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Musical Motion: Some Historical and Contemporary Perspectives*

Bruno H. Repp

The idea that music "moves" has a long and varied history. Some aspects of this notion are metaphorical (e.g., the "motions" between pitches, harmonies, or keys), whereas others are more literal. The latter derive from the performer's actions that bring the music to life. This gestural information is encoded in the expressive microstructure of the performance at several hierarchically nested levels. Some older demonstrations in support of this proposition have used the technique of "accompanying movements", devised and elaborated by authors such as Eduard Sievers, Gustav Becking, and Alexander Truslit. Contemporary approaches, most notably those of Manfred Clynes and Neil Todd, focus instead on performance analysis and synthesis. Todd has provided evidence that tempo modulations in expert performances obey a constraint of linear changes in velocity, suggesting that music is "set into motion" by some kind of force or impulse function. Clynes has proposed (following Becking) that the parameters of these underlying functions distinguish different composers. The notion of *spatio-temporal coupling*, illustrated by Paolo Viviani's work on drawing movements, suggests a theoretical basis for the recovery of spatial movement from temporal information. Physical laws of motion thus impose constraints on performance microstructure, constraints that are also reflected in listeners' perception and aesthetic judgments.

INTRODUCTION

Music is made by moving hands, fingers, or extensions thereof over an instrument, and the dynamic time course of these movements is reflected to some extent in the resulting stream of sounds. Conversely, people listening to music frequently perform coordinated movements that range from foot tapping to elaborate dance. Although these movements on the listener's side are not the same as those of the performer, they are certainly not unrelated. At the very least, they share a rhythmic framework that gets transmitted from player to listener via the sound structure.

In many cultures this close connection of music and movement is so obvious as to hardly deserve comment. In Europe, however, the remarkable development of musical notation and of complex compositional techniques over the last few centuries has led to a focus on the structural rather than the kinematic properties of music, at least of so-called serious music. At the same time, as this music was performed mainly in church or concert halls, a social restriction against overt movement in listeners has long been in effect. As a result of these practices, the close connection of music and motion has receded from people's consciousness, and 20th century aesthetic and technological developments have occasionally even severed that connection, with only few taking notice. Therefore, there is a need today to re-assess the concept of musical motion and its role in performance and music appreciation.

My purpose in this paper is not to review philosophical or musicological treatments of this topic; suffice it to mention the important discussions by Langer (1953), Zuckerkandl (1973), and Sessions (1950), among many others. Rather, I will focus on the limited and far-between attempts to provide empirical demonstrations of the kinematic correlates of Western art music. Also, I will not dwell on the more abstract and metaphoric notions of melodic and harmonic motion common among musicologists, which concern the transitions from one pitch, or one harmony, or one tonality to another—movements that can be seen, as it were, by moving one's eyes over the printed score. I am concerned primarily with *rhythmic* motion, which presupposes a *performance*, a human realization of the music as structured sound, whether actual or imagined. The question I am pursuing, then, is: What is the nature of the rhythmic motion information in music, and how can its kinematic implications be demonstrated?

In this presentation I intend to review briefly the pioneering work of three largely forgotten individuals who were active in Germany during the early decades of this century. In doing so, I hope to inform or remind you of their theoretical accomplishments, however limited their empirical contribution may seem from our modern scientific perspective. Then I will turn to sampling the work of two contemporary researchers who—knowingly in one case, unwittingly in the other—have elaborated upon and increased the precision of the German pioneers' ideas, so that they can now be subjected to rigorous tests. I will conclude with a very brief foray into the motor control literature, again focusing on a single researcher whose work seems to be particularly pertinent to the kinds of motion that music engenders. Because of time constraints I will not be able to do justice to the related work of many others, for example Johan Sundberg and Alf Gabrielsson; to them I apologize, but you can hear about their latest work first-hand at this conference.

Three German pioneers: Sievers, Becking, and Truslit

Whereas no one doubts that there is visual information for motion, the concept of auditory motion information is less widely accepted, especially since it involves an essentially stationary sound source—the musical instrument being played on. One reason for this scepticism may be that visual motion information is generally continuous in time, whereas auditory motion information, especially that in music, is often carried by discrete events (i.e., tone onsets) that only *sample* the time course of the underlying movement. The principal technique for demonstrating that music does convey movement information is the reconstitution of the analogous spatial movement by a human listener. The listener's body thus acts as a *transducer*, a kind of filter for the often impulse-like coding of musical movement.

The first modern attempt to use such a technique in a systematic fashion must be credited to the German philologist Eduard Sievers, who applied it not to music but to literary works. Sievers called his method *Schallanalyse* ("sound analysis"), though it was not concerned with sound as such but rather with body posture and movement as a way of reconstructing and analyzing the expressive sound shape of printed language, mostly poetry. He never published a complete account of his very complex methods. Sievers (1924) provides an overview; for a more recent critical evaluation, see Ungeheuer (1964).

