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Piano

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On the basis of research on the physics and physiology of the keystroke, the acoustics and perception of piano timbre, and the psychology of piano fingering, we explain observations such as the following, and investigate their practical implications. The timbre of an isolated tone cannot be varied independently of its loudness but depends on finger-key, key-keybed, hammer-key noise, and on the use of both pedals. The timbre of a chord further depends on the balance and onset timing of its tones, whereby louder tones tend to sound earlier (melody lead, velocity artifact). Both the sustaining pedal and *una corda* can enhance *sostenuto*. Leap trajectories are curved and asymmetrical. Optimal fingering is determined by physical, anatomic, motor, and cognitive constraints interacting with interpretive considerations, and depends on expertise.

Scientific thinking, methods, and results have influenced piano performance and piano teaching for well over a century, and innumerable piano-pedagogical publications have claimed scientific validity. On the one hand, artistic writers—often great pianists and piano teachers—have tended to fashion complex pseudo-scientific theories post hoc to match their beliefs, so that such theories can be controversial and unreliable. On the other hand, scientific writers tend to focus on simple hypotheses and assumptions that are easy to demonstrate and explain but are of limited interest to musicians. It is little wonder, therefore, that modern piano students are often unaware of the basic findings (Parncutt & Holming, 2000).

Ortmann (1929/1981) successfully challenged influential but unfounded assumptions on touch and relaxation. Like him, we begin with observations that are easy to demonstrate scientifically and move gradually toward more complex ideas that are more likely to be of interest to modern pianists and piano teachers. We attempt a fresh approach by combining old and new acoustical

and psychological thinking and drawing upon our own performing and teaching experience.

Physics and Physiology of the Keystroke

Curved Versus Straight Fingers

The motor independence required to perform the complex sequences of finger movements that are typical of piano performance can only be acquired over many years of concentrated practice. Pianists must control not only the order and precise timing of keystrokes but also their force and the resultant key velocity (Parlitz, Peschel, & Altenmüller, 1998).

The force required to depress a key in the middle register varies by a factor of 100: to hold down the key requires about 0.5 newton (equivalent to 50 grams), and to play *fortissimo* requires about 50 newtons (5 kilograms) (Askenfelt & Jansson, 1991). One way to accommodate this wide range is to vary the curvature of the fingers (Ortmann, 1925).

Loud, scalelike passages are often better played with curved fingers. First, this allows force to be applied vertically and so most efficiently (Ortmann, 1929/1981; Gát, 1965). Second, this reduces the distance between the fingertip and the knuckle, increasing the available force at the fingertip for a given muscle force (lever principle).

Straight fingers are often preferred in softer, slower, single-line melodies, where the fleshy pads of flatter fingers allow a bigger skin area to touch the surface of the key, appropriate for *cantabile*. Extended fingers can also move through a larger horizontal arc than curved fingers and are appropriate when big stretches are required at a low to moderate dynamic level.

Fingers or Arms?

As a rule, *all* moving joints in the arms and fingers are involved to some extent in *all* piano playing; to try to prevent one joint from moving would cause unnecessary tension. Beyond that, basic physics predicts that small, lightweight limbs (e.g., the fingers) are suited for fast and/or quiet playing, while larger, heavier limbs (the upper and lower arm) are best for slow, loud playing (Ortmann, 1929/1981). According to this principle, movements of the hand (from the wrist) and forearm (from the elbow) are suitable for intermediate tempi and dynamic levels and for combinations like fast and loud (e.g., Liszt's Hungarian Rhapsody No. 6, with its right-hand presto octaves and left-hand chord leaps, all marked *sempre forte*). Similarly, scales in fast, lightweight octaves are best played from the wrist, moderately fast and loud octaves from the elbow, and loud, *bravura* octaves from the shoulder (cf. Gát, 1965), examples of all of which are also to be found in Liszt's Hungarian Rhapsody No. 6.

The underlying physical principle is Newton's second law of motion—force equals mass times acceleration (cf. Schultz, 1949)—which states that greater

masses require more force to accelerate them and exert more force when they decelerate (inertia). Thus the fingers can move back and forth more quickly, but the arms can exert more force.

This principle is mirrored in the historical evolution of keyboard technique (Gerig, 1974; Kochevitsky, 1967). In keyboard music of the eighteenth century, the fingertips did most of the work and the arms were held to the sides. In the nineteenth century, a heavier keyboard action, larger concert halls and orchestras, the new mass public, the emergence of the solo recital, and more elaborate writing for the keyboard made wrists and forearms more important (Kalkbrenner, Leschetizky). This led to Deppe's (1885) and Breithaupt's (1905) concept of arm weight and Matthey's (1903) emphasis on relaxation. Their basic idea was to relax the arm in free fall, then introduce minimal muscle tension to control the movement.

