next section, however three important points can be noted:

- The tendency for the AW prell to slip, be pushed backwards, and have to be recaptured, is evident even at the intermediate level, and extreme at fortissimo. This characteristic has implications that will be discussed later.
- On key release the AW and DS prells move in opposite directions until the beak begins its reset under the prell hook (from point H to R in the plots). This is to be expected from the geometric difference in prell configuration. As the hammer falls with the key the forward-leaning AW prell moves further forward, and vice versa for the DS prell.
- The wide range of key velocities according to dynamic level, from about 0.05m/s at pianissimo to 0.3m/s at fortissimo (at the rear key marker), means that the key covers a very different distance during the hammer-string contact. This event covers a tiny portion, only about 0.1 mm, of the horizontal axis in the pianissimo plot of Figure 6; at fortissimo a full mm of rear key motion takes place during string contact.

Dance of the beak and prell

As described in the first paper, 'horizontal escapement' occurs when the prell and beak have moved sufficiently far apart that contact between them is precluded regardless of their relative heights. This geometrically determined condition includes the 'static let off' moment when the hammer drops with the key moving very slowly. Dynamic effects, notably the vibration of the shank, can cause the beak to move away from the prell notch while still underneath it, resulting in loss or substantial reduction in contact. This 'vertical escapement' can happen

Figure 6: Horizontal displacement of prell vs vertical displacement of key rear segment for DS (black) and AW (grey) with three dynamic levels (pianissimo, mezzo, fortissimo) as indicated. Hammer, prell, and key held down against the stop rail are all at rest at H and beak begins reset at R. Motion subsequent to R is shown (dashed), but omitted for clarity where the beginning of the plot would be obscured by it. Axes scales are the same for each subplot for direct comparison.



during the key stroke before the geometrical necessity of horizontal escapement has been reached.[20]

Figure 7 shows the vertical position of the hammer in relation to the horizontal position of the prell for AW and DS at three dynamic levels.

In DS the prell is captured by the beak immediately on contact (after lost motion) and pulled into the rest rail cloth. Vertical escapement occurs with the hammer about 10 mm from the string, allowing the prell to move backwards gradually, due to the decompression of the rest rail cloth. The prell arrives back at its normal rest position immediately before hammer-string contact occurs, and the beak-prell relationship is as it would be for static letoff. The tip of the beak recontacts the prell and pushes it quite gently backwards. Even at fortissimo the DS prell remains within 1 mm from the rest rail.

For soft playing the DS prell settles immediately against the back edge of the beak leather, and the beak rides up the prell, pushing it further back, as the hammer falls to rest on the key. For stronger playing the prell bounces on the back edge of the beak leather instead of sliding, as the hammer falls, and while it rises again after rebounding from the key. These intermittent prell-beak contacts can be seen in the fortissimo plot of Figure 7. If the hammer bounces high enough – in the present DS action about 25 mm – off the key, contact between prell and beak leather is precluded because the prell is on the rest rail. In Figure 8 the prell is seen to bounce on the beak leather six times before this occurs. Between points A and B the prell is on the rest rail. After point B the falling hammer again pushes the prell backwards, and subsequent contact is sliding rather than bouncing. With the key held down and the hammer at rest on it, the dance ends with the DS prell resting against the back edge of the beak leather less than 1 mm from the prell rest rail (point H in Figure 7).

The AW prell is initially pushed backwards by the beak on contact, as much as 0.5 mm at fortissimo, while the hammer shank bends and the head leans forward with no upwards motion. The beak then captures the prell and pulls it forward, but more tenuously than with DS. Vertical escapement occurs as with DS and the prell returns to its rest position as the hammer gets close to the string. The AW prell is ejected backwards forcefully, bouncing against the beak leather of the hammer as it falls and, for stronger playing, after it has been caught on the backcheck as well. When everything is at rest and the key is held down the AW prell sits against the beak about 3 mm from the rest rail (point H in Figure 7).

The differences between the prell-beak behaviour of DS and AW can be attributed largely to a single explanatory factor: Stein used notched prells leaning slightly backwards and Walter used '7'-shaped prells leaning forward. As discussed in the first paper[21] these design elements have significant implications in mechanical function. The DS prell-beak contact remains secure (grabs) when

20 See, for example, Figure 6 and the discussion and image sequence in Figure 7 of S. Birkett, "Observing the 18th century *Prellzungenmechanik*".

21 S. Birkett, "Observing the 18th century *Prellzungenmechanik*".

Figure 7: Vertical displacement of hammer vs horizontal displacement of prell for DS (black) and AW (grey) with three dynamic levels (pianissimo, mezzo, fortissimo) as indicated. Hammer, prell, and key held down against the stop rail are all at rest at H and beak begins reset at R. Motion subsequent to R is shown (dashed) only for DS pianissimo; others are omitted for clarity. Axes scales are the same for each subplot for direct comparison.