Sievers's initial impetus came from observations of a teacher of singing, Joseph Rutz, published by his son Otmar Rutz (1911, 1922), about connections between body posture and voice quality. Certain body postures were said to inhibit vocal production, whereas others facilitated it and gave it a free, uninhibited quality. Sievers initially focused on these static body postures which he symbolized by means of "optic signals" in the form of geometric shapes that were meant to cue different body postures in a speaker reciting a text. Subsequently he elaborated this method into a system of dynamic movements, to be carried out with a baton, with the index finger, or even with both arms while speaking. The crucial criterion was the achievement of "free and uninhibited articulation", and the goal of the analytic method was to find the accompanying movements that interfered least with (or facilitated most) the recitation of the text. The metric, prosodic, and semantic characteristics of the text naturally varied across authors and their individual works, and so did the accompanying movements considered optimal by Sievers. The movements were rhythmically coordinated with the speech and had a cyclic or looping character. However, they could vary in a large number of features, such as the relative smoothness of turns, the tilt of the main axis, rising versus falling direction, etc.

Sievers distinguished two classes of curves, which are illustrated in Figure 1: general curves or "Becking curves", and specific or filler curves (*Taktfüllcurven*). The former, which were suggested to him by Gustav Becking (see below), come in three types that in fact exhaust the possibilities for a cyclic movement with two turning points: pointed-round, round-round, and pointed-pointed. Any individual speaker/writer was said to be characterized by one and only one of these types, if not as an obligatory then at least as a preferred mode of dynamic expression, and hence by a corresponding "voice type". However, many variations are possible within each type. The "special curves", of which there is a bewildering variety, reflect the specific metric and sonic properties of a spoken text (or of music, as the case may be). It was these special curves and their many variations that Sievers devoted most of his efforts to.

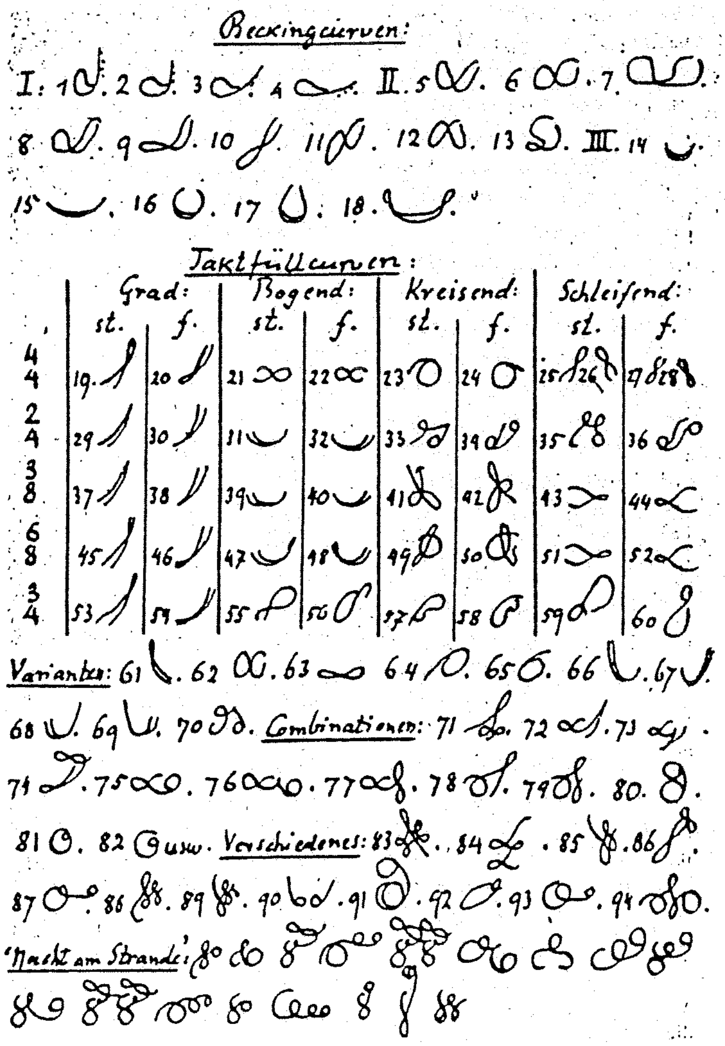

Figure 1. **Examples of movement curves used by Eduard Sievers. Top: general curves. Center: special curves (straight, curved, circular, looping). Bottom: variations, combinations, miscellaneous, and a kinematic interpretation of a text, "Markt am Strande". (Reproduced from Sievers, 1924: 73.)**

Sievers was the only recognized master of the technique he had developed. He claimed to be in possession of an extraordinary "motoric sensibility" that, combined with many years of self-training and observation, enabled him to find the accompanying movements for the most subtle variations in the sound shape of spoken texts. Although his dedication and expertise were never in doubt, the extreme subjectivity of his method obviously reduced its respectability as a scientific procedure. Nevertheless, the basic idea underlying it remains of value: He showed that rhythmic sound patterns have a dynamic time course that can be translated into accompanying body movements. Only the rules governing this translation remained somewhat obscure.