A similar pathway is still traveled by most pianists during their development from beginners to professionals. But advanced technical concepts such as arm weight can also be introduced quite early. For example, György Kurtág's *Jatekók*, a collection of children's pieces elaborated into a system of piano tuition by Kase (2001), introduces larger scale bodily movements from the start, delaying focused finger movements until later.

Leap Trajectories

Performers of pieces like Brahms's *Paganini Variations* and Second Piano Concerto are constantly confronted with high-speed leaps across the keyboard. Ortmann (1929/1981) observed that the optimal trajectory for a leap is not only *curved* but also *skewed* (asymmetrical): it departs close to horizontal and lands somewhere between horizontal and vertical. This minimizes the chance of missing the target and allows the force on the target key to be applied almost vertically.

During a leap, the hand and arm must accelerate from stationary to a maximum velocity and decelerate again before reaching the target. Since acceleration is a vector (with both magnitude and direction), leap trajectories cannot include sharp corners, which would require short bursts of high acceleration (Ortmann, 1929/1981). For similar reasons, it is widely held that rounded or curved movements are preferable in all areas of piano technique: "The shortest distance between two points is not a straight line but a curve" (Neuhaus, 1973).

In general, the likelihood of missing a target increases as the trajectory becomes longer, the time available becomes shorter, and the target becomes smaller (Fitts, 1954; Huron, 2001). For the piano, the margin of error at the target is the width of the key as seen from the approaching finger—greatest if the approach is vertical (from the air) and zero if horizontal (along the keyboard). When approached from the left or bass, the widest black-key targets are the tones C♯ and F♯; from the right or treble, B♭ and E♭. The optimal trajectory toward these keys is therefore flatter, and they can be reached more accurately. According to this logic, the falling leap at the start of Beethoven's Opus 111 (E♭ down to F♯ in left-hand octaves) may be more difficult than a slightly longer leap to a bigger target (e.g., D♭ to E♭).

While performing, pianists tend to be unaware of leap trajectories. The process seems highly automatic and intuitive, with the attention focusing aurally and visually on the target, not the trajectory, and relying on a combined tactile-auditory-visual memory of the keyboard. If unnecessary tension is avoided, an appropriately curved and skewed trajectory results automatically. The kinesthetic sense of joint, tendon, and muscle movements during the trajectory can be developed either by practicing leaps out of context without depressing the target tone (just preparing it) or by practicing leaps in the dark (without visual feedback). It is difficult to practice leaps at a slow tempo, just as high jumpers cannot practice in slow motion.

Tone Repetitions

High-speed repetitions are usually easier to perform by changing (alternating) fingers, because it is easier to move one finger horizontally off the key and drop another finger onto it, than to quickly move the same finger up and down. The latter requires more finger acceleration, which in turn requires more muscle force. Slow tone repetitions are often best performed *without* changing fingers, because at slower tempi the listener is more sensitive to the unevenness (variation in loudness) that can result from the differing strengths of the fingers. Moreover, at slow tempi there is less finger-key noise. Conversely, changing fingers can be useful if accentuation (i.e., *deliberate* unevenness) is required.

Fast repetitions were enabled by Sébastien Érard's *repeating action* of 1823 (Frey, 1933). The *let-off distance* (Askenfelt & Jansson, 1990) is the distance between the string and the top of the hammer after a key is slowly and silently depressed. Typically some one to three millimeters, it is also the distance traveled by the hammer in free flight after the jack is pushed away by the escapement dolly. The roughly corresponding *let-off point* of a piano key is found by slowly pressing the key until resistance is felt (as the jack escapes).

Depending on tempo and dynamics, fast repetitions may be best played *under the surface*, that is, by depressing the key to the keybed, lifting to the let-off point, and depressing again. The minimum time between repetitions is the time taken for the jack to return to its original position. A short setting of the let-off distance facilitates fast, quiet repetitions, as for example in the left-hand opening (*pp, très fondu, en tremolo*) of *Scarbo* from Ravel's *Gaspard de la nuit*. Playing from the let-off point also prevents the damper from reaching the string between keystrokes, so that a continuous sound can be obtained without pedaling.