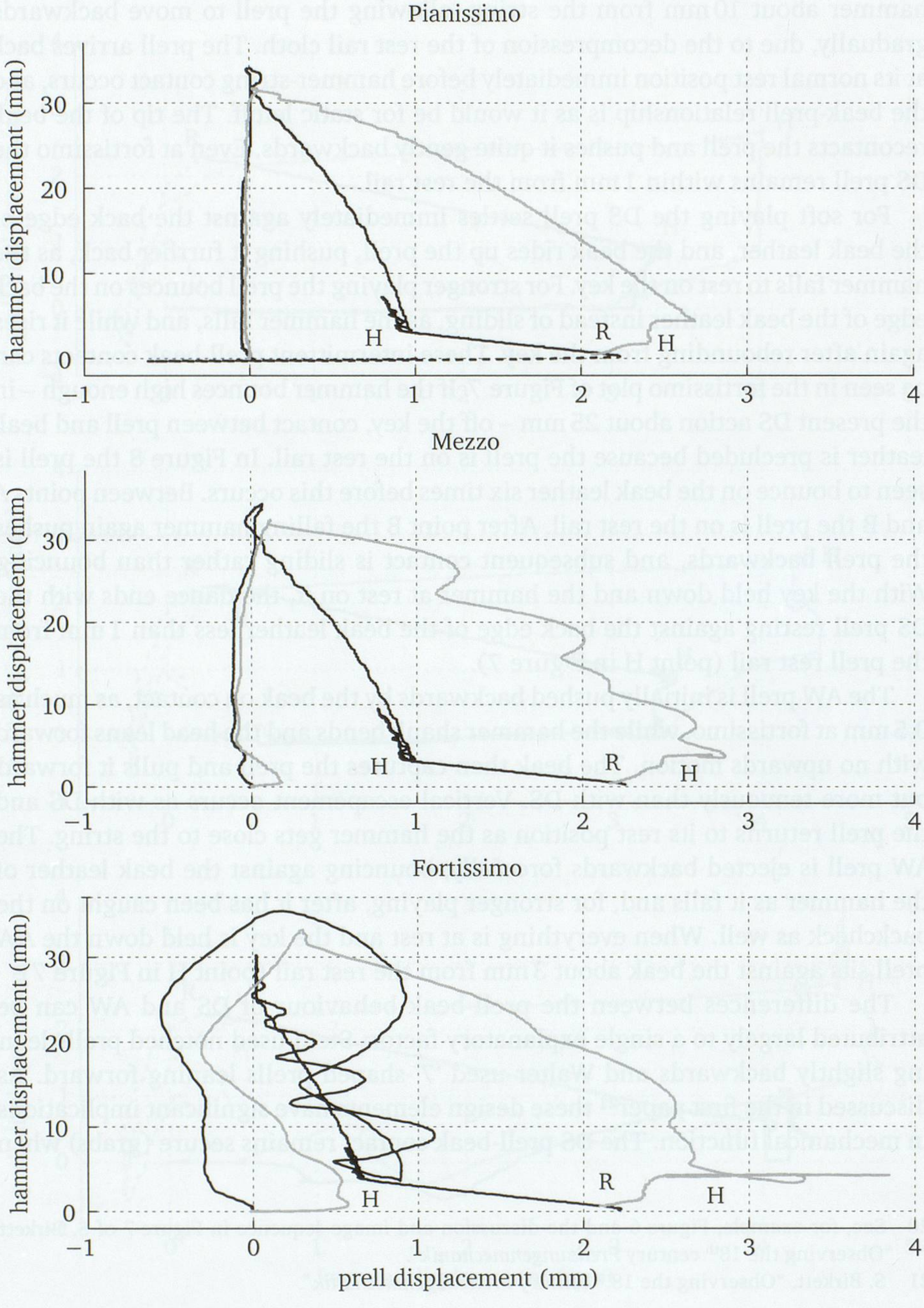
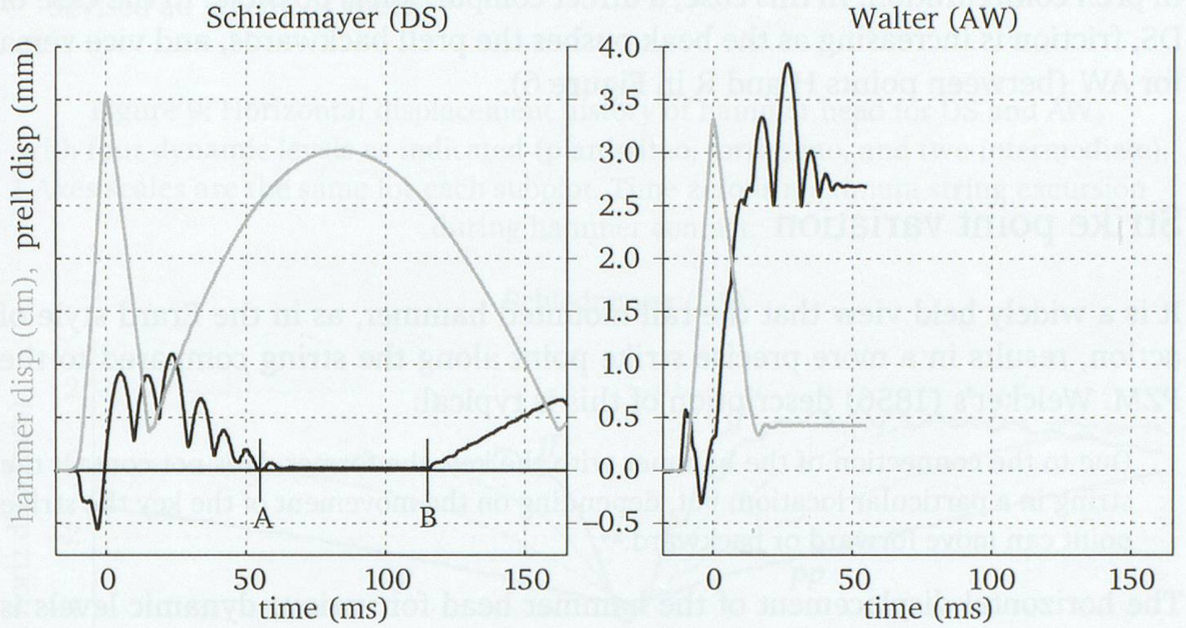