Sievers benefited from his interaction with Gustav Becking, a young musicologist who developed his own ideas in a monograph entitled *Der musikalische Rhythmus als Erkenntnisquelle* (Musical Rhythm as a Source of Insight) that appeared in 1928. Becking's pivotal assumption is that there is a *dynamic rhythmic flow* below the musical surface. This flow, a continuous up-down motion, connects points of metric gravity that vary in relative weight. Becking's important and original claim is that the distribution of these weights varies from composer to composer. The analytic technique for determining these weights is Sievers's method of accompanying movements, carried out with a light baton. A downbeat always accompanies the heaviest metric accent; then an upward movement follows which leads into the next downbeat. The *dynamic shape* of this movement cycle is of interest. For example, the strongest pressure in the downbeat is never at the beginning but at varying delays; the movement may be deep and vertical or shallow and more nearly horizontal; and the connection of down and up movements may be smooth or abrupt.

Becking's primary interest was not in the differentiation and proliferation of movement curves for individual works of art but in the personal constants of individual composers—in other words, invariance rather than variability. He says that the personal curves reflect a composer's individual "management of gravity". Gravity being a physical given, different composers' solutions reflect different philosophical attitudes towards physical reality—as something to be overcome, to adapt to, or to be denied, as the case may be. Becking's ultimate goal thus is a typology of personal constants linked to a typology of *Weltanschauungen* (world views)—a philosophical undertaking in which he was preceded by Nohl (1920), among others.

As already mentioned in connection with Sievers's "Becking curves", Becking distinguishes three types of "personal curves", examples of which are illustrated in Figure 2: *Type I* has a sharp, pointed onset of the downbeat, which is straight and usually vertical but nevertheless actively guided rather than passively falling. At the bottom, there is a narrow but round loop ending in a small downward movement (a secondary accent between downbeats) before leading vertically upward, resulting in a figure somewhat resembling a golf club. This pattern, with its strong differentiation of rhythmic accents but nevertheless organic dynamic shape is attributed to the "Mozart family", which also includes Handel, Haydn, Schubert, Bruckner, and most Italian composers. These composers are said to be monists (in that they largely obey the physical force of gravity) as well as idealists, because they actively impose a personal dynamic shape. *Type II* has a round, curving, inward-going (towards the body) onset of the downbeat and a similarly round, outward-going turn upwards, leading to a figure resembling a horizontal or tilted figure "8". Differences in accentuation among metric subdivisions tend to be reduced here. Composers characterized by this personal curve form the "Beethoven family", which also includes Weber, Schumann, Brahms, Richard Strauss, and many other German masters. According to Becking, they aim to overcome gravity and force it into a winding path. Thus they are dualists (in that they oppose the material force with their own spiritual force or will) as well as idealists (in that they impose an organic dynamic shape on the raw pulse of the music). Finally, *Type III* is characterized by a pointed downbeat as well as a pointed return, resulting in a semicircular, pendulum-like curving motion from right to left and back. Consequently, the main accents on the downbeats and the secondary accents in between tend to be equally strong and form a rigid rhythmic framework. This pattern Becking ascribes to the "Bach family", including Mendelssohn, Chopin, Wagner, Mahler, and most French composers. These composers are said to be naturalists because they follow the force of gravity without opposing it or necessarily imposing a personal pulse on it. Yet there are numerous personal variants of the trajectory between the two rigid endpoints, resulting in more or less idealistic curves (e.g., Wagner). Nevertheless, all these composers accept the objective, even pulse and hence are only minor idealists, with Bach being the least idealistic and most objective of all.

Becking's method of determining the personal curve of a composer was highly subjective. It required a thorough acquaintance with a composer's oeuvre as well as, presumably, with performances by great interpreters and biographical details that help elucidate the artist's personality. The personal curve is *not* derivable from the score, nor is its subjective fit to a particular piece of music necessarily perfect, especially if that music is an early or otherwise atypical creation. Rather, knowledge of the personal curve, verified on the composer's most characteristic works, enables the scholar or performer to imbue even the less characteristic works with the composer's identity. Clearly, this method is somewhat circular and not at all scientifically rigorous. However, Becking's extraordinary perspicacity, his well-chosen musical examples, and his eloquent verbal characterizations make his book a unique and fascinating document.

The third important person among the German pioneers is the one least known today—a man named Alexander Truslit, whose book, *Gestaltung und Bewegung in der Musik* (Shaping and Motion in Music), appeared in 1938. Truslit's orientation is much closer to the natural sciences than that of his predecessors and in some ways presages James Gibson's (1979) writings on ecological perception and action. Unlike Becking, who believed that composers' personal dynamics take place largely beneath the musical surface (i.e., in the listener's musical imagination), Truslit focuses on the information in the sound pattern.