Acoustics and Perception of Piano Timbre

Relationship Between Timbre and Loudness

We use the words *timbre* and *loudness* in the widely accepted psychoacoustical sense of how a sound is perceived or experienced by a listener (H. Fletcher, 1934). In general, the timbre of a sound—its perceived tone quality or color—depends

on at least two physical variables: its *spectral envelope* (relative amplitude of spectral partials at a given moment) and its *temporal envelope* (which rises suddenly as the hammer hits the string and then decays gradually). The critical importance of temporal envelope for piano timbre becomes clear when a piano tone is recorded and played backward. If the amplitude gradually increases instead of decreasing, with the hammer noise at the end instead of the beginning, the result sounds strangely like an organ (Houtsma, Rossing, & Wagenaars, 1987).

The experience of loudness may be distinguished from the physical measurement of *SPL*, measured in decibels, and from *dynamic level*, which is an instruction, recommendation, or suggestion from a composer to a musician. For practical purposes, loudness, *SPL*, and dynamic level are often the same, but they do diverge in everyday musical situations. Consider for example a thick bass chord marked *ppp*. The physics of the piano do not allow such a chord to be played with a very low *SPL* (as measured with an *SPL* meter). But a pianist playing as softly as the piano allows can manipulate other contextual variables such as timbre (pedaling, relative key velocity) and timing (tempo, delay) to enhance the impression of *ppp*.

Against the backdrop of these definitions, we may assert that the spectral and temporal envelope of an isolated piano tone cannot be changed independently of its *SPL*; hence, timbre cannot be changed independently of loudness (Baron & Hollo, 1935; Gát, 1965; Gerig, 1974; Hart, Fuller, & Lusby, 1934; Ortmann, 1937; Seashore, 1937). In a simple physical model of the piano action (Fletcher & Rossing, 1998, Figure 12.1), both the *SPL* and the spectral and temporal envelopes of a piano tone are determined uniquely by *hammer velocity*—the speed with which the hammer hits the string, which is determined in turn by key velocity (cf. Palmer and Brown, 1991). The crucial point is that the hammer hits the string in *free flight*: at (and just before) impact, there is no physical contact between the key and the hammer. Thus—apart from some interesting possibilities described later—the pianist cannot influence *how* the hammer hits the string, only the *speed* with which it does so.

Acousticians and psychologists have often wondered why, in spite of this evidence, so many pianists still believe that the timbre of a piano tone depends on *touch*—not only how fast but also *how* the key is depressed. A possible reason is that movements of a pianist's body and arms (smooth and round versus jagged and tense) seem to both performers and audiences to result in different timbres. We cannot necessarily rely on this impression for the following reasons:

- Pianists almost never perform isolated tones without pedal, and the timbre of more complex textures clearly depends on a range of factors other than the way each individual key is depressed (see later).
- Movements that directly affect *control* may indirectly affect timbre. Consider the difference between *percussive* (or *staccato*) *touch* (when keys are hit from a distance above the surface) and *nonpercussive* or *legato touch* (when the key is depressed from the surface). Ortmann (1925) found that nonpercussive touch permits finer key control.
- Listeners can easily perceive timbral differences between piano performances but are not necessarily able to explain the origin of those differences (Heinlein, 1929b).

- Listeners cannot necessarily separate timbre from other perceptual variables. Timbre is often confused with pitch in ratings of performed intonation (chapter 12) and in other psychoacoustic experiments (Singh & Hirsh, 1992). Listeners regularly use the interdependence of timbre and loudness to deduce dynamic level in situations where sound intensity cues are lacking or unreliable, such as recordings. In most instruments (including the voice), louder tones have more jagged waveforms and hence relatively more high-frequency energy. In the piano, a sharper hammer blow produces sharper waveform peaks (Hall, 1991). The strongest perceptual cue to the original dynamic level of a piano recording is its timbre—regardless of how loudly the recording is played back.
- In general, auditory perception is influenced by visual perception (intermodal interference). Visual processing can affect the appraisal of piano performances (Behne, 1990; Shimosako & Oghushi, 1996), and an important part of the emotional and interpretive message sent from a performer to an audience is visual (chapter 15 in this volume; Rosen, 1995). For example, if an audience sees a pianist brutally hitting the keys, they may get an impression of a hard or brittle tone—beyond what the music actually sounds like.
- Pianists' perceptions of their own performances are multimodal (Galembo, Askenfelt, & Cuddy, 1998): the pianist's perception of timbre can be influenced by kinesthetic feedback from finger contact with the keys.