Figure 8: Horizontal displacement history of prell (black) for DS and AW with fortissimo dynamic level. Vertical displacement of hammer (grey) also shown (note cm used for visual clarity). Between points labelled A and B the high hammer and at-rest prell preclude beak-prell contact. Axes scales are the same for each subplot. Time zero is maximum string excursion.



contact with the beak occurs, while the AW prell has a tendency to escape from the beak (slips) unless held securely by friction. This difference is responsible for the DS prell remaining very close to the beak after string contact, and the forceful ejection of the prell in AW.

The timing of the prell bouncing against the beak, which is independent of the amplitude of prell motion, is determined by the mass of the prell and the strength of the spring. There is no significant difference between these bounce times (9ms for DS, 10ms for AW). Prell reset times (15ms for DS, 13ms for AW) are also almost identical, contradicting Cole's suggestion[22] that the Walter Prell "is thinner, lighter, and therefore more prompt in action, since there is less mass for the brass spring to move". The observed times also contradict Cole's argument based on prell configuration:

> The Walter [prell] is angled forward. After escapement has occurred, the hammer in the Stein type must push against the spring as the key is released. This is a slight (but real) impediment to the hammer's return. Because the [prell] in Walter's design is not leaning backwards after escapement has taken place, the fall of the hammer when the key is released demands much less work against the spring's resistance – hence the quick and faultless re-engagement.[23]

22 M. Cole, *The Pianoforte in the Classical Era*, p. 223.
23 *Ibid.* p. 223.

In reality, the prell-beak contact with stronger playing is intermittent, and, in any case, the prell spring in DS is actually less compressed than that of AW, despite the prell having to move backwards.

The somewhat longer keyfall time, from key release to arrival at the rest cloth, for DS (110ms) compared to AW (70ms) might be attributed to the differences in prell configuration. In this case, a direct comparison is possible. In the case of DS, friction is increasing as the beak pushes the prell backwards, and vice versa for AW (between points H and R in Figure 6).

Strike point variation

It is a widely held view that the rail-mounted hammer, as in the Erard style of action, results in a more precise strike point along the string compared to the PZM. Welcker's (1856) description of this is typical:

> Due to the connection of the hammer with the key, the former does not contact the string in a particular location, but, depending on the movement of the key the strike point can move forward or backward.[24]

The horizontal displacement of the hammer head for various dynamic levels is shown in Figure 9. The change in strike point, at least for these 18th century actions, is very marginal. It is quite consistent at all levels with AW, and for all but fortissimo level with DS, for which there is a scant 0.5 mm change.[25] The horizontal oscillation of the hammer head due to flexing of the shank and the kapsel stem is particularly noticeable for AW, because of the tall hammers and the comparatively flexible, thin brass kapsel stem used in the Viennese version of the PZM.

It can also be seen in these plots that the AW hammer head moves almost 6 mm horizontally prior to to string contact, considerably more than the corresponding 4 mm for the DS hammer head. This difference must be attributed to action geometry, because it is the same at all dynamic levels.

Backcheck or not?