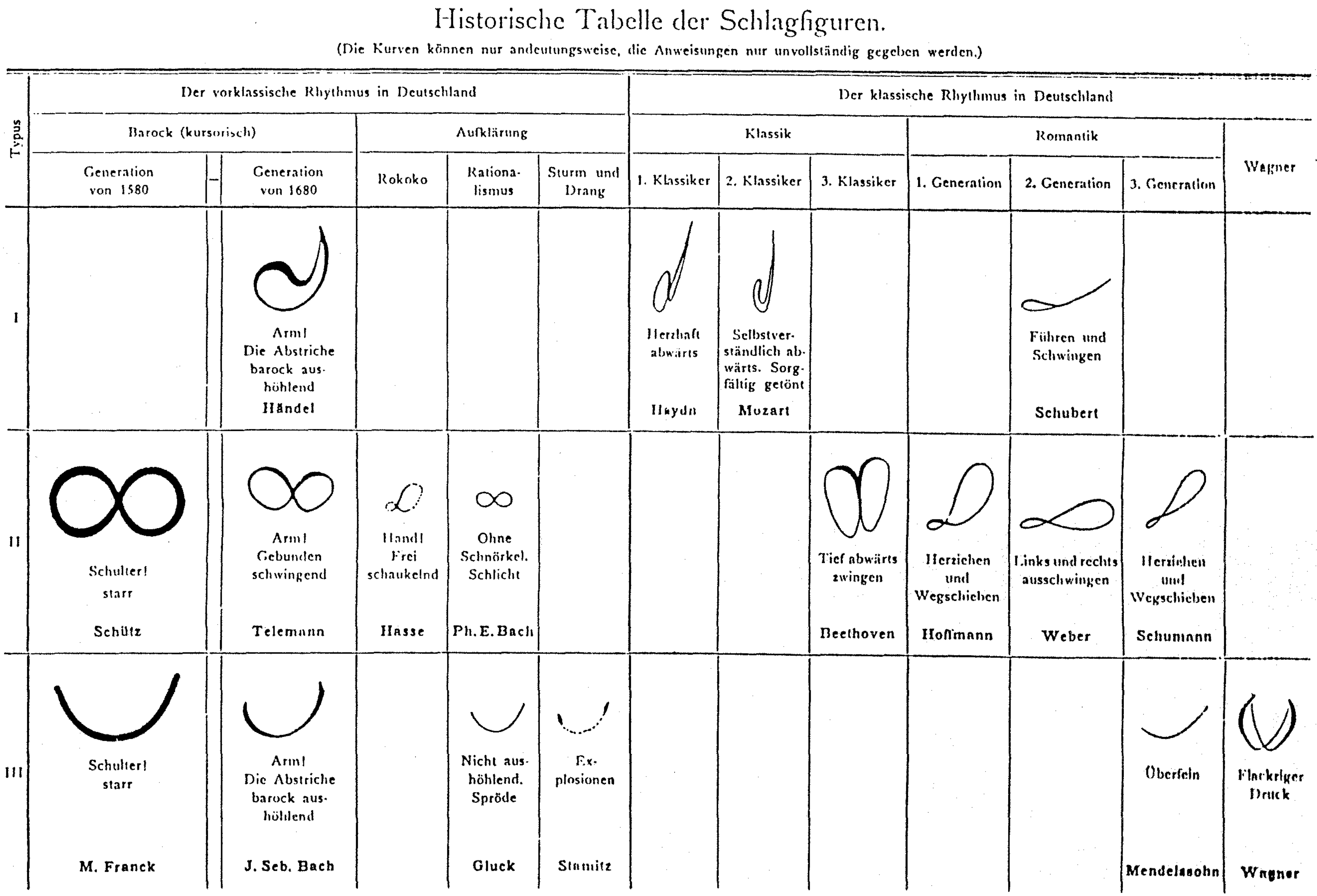

Figure 2. **Becking's historical table of conducting curves for selected German composers. (Reproduced from the end plate in Becking, 1928.)**

He contends that the musical dynamics and agogics (i.e., timing variations) convey movement information directly to the sensitive listener, who can then instantiate these movements by acting them out, if necessary. The goal of music performance is to arrange the musical surface in accord with the appropriate underlying movement.

Like Becking, Truslit distinguishes three basic types of movement curves: "open", "closed", and "winding" (*gewunden*). In Figure 3, they (b-d) are contrasted with an unnatural linear motion path (a). Superficially, they resemble Becking's three types; in particular, the winding curve seems very much like Becking's Type II, and the open curve resembles Becking's Type III. However, these similarities are more apparent than real. Truslit's curves are not conducting movements; they are to be carried out slowly and with outstretched parallel arms, so that the whole upper body is involved. Their height in space tends to follow the pitch contour of the melody; thus they often start at the bottom and move upwards rather than beginning with a "downbeat". They are a means of portraying the melodic dynamics in space, with the speed of movement and the consequent relative tension being governed mainly by the curvature of the motion path. That is, a relative slowing down and increased tension in the music is portrayed by a tight loop, whereas faster, more relaxed stretches correspond to relatively straight movements. The varied melodic structure of a composition elicits complex paths of various combinations of clockwise and counterclockwise turns, interpolated loops, etc. Even the type of movement may change within a composition. Figure 4 illustrates the combination of closed and winding movements that Truslit found most appropriate for the initial section of Brahms' Rhapsody in G minor.