Askenfelt and Jansson (1991) suggested the possibility that *hammer-shank vibrations* at around 50 Hz might be greater in percussive touch and could theoretically affect piano string vibration—either by changing the angle of impact and thus shifting the striking point (only significant in the extreme treble: Galembo et al., 1998) or by allowing the hammer to rub along the string during contact. But Hart, Fuller, and Lusby (1934) and others (see Galembo et al., 1988) had already concluded that the influence of the hammer shank on the physical string motion is negligible, and when the matter was tested empirically Askenfelt and Jansson (1991) were unable to observe any rubbing motion between hammer and string. Even if effects of this kind are possible, the pianist can hardly manipulate them independently of finger-key noise (see later), so they cannot contribute *independently* to piano timbre.

Tone quality in piano performance is determined not only by the physics of individual keystrokes but also involves a complex and largely intuitive interaction among body movements, technical finesse, and musical interpretation (Kochevitsky, 1967). For example, it is possible that the exact timing of a *rubato* melodic phrase affects the global perception of timbre. The ability to produce a variety of timbres and to apply them appropriately to the interpretation of repertoires can only develop gradually over years of concentrated practice and careful listening.

Timbre of a Chord

The timbre of a piano chord depends on the timing and relative loudness of the tones (Baron & Hollo, 1935), because these affect both the temporal and the spec-

tral envelope. The attack portion of the temporal envelope can be manipulated by adjusting the timing of the tone onsets. An extreme case is an arpeggiated chord, whose timbre depends on the speed and direction of the arpeggiation—an expressive strategy employed by both performers (e.g., Glenn Gould's interpretations of Bach) and composers (e.g., Boulez's *Sonate No. 3, Constellations*). The spectral envelope can be manipulated by playing some tones louder and some softer. If the louder tone takes on a singing quality, it is either because its pitch becomes more *salient* (clear, prominent, audible, able to attract attention: Terhardt, Stoll, & Seewann, 1982) and/or because the timbre of the whole sonority becomes less rough (the roughness of a beating pair of pure tones falls rapidly as the difference between their amplitudes increases; cf. Terhardt, 1974). The technique of bringing out a tone is addressed later under "Melody Lead and the Velocity Artifact."

Sources of Percussive Noise

Percussive onset noise is as characteristic and integral to piano timbre as is the scraping of the bow of a stringed instrument or the breath activation of a wind instrument. This is clearly demonstrated when onset noise is electronically excluded from the tone, creating a drastic change in timbre. Normally, we hear holistically—we do not, and perhaps cannot, hear the onset noise separately. If the amount of noise increases, we hear the sound as increasingly harsh, dry, ugly, or forced and may be unaware of the physical source of the timbral change.

The three main sources of noise in piano timbre are *finger-key*, *key-keybed*, and *hammer-string*. Finger-key noise can be varied independently of string amplitude, but the biggest contributor to the noisy onset, hammer-string noise, cannot (Baron, 1958; Baron & Hollo, 1935; Hill, 1940), and, for practical purposes, neither can key-keybed noise.

Hammer-String Noise. The physical intensity of the hammer blow depends directly on its velocity, being most intense in *fortissimo*. For this reason, *cantabile* can sometimes be enhanced by limiting loudness. Perceptually, the situation is more complex, because the tone's partials mask the onset noise, so louder tones do not always *seem* more percussive. If higher tones seem more percussive than lower tones, it is because their noise component is more intense by comparison to the partials—not because the noise is more intense in an absolute sense.

Finger-Key Noise. This can contribute to the percussiveness of piano sound (appropriate, e.g., in many of Bartók's *Mikrokosmos*). It can also enhance an impression of *staccato* (Gát, 1965). Its audibility can be demonstrated by holding down a cluster of keys with one hand hitting them with the fingertips of the other hand. In practice, finger-key noise is not completely independent of hammer-string noise, because pianists tend to play louder when using percussive touch (Ortmann, 1925).

The impact between finger and key causes a sudden high acceleration and associated shock excitation (or thump) dominated by two flexing resonances of

the key at about 290 and 445 Hz (Steinway); this is transmitted through various structural parts of the piano to the soundboard (Askenfelt & Jansson, 1990, 1991). It is called *touch precursor* because it precedes the hammer blow by about twenty to forty milliseconds, depending on dynamic level (Askenfelt, 1993). Like early reflections in a concert hall (Hall, 1991; chapter 17 in this volume), the touch precursor can contribute to timbre but cannot be heard separately.

In a musical context, the tonal part of the piano sound may partially or completely mask finger-key noise, depending on dynamic level, texture, register, room acoustics, and position of the listener. Finger-key noise is more audible in higher registers, because it is less masked by the tone.