After string contact it is essential to constrain the hammer motion if it is not to rebound and re-strike the string, causing a stuttering effect, as well as to make controlled rapid repetition possible and predictable. The most obvious solution is

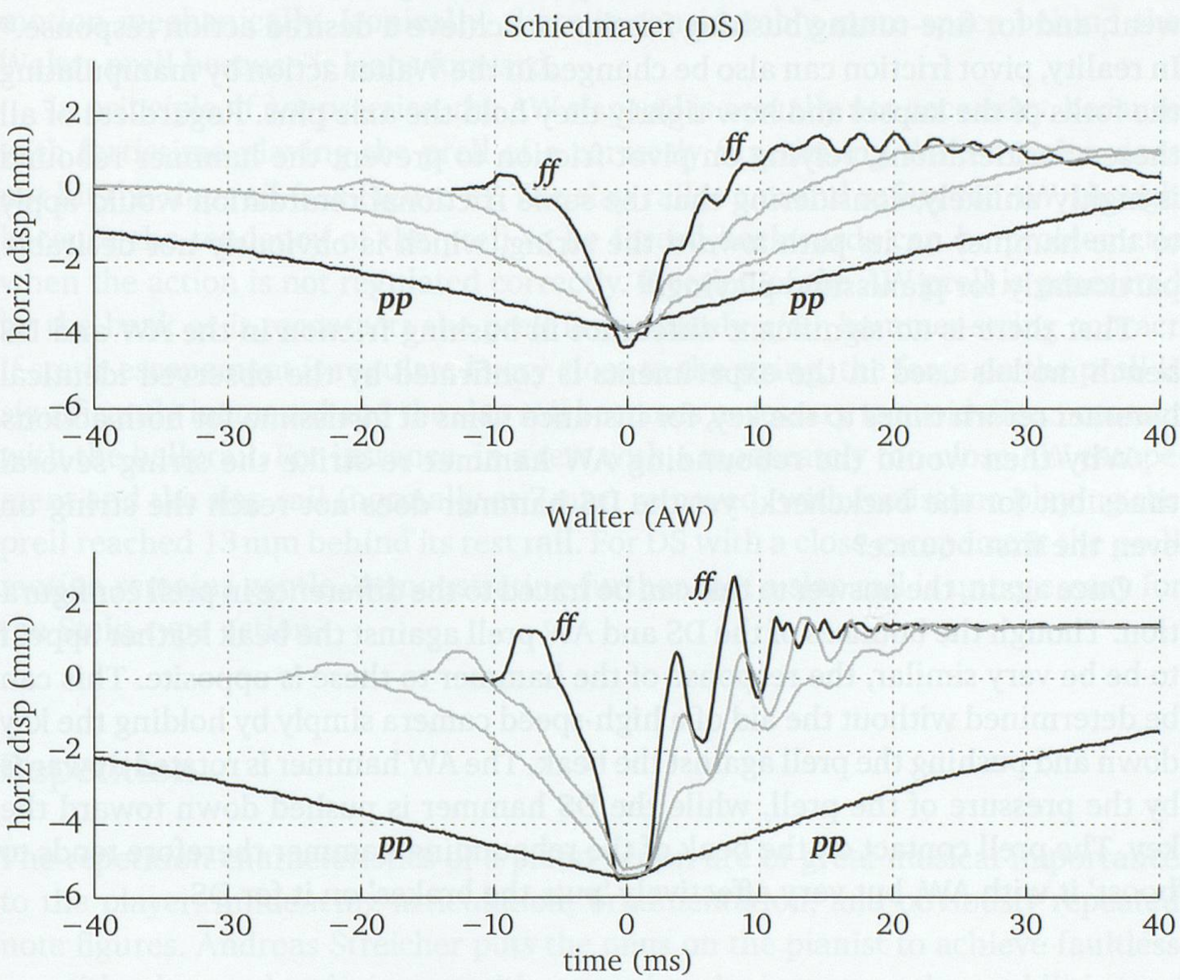
24 H. Welcker von Gontershausen, *Der Flügel oder die Beschaffenheit des Piano's in allen Formen*. Frankfurt, 1856, p. 29. "Durch die Art der Verbindung des Hammers mit dem Tasten, ist derselbe bei dem Aufsteigen auf keinen bestimmten Raum angewiesen, sondern es kann, je nachdem man letzteren bewegt, ein Vor- und Zurückschlagen möglich werden."

25 This shift is comparable with that which can occur even for a modern piano action due to the hammer shank flexing.

to arrest the motion of the hammer by capturing it on a backcheck, the method adopted by many piano builders, including Walter:

> The [Walter] brass *Kapsel* has [···] an almost friction-free bearing, so the hammers fall back from the strings very promptly. They therefore tend to bounce as they land with a thud on the key [···] To remedy this defect, so as to improve the repetition, Walter devised an ingenious check.[26]

Figure 9: Horizontal displacement history of hammer head for DS and AW with four dynamic levels as indicated (pianissimo, fortissimo, and two intermediate). Axes scales are the same for each subplot. Time zero is maximum string excursion during hammer contact.