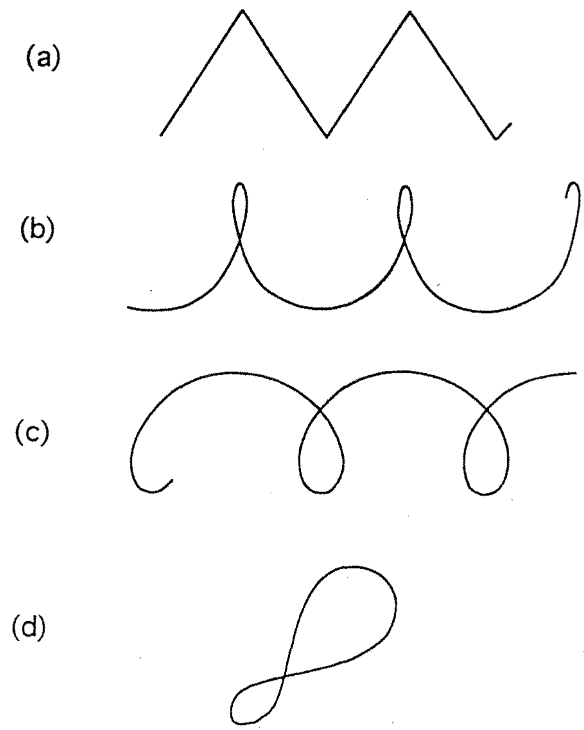

Figure 3. **Truslit's movement types: (a) straight (mechanical); (b) open; (c) closed; (d) winding. (After Truslit, 1938: Plate 2; reproduced from Repp, 1993: 54, with permission of the publisher.)**

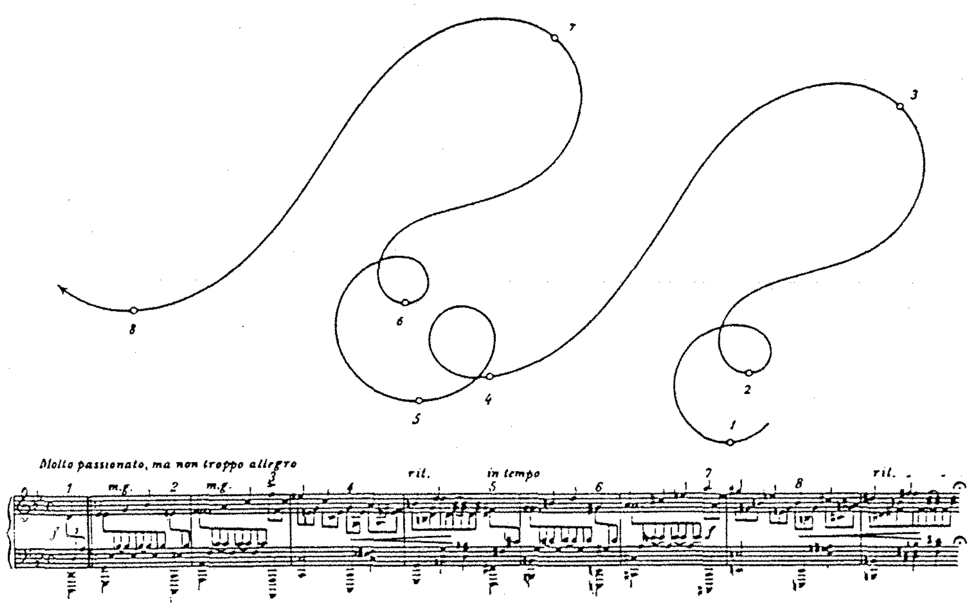

Figure 4. **Truslit's kinematic interpretation of the beginning of Brahms' Rhapsody in G minor, op.79, No.2. Numbers along the movement curve correspond to numbered points in the score. (Reproduced from Truslit, 1938: 144, with permission of the publisher.)**

Truslit's curves are not at all "personal" and composer-specific; rather, they are work-specific. In that respect, he is somewhat closer to Sievers than to Becking. He explicitly assigns a secondary and subordinate role to rhythmic patterns: They should not be too pronounced, so as not to disrupt the smooth flow of the melody. Rhythmic patterns affect the limbs, he says (which is consistent with Becking's use of the hand to conduct), whereas the more global melodic patterns affect the large muscles of the back and hence the whole body. Thus Truslit's curves often extend over a number of measures, with the more detailed rhythmic structure being marked by small local loops, if at all. Not surprisingly, Truslit seems to be most interested in music that exhibits a pronounced gestural character; many of his musical examples come from Wagner, while there are no Mozart or Bach examples in his book. His most intriguing speculation is that the perception and translation of musical movement at the scale he is interested in may be mediated by the vestibular organ, which controls body orientation and equilibrium. In support of this claim he cites scientific evidence from early physiological experiments. Furthermore, to illustrate the concrete instantiation of different movement types in music performance, Truslit presents recorded sound examples as well as some measurements of their acoustic microstructure. Although his empirical contribution is fairly negligible, his very modern theoretical ideas and the clarity and force with which they are presented must be greatly admired. (For an English translation of the gist of his book, see Repp, 1993.)