Finger-key noise may seem important to the performer but be irrelevant to the listener. Preliminary experiments suggest that listeners can discriminate percussive from nonpercussive touch, but only within some twenty centimeters of the string (Galemba et al., 1998; Koornhof & van der Walt, 1993). Pianists' perceptions of their own finger-key noise may also be influenced by the kinesthetic sensation of the finger hitting the key.

Key-Keybed Noise. This may be separately heard by holding the hammer against the string while pressing the key. In a musical context, key-keybed noise occurs almost simultaneously with hammer-string noise and so blends easily with it. Its low frequency gives it a deep timbre.

Theoretically, pianists can indirectly control key-keybed noise (Askenfelt & Jansson, 1991, Figures 4 and 5). In nonpercussive touch, the key velocity increases steadily during the key depression, reaching a maximum at the keybed. In percussive touch, the key velocity first increases, then decreases (as the energy is transferred to potential energy in parts of the action and kinetic energy in vibrations of the hammer shank), then increases again. So for a given dynamic level, key-keybed noise is greater in percussive than nonpercussive touch. In practice, due to limitations of sensory feedback to motor control, it is virtually impossible to vary key-keybed noise independently of the percussiveness of touch and dynamic level.

Cantabile and the Pedals

Cantabile means “singable” or “songlike.” The sustaining pedal enhances the singing quality of a piano melody by improving the legato and enriching the timbre. The *una corda* pedal can also enhance *cantabile*, by increasing the effective tone duration.

The Sustaining Pedal

Banowetz (1985) regarded the sustaining pedal as “equivalent to the vibrato of the singer or the string player” (p. 13). Pianists do not simply depress and release the pedal but take advantage of a quasi-continuous series of intermediate positions that allow for more or fewer dampers to clear the strings in different

registers—part-pedaling (half, quarter, three-quarter, etc.), pedal squeezing, and flutter (or vibrating) pedal (K. U. Schnabel, 1950). The effectiveness of these techniques depends on a variety of physical factors (the instrument's make; wear and tear of the hammer heads; pre- and postrelease duration of tones in a given register; room acoustics), technical considerations (how many fingers are held down at a given instant), and interpretation (phrasing, tempo, dynamic and timbral shading, tonal relationships) and is controlled by highly intuitive auditory reflexes and responses (Heinlein, 1930; Repp, 1999)—which may explain the considerable differences in pedal usage observed even among expert pianists (Heinlein, 1929a).

Walter Gieseking considered that “just as one learns correct finger technique from the head and not the fingers, so one learns correct pedaling from the dictates of the ear and not the foot” (Banowetz, 1985, p. 231). The independent manipulation of pedal and fingers, as well as the ability to adjust to a variety of instruments and acoustic conditions, is one of the most difficult and important pianistic techniques to learn. This complexity makes pedaling hard to investigate scientifically.

Decay Time and Melody

Is the piano a suitable instrument for the performance of melody? Two of the perceptual factors that encourage a sense of melody (across cultures) are *sustain* (slow decay) and *pitch salience* (Huron, 2001). The piano best satisfies both conditions in the middle registers: high tones decay quickly, and both very high and very low tones have low pitch salience (cf. Terhardt et al., 1982).

By convention, the decay time of a sound is the time taken for its SPL to fall by 60 dB. This corresponds roughly to its perceived or effective duration. The decay of a piano tone before the finger is lifted is called *prerelease decay*, and varies from some 15 seconds in the deep bass to 0.5 second in the highest register (Hall, 1991; Repp, 1997; Martin, 1947). *Postrelease* decay times are roughly half a second in both treble and bass (Repp 1997, Figure 4), but they vary unpredictably from tone to tone, depending on the state of the dampers and their pressure on the string. The timbral effect of damping the string is more audible in the lower registers where the strings are heavier.

A sense of melody may be created in high registers by use of the sustaining pedal and by *legatissimo*, the overlapping of successive keystrokes (Repp, 1997). *Legatissimo* can be acoustically effective in all but the extreme high register where there are no dampers. Finger legato is important not only where the pedal is being changed frequently but also where part- or flutter pedaling is being used, which tends to damp the upper strings more than the lower.

Another way to create an impression of melody is suggested by Bregman's (1990) theory of *auditory streaming*. Successive tones are more likely to hang together as melody if they are close in pitch and time and similar in loudness and timbre. Thus a pianist can optimize *cantabile* by holding key velocity relatively constant, compensating for the piano's acoustic discontinuity in the higher registers. If a passage calls for metrical or structural accentuation (chapter 13),

other means may be used, such as agogic accents in the melody or dynamic accents in the accompaniment.