Neither Stein nor his followers chose to include a backcheck in their actions.[27] The analysis above seems to suggest that Walter's introduction of the hammer pivot consisting of sharpened steel pins rotating in the dimples of a brass kapsel

26 M. Cole, *The Pianoforte in the Classical Era*, p. 223.

27 Individual backchecks are present on a ca. 1795 J.L. Dulcken piano with an otherwise Stein type action. Smithsonian Institution, accession No. 303,537, based on the published drawing by Thomas Wolf et al.

reduced friction sufficiently that the backcheck became necessary to control the rebounding hammer. The implication is that Stein did not need a backcheck because friction in his hammer pivot, consisting of a metal pin rotating in a felt bushing, could be sufficient to brake the rebounding hammer. Latcham[28] explicitly suggests this, and proposes that "the friction of the felt could be adjusted in order to regulate the movement of the hammer". He also notes that the action of one 1783 Stein piano has "two small wedges mounted in the arms of the *Kapsel* which can be pushed in to bear on the axle, thus also retarding the hammer".[29] In fact, an adjustable screw mechanism of this kind is not uncommon, and can be seen in many 19th century pianos, and even some more modern pianos, all of which have backchecks. This practical expedient, also used on keys, simplifies action maintenance, to correct problems arising from changes in ambient conditions or wear, and for fine-tuning bushing friction to achieve a desired action response.[30] In reality, pivot friction can also be changed in the Walter action by manipulating the forks of the kapsel and how tightly they hold the axle pins. Regardless of all these considerations, relying on pivot friction to prevent the hammer rebound is highly unlikely, considering that the same frictional retardation would apply to the hammer on its path *toward* the string, which is obviously not desirable, particularly for pianissimo playing.[31]

That there is no significant difference in bushing friction in the AW and DS bench models used in the experiments is confirmed by the observed identical hammer return times to the key, for instance 13ms at fortissimo for both actions.

Why then would the rebounding AW hammer re-strike the string several times but for the backcheck, yet the DS hammer does not reach the string on even the first bounce?

Once again, the answer to this can be traced to the difference in prell configuration. Though the bounces of the DS and AW prell against the beak leather appear to be be very similar, the response of the hammer to these is opposite. This can be determined without the aid of a high-speed camera simply by holding the key down and pushing the prell against the beak. The AW hammer is rotated upwards by the pressure of the prell, while the DS hammer is pushed down toward the key. The prell contact on the beak of the rebounding hammer therefore tends to 'boost' it with AW, but very effectively 'puts the brakes' on it for DS.

28 M. Latcham, "Mozart and the pianos of Johann Andreas Stein", p. 139.
29 *Ibid.* p. 140.
30 Anne Acker is thanked for her reminder of the importance of friction adjustment in action regulation.
31 In his 1993 paper "The check in some early pianos" Latcham expressed a similar view about bushing friction, proposing instead that the rest cloth is responsible for energy dissipation of the rebounding hammer (p. 34). In his later paper "Mozart and the pianos of Johann Andreas Stein" (1998) Latcham reversed this opinion, proposing that bushing friction could indeed play an important braking role (p. 139–140). As explained in the present paper, the primary braking mechanism in a Stein action is actually derived from the prell-beak contact.

The slap rail

A slap rail behind the prell to constrain and cushion its backwards motion is another innovation attributed to Walter:

> Walter provided a slap rail behind the springs [of the prells] to prevent the possibility of the escapement [prell] being thrown back to any needless distance (which it could otherwise, when played violently). This limitation on the movement again helps with prompt repetition.[32]

Stein and his followers did not use a slap rail, and despite the close proximity of the bellyrail to the back of the prell (about 4 mm), contact between these is avoided by the functional design of Stein's action which constrains the prell motion mechanically. Ironically, there is considerably more space behind the Walter prell because it leans forward.

In principle, if not practice, the AW slap rail is actually not necessary, because with fortissimo playing the prell of a correctly functioning Walter action does not hit the slap rail (see Figure 8). The slap rail is a useful safety for AW, though, because the tendency of the prell to be forced backwards can be problematic when the action is not regulated correctly. Ejection of the AW prell is generated by the beak as it recontacts the prell immediately *after* hammer-string contact. If static escapement is regulated very close to the string, the force on the prell is significantly increased and the slap rail becomes necessary to avoid direct contact with the bellyrail. For instance, in a test with a moderately too-close AW escapement and the slap rail (normally at 7 mm) removed, with fortissimo playing the prell reached 13 mm behind its rest rail. For DS with a close escapement the prell motion remains gentle, demonstrating further that a slap rail is unnecessary for the Stein-type action.