Two modern successors: Clynes and Todd

Despite the many interesting observations that these German pioneers, especially Becking and Truslit, have to offer to the modern reader, their work seems to have been largely forgotten. Some of their ideas may indeed be outmoded, but others are clearly relevant to more recent research on musical expression and performance. Among the small group of researchers active in this area, two seem particularly close in spirit to the German pioneers: Manfred Clynes and Neil Todd. Clynes was acquainted with Becking's work as he began in the 1970s to develop the concept of composers' "personal curves" further, making ingenious use of computer technology. Todd independently developed ideas resembling those of Truslit, without actually being aware of his work.

Over a number of years, Clynes (1977) developed the notion of *essentic forms*, dynamic shapes that characterize basic emotions. To measure these shapes, he devised a simple apparatus called the *sentograph*. It consists of a button sensitive to finger pressure in vertical and horizontal directions and a computer that registers the pressure over time and averages successive pressure cycles. Subjects who imagine certain basic emotions (love, anger, grief, etc.) while pressing rhythmically on the sentograph produce very different pressure curves for different emotions.

Clynes argues that meaning in music derives from essentic forms, which are conveyed by the musical structure (melody, rhythm) and microstructure (dynamics, agogics). The more closely an essentic form is approximated, the more beautiful and meaningful the music is perceived to be. This emotional "story", however, unfolds against the background of a fixed, repetitive, dynamic rhythmic pattern that represents the composer's individuality and "point of view". This is the composer's "inner pulse"—a concept clearly derived from Becking's theory of "personal curves". In his most recent writings, Clynes (1992) has referred to this as his "double stream theory" of musical expression.

The sentograph offered itself as a suitable instrument for measuring the essentic shapes of a piece of music as well as the composer's inner pulse. To assess the former, the (musically experienced) subject presses the button in synchrony with larger musical gestures or phrases while listening to or imagining a piece of music. To assess the latter, the subject presses more rapidly (about once per second) in synchrony with successive downbeats. These repeated pressure curves can then be averaged, yielding a stable average pulse shape. Such averaging is not easily possible with the longer essentic shapes, which may be one reason why Clynes has done little work to explore this aspect further.

To determine the shape of famous composers' inner pulses, Clynes used several outstanding musicians (including Pablo Casals, Rudolf Serkin, and himself) as subjects. They were asked to press rhythmically on the sentograph while imagining various works of Beethoven, Mozart, Schubert, and others. It was not a counterbalanced experiment—not every subject produced every composer's pulse, while some produced several pulse shapes for different pieces by the same composer. In any case, as can be seen in Figure 5, the average vertical pressure curves (see Clynes, 1977) show striking differences between composers (here, Beethoven, Mozart, and Schubert) and considerable agreement within composers across different subjects and different pieces.

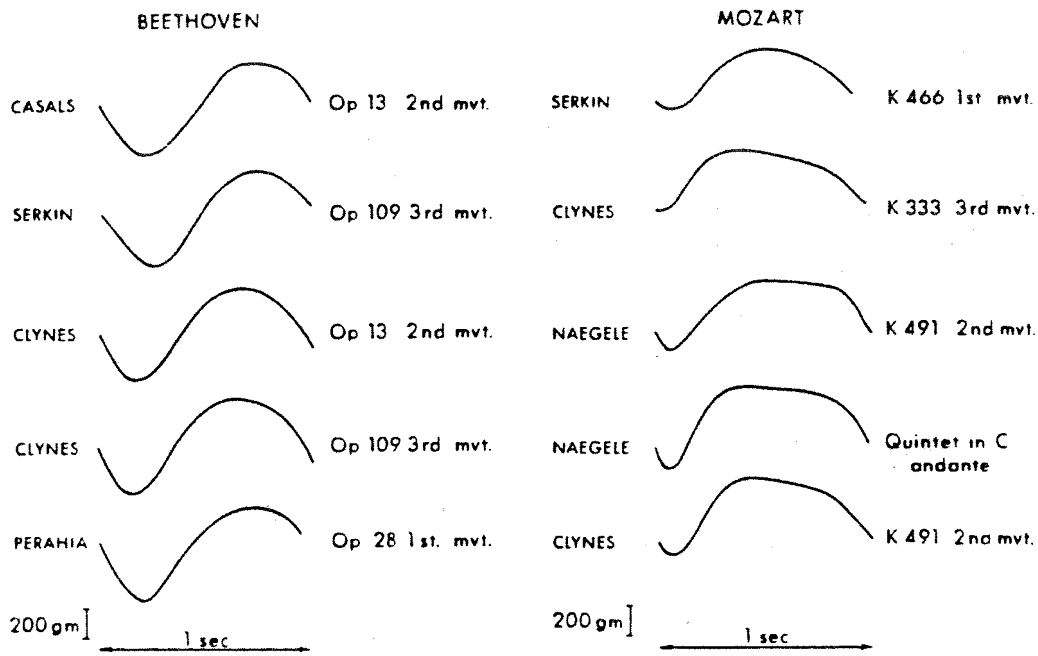

Figure 5. **Average sentograph responses (vertical pressure curves) of several distinguished musicians as they mentally rehearsed compositions by Beethoven and Mozart. (Reproduced from Clynes, 1969: 200, with permission of the publisher.)**