The Sustaining Effect of Una Corda

Casella (1936) considered that the *una corda* (soft) pedal “allows the executant to interpret a *cantabile* melody with greater depth of touch while never overstepping the mark” (our translation). Rubinstein (1980) remarked that he often produced his best *cantabile* by playing the melody *ff* with soft pedal.

The underlying physics was explained by Weinreich (1977; see also Hall, 1991; Fletcher & Rossing, 1998). The *una corda* pedal reduces the decay rate of the tone and so increases the effective duration. On a grand piano, the pedal shifts the mechanism sideways so that the hammer strikes only two (not one, as the Italian name suggests) of three unison strings. This reduces loudness, mellows the timbre, and modifies the hammer-string noise, because a different part of the hammer—the ridges between the grooves formed during normal playing—strikes the strings.

When the *una corda* pedal is *not* depressed, the three unison strings initially vibrate in phase, allowing them to transmit energy efficiently to the bridge and causing the sound level to fall rapidly. But the strings are never tuned to exactly the same frequency—and good tuners sometimes deliberately slightly mistune unison strings, for timbral reasons (Wead, 1921; Weinreich, 1977). So they soon get out of phase with one another, reducing the efficiency of sound transmission to the bridge. Once the phase relationship between the strings is effectively random, a second, slower decay phase—the *aftersound*—begins. With the *una corda* pedal depressed, one string begins almost at rest. Over the next few seconds, energy is transferred from the struck to the unstruck strings via the bridge. The overall decay rate is slower, because the struck and unstruck strings are out of phase from the start; the aftersound begins sooner and lasts longer (Hall, 1991, Figure 10.9).

We recommend experimenting with the sustaining effect of *una corda* in relatively quiet passages whose timbre is not adversely affected by the soft pedal. Melodic tones should be relatively long (say, a full second or more), to give the unstruck string time to start vibrating. The audibility of the effect will of course vary according to the instrument, chosen register, and room acoustics.

Melody Lead and the Velocity Artifact

Integral to piano technique is *polyphonic touch*, or the differentiation of dynamic levels within a chord, which enables melodies to be brought out of a contrapuntal context. Pianists have been doing this since the earliest clavichords and fortepianos allowed key velocity to determine dynamic level, allowing for example the entries of Bach fugal subjects to be projected. Sophisticated exercises and studies that addressed this technique appeared in the late nineteenth century. For a later generation, Artur Schnabel suggested that students play the

cluster CDEFG repeatedly with fingering 1-2-3-4-5, each time bringing out a different tone to create a melody, for example, 5-3-3, 4-2-2, 1-2-3-4-5-5-5 (“Hänschen klein,” a German nursery tune) (Wolff, 1972, p. 177). In the eighth measure of his Klavierstück Nr. 2 (1) of 1954 (London: Universal), Stockhausen notated a widely spaced five-note chord for the right hand and labeled the individual tones *ff*, *fff*, *f*, *mf*, and *f*—a tall order for a human performer but something that the piano is at least physically capable of.

Vladimir Horowitz recommended that “in striking a chord, in which a single note is to be accented, the effect can be produced by holding the finger which is to play the melody note a trifle lower and much firmer than the fingers which are to play the unaccented notes. The reason for holding the finger a trifle lower is only psychological in effect; in actual practice, it isn’t altogether necessary” (Eisenberg, 1928). Along similar lines, Schultz (1949, p. 176) suggested that “to accent the *C* in the chord *E-G-C* . . . fingered 1-2-5, the thumb and second finger show more joint-movement than the fifth, the muscles of which contract relatively strongly. The accented tone is actually played a fraction of a second before the unaccented ones, but the difference in time is too small to be readily observable.”

The asynchrony referred to by Schultz is known in modern music-psychological literature as *melody lead*. In the piano, the time taken for a single key to fall from the surface to the keybed ranges from about 25 ms in *forte* to 160 ms in *piano* (Askenfelt & Jansson, 1991). When fingers strike the key surface simultaneously but descend at different velocities, the maximum possible asynchrony is around 100 ms (remembering that, in quiet percussive touch, the hammer reaches the string up to 35 ms before the key reaches the keybed but only 2 to 5 ms in *forte*: Askenfelt & Jansson, 1990, Figure 8). In practice, melody leads are typically in the range of 20 to 40 ms, which is short enough to be inaudible (again, like early reflections in a concert hall). They are observed in performances at all levels of expertise (Palmer, 1989, 1996; Repp, 1996).