Repetition

The repetition characteristics of a piano action are of great musical importance to the player, influencing articulation, ornamentation, and obviously repeated note figures. Andreas Streicher puts the onus on the pianist to achieve faultless repetition by good technique, tacitly assuming the instrument's capabilities are no limitation:

> In the fastest tempo, he strikes the same chord *often*, and in *quick* repetition, without ever dropping a note. One thinks one hears the same notes sustained continuously and at the same volume. This is easy for him since his hand is in the quietest position. It is true that his fingers always remain on the keys; but they are raised high enough

32 M. Cole, *The Pianoforte in the Classical Era*, p. 223.

to allow the keys to return to rest, so that at every fresh stoke the hammer-beak can engage the *Tangente* [i. e. prell].[33]

To put this into context with two examples: the repeated triplets in Schubert's *Erlkönig* (composed 1815), taken at the publisher's (Diabelli, 1821) mm = 152 (quarter notes) require about 7.6 notes per second; early editions (1830s) of Beethoven's sonata Op. 57 (composed 1804) have the first movement dotted quarter notes indicated in the range mm = 120–138,[34] equivalent to 6–7 notes per second. Acciacciatura and other rapid articulative figures and ornamentations are common, and could involve even faster repetition of single pairs. Thus, an estimate of 8 notes per second, or 125ms per repeated note, is not an unrealistic demand for the instrument.[35]

Repetition of AW and DS was tested by playing a rapid four-note pattern with alternate fingers on the same key and leading to a held final note. As can be seen in the hammer and key position histories of Figure 10, DS is very regular in the note timings (117, 134, 123, 131ms), while AW is somewhat irregular (154, 126, 140, 166ms). It is also evident that the key reaches the stop rail very soon after the hammer-string contact for DS, but later in AW, not until the hammer is already down at the key level.

For a successful repeated note to be possible the hammer must be in a position which allows the beak to catch the prell hook; this is dictated by both the rotation of the hammer and the fall of the rear of the key. The key must be close to its rest position or the hammer can never be high enough to reset the beak. For DS, key position is a limitation until about the same time as the peak of the first hammer bounce, which is consistently 75ms after the string contact (see Figure 10 and also Figure 8). This is the earliest time that beak reset can occur to initiate a re-strike. The prell is also ready for the reset at this time, because its bounces on the back of the beak leather have been damped (see Figure 7). In the test the 125ms repeat was achieved with the re-strike beginning 30–40ms later than it could have been initiated; the key had just returned to its rest position and the hammer was already falling back towards the key. This suggests that the DS action is actually capable of a faster repetition, up to 10 notes per second, by playing the keys so the fronts do not fully return to rest position.

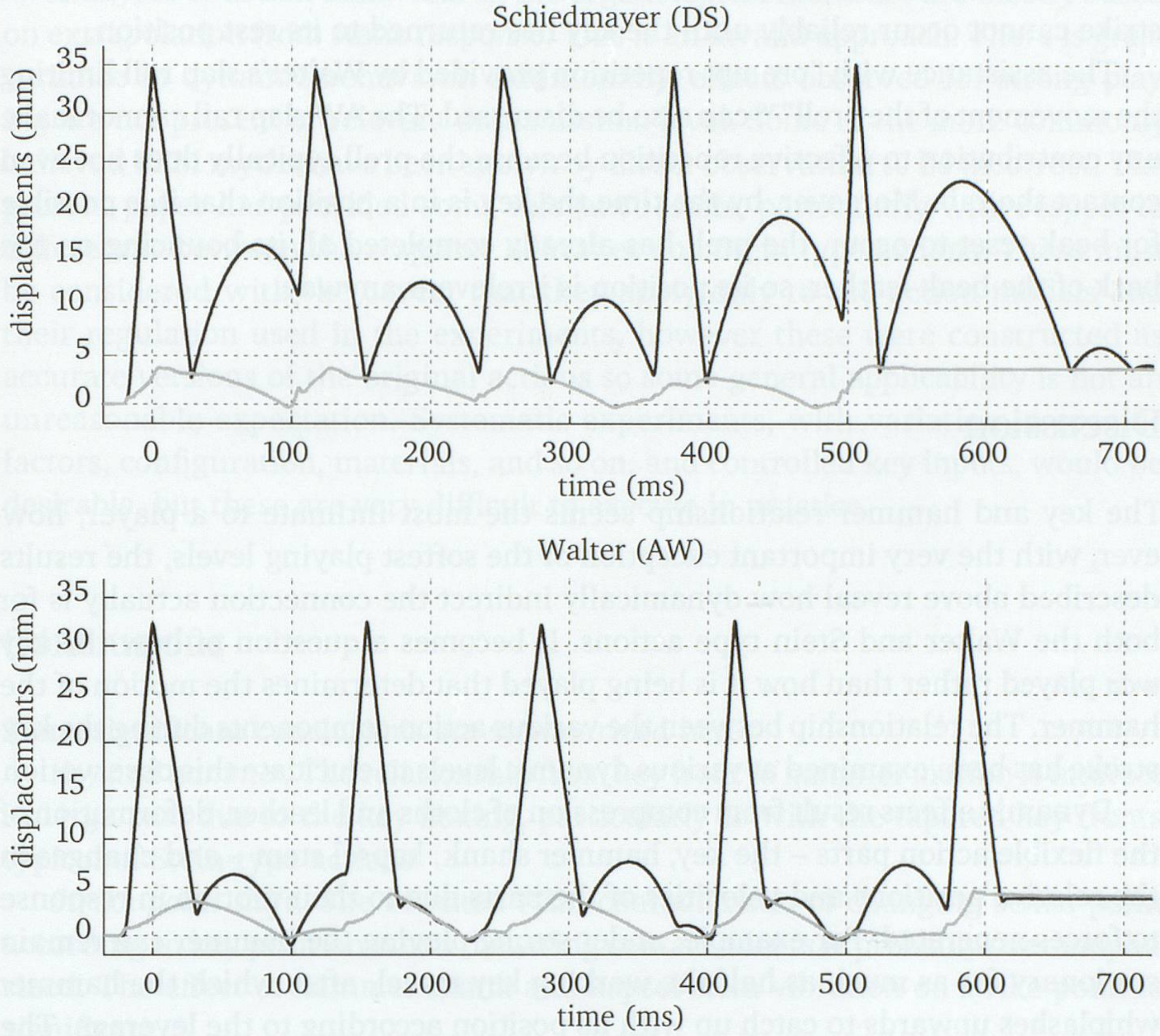
The AW repetition function is similar to DS in principle. Interference from the check constrains the hammer rebound, but also introduces an undesirable unpredictability to the repetition state. In the test the hammer was caught on the backcheck after the second note, partially caught after the fourth, and only scuffs it after the other two notes. This contact, and the associated partial blocking of