Clynes thus went one step beyond Becking by registering the "conducting" movements that Becking represented only schematically by means of graphs. Even though the finger movements on the sentograph are different from the baton-aided hand movements Becking had in mind, they seem to capture some of the composer-specific characteristics that Becking talked about. The main analogy between Becking's and Clynes's curves seems to lie in the onset time, relative speed, and depth of the downward movement.

Some years after his demonstration of composers' inner pulses on the sentograph, Clynes (1983) advanced towards an objectivization of the pulse concept. Although Becking had provided some hints towards the manner in which individual composers' pulses might be manifested on the musical surface of a performance, he basically thought of them as mental or "inner" phenomena. Clynes pursued the idea that composers' personal pulses must somehow be manifested in the expressive microstructure of an expert performance. Rather than analyzing the performances of great interpreters, he developed a computer program that enabled him to play back music with different agogic and dynamic patterns, repeated cyclically from bar to bar. Using himself as a listener and judge, he manipulated and refined these objective pulse patterns for various compositions of different composers, primarily Beethoven, Mozart, and Schubert. He eventually arrived at settings that he found optimally appropriate for each composer; these patterns were quite different across composers but seemed to fit different compositions by the same composer. They could be specified numerically in terms of the relative amplitudes and durations of the tones within a metric cycle. Subsequently, Clynes (1986) expanded his scheme to encompass one or two higher levels within which the basic pulse cycles are nested, and which in turn exhibit the temporal and dynamic relationships of the composer's inner pulse, so that the rhythmic surface pattern is a multiplicative combination of higher- and lower-level pulse parameters.

These pulse patterns, then, represent Clynes's subjective judgment, which identifies his enterprise as being partially in the intellectual tradition of Sievers and Becking. What distinguishes it from its historic precedents, however, is that the pulses are *quantified* and hence open to empirical tests. Several attempts have been made to test the effectiveness of Clynes's specifications in conveying the composer's individuality to unbiased listeners. The method was to generate computer performances of several composers' pieces with each composer's pulse, in a factorial design, and to see whether listeners prefer the performances with the "appropriate" pulse over the others.Several experiments by Thompson (1989) and by me (Repp, 1989, 1990a) have yielded mixed results, but the most recent study, conducted by Clynes himself (in press), provided unambiguous evidence that highly trained musicians prefer the appropriate composers' pulses over inappropriate pulses in computer-generated performances. However, questions remain about how a composer's inner pulse is manifested in human performances, where many factors besides the composer's individuality may affect the expressive microstructure (see Repp, 1990b; 1992).

In these studies, the emphasis was on the quantification and perceptual evaluation of cyclic pulse patterns, not so much on their relation to physical movement. Clynes and Walker (1982) addressed this latter point by investigating the biological "transfer function" between rhythmic sound patterns and the rhythmic movement of a human listener. The subject pressed on a sentograph while listening to cyclic repetitions of two tones having variable onset times, durations, and amplitudes. The resulting averaged pressure curves varied systematically with the sound patterns presented. For example, the downward movement of the finger, which usually accompanied the louder of the two tones, depended on the temporal separation of the softer tone from the louder tone. The timing of the upward movement depended on tone duration: Patterns of long tones resulted in smooth, round movements, whereas patterns of short tones (with long gaps in between) induced sharp, angular movements.

To relate these results, obtained with arbitrary rhythmic patterns, to the hypothesized pulse patterns of actual music, Clynes and Walker matched two-tone patterns to synchronously played music. They adjusted the physical parameters of the two tones until they perceived a congruence with the musical rhythm. Subsequently, they had subjects press the sentograph when listening either to the music or to the matched two-tone "sound pulse". Figure 6 shows that there was a significant similarity between these motoric responses, indicating that the simple two-tone pulse patterns captured the rhythmic pulse of the acoustically much more complex music.

Clynes's theories and research (of which I have provided here only a brief glimpse) represent a highly original and important contribution to music psychology. However, his observations are in need of extension and replication in other laboratories, as they are often based on very limited data. I find it regrettable that so few researchers have pursued the intriguing avenues opened up by this exceptionally creative mind in our midst.