Goebel (2001) found that melody lead times could be predicted accurately by calculating key and hammer travel times on the basis of their measured velocities, confirming that in one-hand chords his pianists were striking the key surfaces almost simultaneously, regardless of emphasis. This was consistent with the pianists’ apparent lack of awareness of melody lead in interviews. Melody lead may thus be regarded primarily as an *artifact* of keyboard construction.

Melody leads of similar duration also occur in ensemble performance (Rasch, 1979). This could be an artifact of a different kind: those that lead an ensemble tend to do just that and play infinitesimally earlier than the others who follow—just as less-experienced piano accompanists sometimes tend to drag. Alternatively, the effect may be a deliberate or intuitive expressive device to help bring out the melody. Pianists, too, may *deliberately* anticipate melody tones by different degrees, depending on the expressive intention (Rasch, 1978; Henderson, 1936; Palmer, 1989, 1996). But this is difficult to confirm experimentally, as one must first subtract out the effect of the velocity artifact.

Melody lead (or lag) can render a tone more salient than other tones in a chord, independent of the associated intensity differences. The anticipated tone is ini-

tially not masked by the other tones; and according to Bregman's (1990) theory and experiments, a slightly asynchronous tone is more easily heard as part of a melody. Thus, from a perceptual point of view, it may be unnecessary or even inappropriate to develop a deliberate strategy to compensate for the velocity artifact—that is, to attempt to control the relationship between key velocity and synchrony.

A pianist who wishes to do this consciously and thereby widen the range of available interpretive possibilities is faced with a technical problem. Due to intrinsic motor and physiological limitations, it is extremely difficult to directly manipulate the timing of almost-simultaneous finger movements, because the time required by sensorimotor and aural-neurophysiological feedback between the fingers and the brain would be similar to the typical duration of melody lead times (some tens of ms). The first author of this chapter gets around this by raising the finger whose onset is to be delayed and setting all fingers in motion at about the same time, applying more force and velocity to the raised finger. That finger then hits the key surface slightly later than the others—not earlier, as suggested by Horowitz, and perhaps corresponding to the “diametrically opposed” method referred to by Eisenberg (1928). By adjusting the height of the raised finger and listening carefully, the asynchrony at the keyboard can be reduced. The technical and artistic effectiveness of this technique, which follows logically from the psychological findings but seems to contradict much pianistic practice, is yet to be systematically investigated.

We have not addressed the tendency of some pianists—especially pianists from the early days of recording—to deliberately *delay* the melody (sometimes called bass lead: Goebel, in press; Repp, 1996; Vernon, 1936). This is technically relatively easy, since the asynchrony is between rather than within hands and may be regarded as a kind of agogic accent (chapter 13).

Psychology of Piano Fingering

To impose a fingering cannot logically meet the different conformations of hands . . . the absence of fingerings is an excellent exercise, suppresses the spirit of contradiction which induces us to choose to ignore the fingerings of the composer, and proves those eternal words: “One is never better served than by oneself.” Let us seek our fingerings!

Debussy, *Douze Etudes*

How do pianists determine fingerings? What are the underlying criteria? How do fingerings differ among pianists? Only recently have questions such as these been regarded as amenable to psychological research methods.

In the following, we limit ourselves to psychological aspects of fingering and assume that pianists are free to choose their own. The question of whether

fingerings prescribed by composers such as Schubert, Chopin, Brahms, Liszt, Rachmaninoff, and Bartók should be followed (as, for example, Claudio Arrau has insisted) is a cultural, historical, and perhaps even ethical one and beyond our scope here.

Optimal Fingering

Optimal fingering emerges from a trade-off or compromise among various physical, anatomic, motor, and cognitive constraints, in conjunction with interpretive considerations. It depends on the relative importance of these different aspects for a given pianist or musical context. The complex interaction among these various constraints and their dependence on pianist and style mean that one can rarely speak of a single best fingering for a given passage.

Physical constraints on fingering include the horizontal and vertical arrangement of the black and white keys. In the determination of fingerings, these interact with *anatomic* constraints and associated individual differences: hand size and shape (measured by Wagner, 1988; see photos of pianists' hands in Gát, 1965) or the maximum comfortable stretches between pairs of fingers (included in the model of Parncutt et al., 1997; see also Jacobs, 2001).

Motor constraints can apply either within a single hand or between hands. Within a hand, they limit finger independence. According to Ortmann (1929/1981), such motor constraints can be reduced by practice but never eliminated. Between hands, motor constraints are involved in the coordination of tremolos, two-hand trills, and shakes; the execution of seamless transitions from one hand to another within Thalberg-style thumb melodies or accompanying figures; and the sharing of technically difficult figurations between the hands.