33 Transl. P. de Silva, *The Fortepiano Writings of Streicher, Dieudonné, and the Schiedmayers*, p. 61. Italics are Streicher's.

34 S. Rosenblum, *Performance Practices in Classic Piano Music*. Bloomington IN: Indiana University Press, 1988, Chapter 9.

35 The metronome tempi provided are 19th century indications, so relevant to the later Viennese style PZM with backcheck that emerged from Walter's design.

Figure 10: Vertical displacements of hammer tip (black) and key rear segment (grey) for DS and AW with repeated note figure played forte (4 note pattern leading to held final note).



the hammer, cause drag on the key response while it is being depressed. The backcheck is therefore responsible for the irregularity of the note timing, and, in a less well-regulated action can also cause missed repeated notes. This does not happen in an action of the Stein type with no backcheck to interfere.

These observations show that Walter's "ingenious check" certainly does nothing to "improve the repetition".[36] Its presence is, in fact, detrimental to repetition, although it is essential in a Walter-type action to have the backcheck to control the hammer bounce on the key if repetition is to be possible at all.

Latcham characterizes the unconstrained hammer in a Stein-type action as somehow problematic for the player with repeated notes.[37] In fact, this behaviour is the reason the action works so well with repeated notes. The gently hovering

36 As proposed in M. Cole, *The Pianoforte in the Classical Era*, p. 223.
37 M. Latcham, "The check in some early pianos", p. 30.

Stein hammer provides a predictable and reliable window of opportunity, ready for the next key strike, even before the key has returned fully to rest position if desired. This can be contrasted with AW, for which the hammer is kept closer to the key due to the interaction with the backcheck, with the result that the next strike cannot occur reliably until the key has returned to its rest position.

The assistance with "prompt repetition provided by Walter's slap rail limiting the movement of the prell"[38] can also be dismissed. The AW slap rail cannot make any contribution to effective repetition because the prell typically does not even contact the rail. Moreover, by the time the key is in a position that it is possible for beak reset to occur, the prell has already completed all its bouncing on the back of the beak leather, so its position is irrelevant anyway.

Discussion

The key and hammer relationship seems the most intimate to a player, however, with the very important exception of the softest playing levels, the results described above reveal how dynamically indirect the connection actually is for both the Walter and Stein type actions. It becomes a question of how the key *was* played rather than how it is being played that determines the motion of the hammer. The relationship between the various action components during the keystroke has been examined at various dynamic levels to elucidate this observation.

Dynamic effects result from compression of cloths and leather, deformation of the flexible action parts – the key, hammer shank, kapsel stem – and changes in the relative positions and velocities of the parts due to their motion in response to forces generated. For example, under strong playing the hammer can remain stationary for as much as half the working key travel, after which the hammer whiplashes upwards to catch up with its position according to the leverage. The key was shown to flex quite significantly, and more so the tapered Stein-type key. The comparatively stiffer Walter key is probably an important contributing factor previously overlooked in explaining von Schönfeld's directing those who want a 'feast for the ear' to the Walter piano. Stein's use of a flexible tapered key is entirely consistent with an expectation that the player will exercise restraint, because excessively strong playing produces diminishing returns at the business end of the key.