Cognitive constraints determine how well we can encode and retrieve complex finger patterns and their context dependencies. Fingerings that stay the same in different keys may reduce cognitive demands but are physically and anatomically more difficult. A change of fingering at a key change may be worthwhile if the anatomic and physical advantages balance the added cognitive load. To master these difficulties, many piano pedagogues, including Liszt (and, e.g., Frey, 1933), have recommended transposing difficult passages to all keys without changing the fingering.

Interactions between the two hands are primarily limited by cognitive constraints. In sight-reading unison passages (hands an octave apart), for example, two different fingerings must be planned and executed simultaneously (Parncutt, Sloboda, & Clarke, 1999). The cognitive load is reduced in mirror-image patterns in contrary motion, where fingerings can be identical in both hands—for example, in Messiaen's *Vingt regards sur l'enfant Jésus* (Troup, 1983, 1995).

By *interpretive* considerations we mean both communication of musical *structure* (chapter 13) and *emotion* (chapter 14). Fingering choices are often determined by matching a constraint to a given interpretive intention, for example, thumb on black at the start of a measure or phrase (Clarke et al., 1997) or second (index) finger at the end of a phrase. A more general interpretive consideration

is flexibility: pianists need a fingering that allows for changes of interpretation without changes of fingering that would increase the rate of errors (Sloboda et al., 1998).

Procedural Versus Declarative Knowledge

The knowledge (or memory) that underlies fingering choices may be described as episodic or semantic, or as procedural or declarative. These terms are defined in psychology (see, e.g., introductory texts) as follows. *Episodic* knowledge refers to a specific event: a pianist may finger a passage in a certain way because the passage resembles a previously encountered and fingered passage. *Semantic* knowledge is more generalized: here it includes rules and principles of fingering. Both episodic and semantic knowledge can be either declarative or procedural. *Declarative* knowledge can be verbalized (knowing *that*), but *procedural* knowledge (knowing *how*) typically refers to *automated* movements that underlie a skill, such as riding a bicycle or producing grammatically correct sentences: a five-year-old may be able to do both but is unable to describe the underlying physical or grammatical rules or principles.

All four aspects are important at all levels. Even the most experienced pianists try out fingerings at the keyboard (procedural) but can also explain their fingering choices (declarative: Clarke et al., 1997). Procedural knowledge of fingering may be acquired either by applying declarative knowledge (rules) to repertoire excerpts (episodic: see, e.g., technical methods of the 1920s and 1930s) or by improvising exercises to address specific fingering issues (semantic: e.g., Cortot, 1958; Gellrich & Parncutt, 1998).

Dependence on Task

Optimal fingering depends on whether a passage of music is improvised, sight-read, played from the score after rehearsal, or performed from memory. For example, marked differences were observed between fingerings spontaneously used by pianists in the sight-reading task of Sloboda et al. (1998) and fingerings written on scores of the same music by the same participants several months previously (Parncutt et al., 1997). Standard fingerings for scales and arpeggios are of course more useful in sight-reading (where they reduce the cognitive load) than in memorized performance, where the pianist has time to automate new fingerings (Clarke et al., 1997)—although this does not necessarily apply to professional sight-readers, who have usually seen the score in advance (chapter 9).

Differences between written and sight-read (or improvised) fingerings may be explained if we assume that writing primarily taps declarative knowledge and sight-reading (or improvisation) primarily taps procedural knowledge. Only during rehearsal does a pianist have the chance to allow declarative and procedural knowledge to interact, as new fingering patterns are deliberately learned and automated. Teachers and performers may therefore develop different fingering approaches and strategies for sight-reading as apart from rehearsed per-

formance, beyond merely learning standard fingerings for scales and arpeggios (cf. Deutsch, 1959).

Dependence on Expertise

Fingering depends on expertise (Clarke et al., 1997; Sloboda et al., 1998), because technique (finger independence, coordination of finger, arm, and hand movements, and so on) typically matures before interpretive ability and personal style. Beginners focus almost entirely on anatomic and physiological constraints but may not yet have the experience and knowledge necessary to choose the easiest variant. Young professional pianists (e.g., conservatory graduates) tend to use a fingering that is anatomically and physiologically optimal. Seasoned artists with consummate techniques usually focus on interpretive considerations; for example, Schnabel was famous for sacrificing digital expediency for interpretive integrity, regarding hand position (“handing”) as more important than fingering (Wolff, 1972). Thus a teacher’s best fingering is not necessarily best for a student, and while it is always advisable to extend the student’s awareness of available fingerings, it may be unwise to expect rigorous imitation.

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