Mechanical function also puts demands on material properties. For example, the Walter beak leather must be solid enough not to shear, as well as have a surface that can generate the necessary friction with the beak, both of which are essential to avoid a misfire of the prell; in the Stein the back edge of the beak leather must be supple enough to properly damp the prell bounces, yet the leather must have sufficient body to allow the beak to release the prell. Appropriate materials

38 Paraphrased from M. Cole, *The Pianoforte in the Classical Era*, p. 223.

to meet these requirements are best determined empirically, and generally they are severely compromised or absent altogether on extant instruments, so investigation is difficult.

Analyses of action behaviour in the organological literature are mostly based on extrapolation from static response. This is an invalid approach. There is great variance in dynamic behaviour. Additionally, effects observed for strong playing are not present or relevant at pianissimo level. Some of the more commonly believed PZM myths have been shown by direct observation to be incorrect. The present paper has provided some relevant results, particularly with respect to differences between the response of Walter and Stein type actions. These must be considered with the caveat that they apply only to the action models and their regulation used in the experiments, however these were constructed as accurate versions of the original actions so some general applicability is not an unreasonable expectation. Systematic experiments, with variation in specific factors, configuration, materials, and so on, and controlled key inputs, would be desirable, but these are very difficult to execute in practice.

Conclusions

Some significant conclusions are summarized here.

Key and hammer. The relationship from key front to hammer motion is indirect, in large part due to the key flexing, particularly so with the tapered key fronts typical of Stein-type actions.

Strike point shift. The oft-cited PZM characteristic of changing strike point according to key position when the string contact occurs is probably over-emphasized. The effect of hammer shank and kapsel stem vibration on strike point is significant.

The Stein prell. The configuration of the Stein prell locks it on the beak throughout the key stroke, as well as constraining the extent of prell motion after string contact, and providing a braking effect on the rebounding hammer via contact on the back of the beak leather which acts to push the hammer back down toward the key.

The Walter prell. The configuration of the Walter prell creates a tendency for it to slip backwards off the beak unless held securely by friction. Immediately after the end of hammer-string contact the prell is ejected backwards by the beak. Contacts with the back of the beak boost the rebounding hammer upwards.

Slap rail. The importance of the slap rail is over-rated. Forced ejection of the AW prell on escapement creates the potential for excessive backwards motion, but only if the action is regulated with static escapement too close to the string. There are no circumstances that require the slap rail in a Stein-type action.

Controlling the hammer rebound. After string contact, the only mechanism for meaningful hammer energy dissipation is derived from contact between beak and prell, and this is only useful in the Stein-type action. Neither the hammer rest cloth nor the hammer pivot friction can provide any useful damping of the hammer motion to control the rebound.

The backcheck. A backcheck is essential for the Walter-type action to constrain the hammer after string contact. Its position must be carefully chosen if it is to function properly at all dynamic levels, and avoid contact with the hammer on its path toward the string. This requires a more generous aftertouch than that acceptable in a checkless action.

Repetition and the prell. Successful repetition is not governed by prell behaviour for a properly functioning action of either type, because the prell is effectively at rest in the required place well before the key and hammer are capable of executing a re-strike.

Repetition and the key. Key return is the limiting factor for repetition because, regardless of hammer position, the beak cannot reset until the key is fairly close to its rest position.

Repetition and the backcheck. The Walter backcheck is a necessary evil in terms of repetition. It is essential to control the hammer rebound, but its presence interferes with reliable execution of the repeated key strike, causing irregular timing and possibly missed notes. The hammer is also kept close to the key, so the key must be at its rest position before the beak can reset for a re-strike.

Repetition in the checkless action. The Stein hammer hovers above the key after rebounding from it. The beak can reset, and a re-strike begin, well before the key has reached its rest position. This increases the reliability and potential speed of repetition compared to an action with backcheck. In effect the Stein action behaves like an Erard action with an imaginary repetition lever.

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Summary

The behaviour of the *Prellzungenmechanik* (PZM) is investigated experimentally using highspeed imaging and specially constructed benchtop models. Two 18th century versions of this fortepiano action, the Stein- and Walter-types, co-existed until about 1805, and were associated with different styles of playing. These two actions are compared by direct observation of their dynamic response, that which is relevant to all but the softest of playing. The effect of deformation of flexible components and compression of felts, cloths, and leather at the contacts, makes response very different from what is usually predicted by considering what happens with a slow key motion. With stronger playing the relationship between key and hammer becomes quite indirect, particularly so with the significant bending of the thin front-tapered keys used in the Stein version. The configuration of the Stein prell constrains the extent of its backward motion after the hammer-string contact, and is also responsible for the primary braking mechanism that controls the rebounding hammer; the different configuration of the Walter prell makes it essential to capture the hammer on a backcheck to prevent it bouncing up and re-striking the string. Repetition efficiency and reliability are examined quantitatively for both action types. Some well-established assumptions about PZM function are shown to be incorrect using the observations presented here.

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