While Clynes was inspired by the ideas of Becking, Todd is in some ways the intellectual heir of Truslit. The most obvious coincidence is both authors' hypothesis that the perception of musical motion may be mediated somehow by the vestibular system (Todd, 1992a, 1992b, 1992c; 1993). Although there is little evidence that vestibular stimulation actually occurs in ordinary music listening conditions, perhaps this is not really necessary: The sound patterns that characterize body movement could be recognized at an abstract auditory or cognitive level. They may be the very same as those that, under certain extreme conditions (e.g., in very loud music), can evoke vestibular sensations.

Like Truslit, Todd is concerned primarily with motion at the level of the whole body, rather than of the limbs or fingers. He, as did Truslit before him, appeals to physiological evidence for two distinct motor systems, the ventromedial and lateral systems (Todd, 1992b). The former controls body posture and motion, and is closely linked with the vestibular system. Since larger masses are to be moved, the movements are slower than those possible with feet, hands, and fingers, which are controlled by the lateral system. Typically their cycles extend over several seconds, whereas the pulse microstructure studied by Clynes (and executed by finger pressure on the sentograph) is contained within cycles of roughly 1 s duration that may be nested within the larger cycles described by Truslit and Todd. Recently, Todd (1992c; Todd, Clarke, & Davidson, 1993) has begun to study the motoric instantiation of these larger cycles in the "expressive body sway" of performers. His preliminary data indicate that pianists' head movements are synchronized with expressive tempo fluctuations in the music, such that tempo minima coincide with turning points in the head movement. Observations such as these have led Todd to propose that expressive variation in tempo and in the correlated dynamics may be a representation of self-motion. Clearly, such a representation has the potential of inducing actual or imaginary motion of a similar kind in a listener/observer.

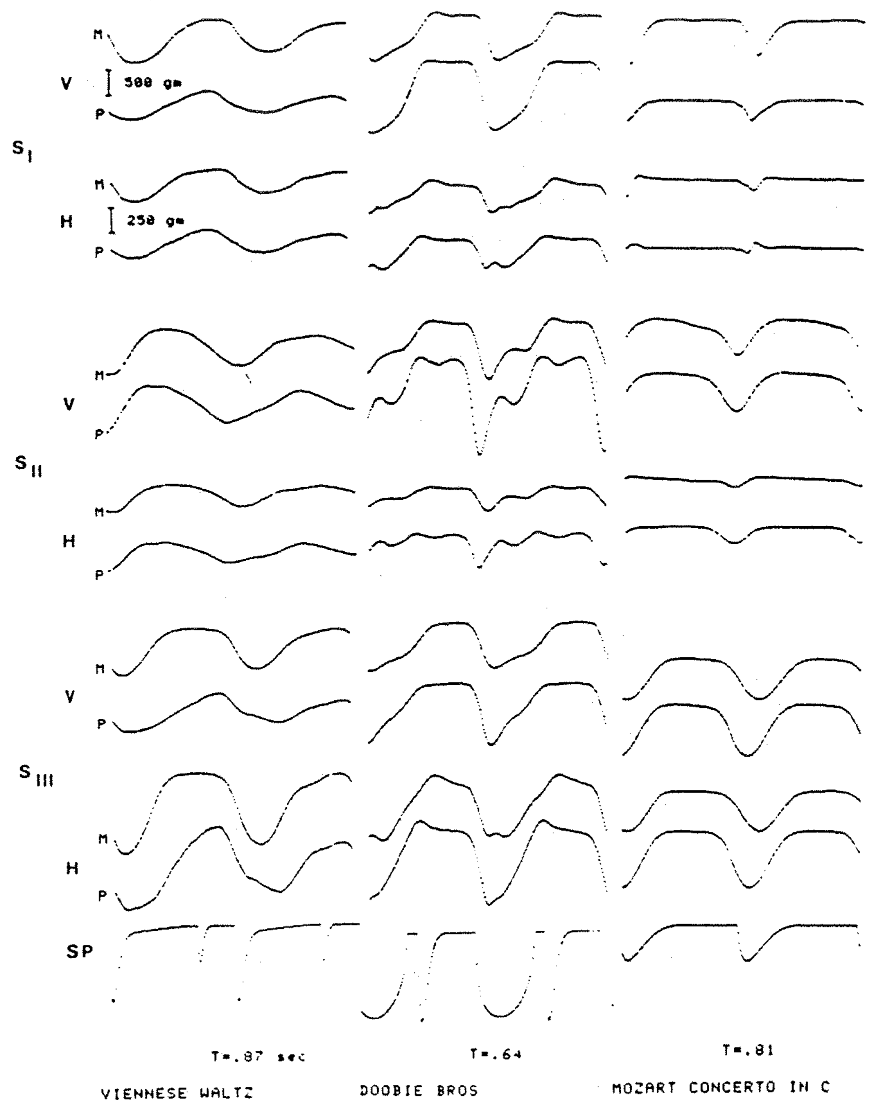

Figure 6. **Vertical (V) and horizontal (H) sentograph pressure curves for three subjects (S_I, S_{II}, S_{III}) who listened either to music (M) or to a simple sound pulse (P) matched to the music. Each column represents a different piece of music. The amplitude envelope of the sound pulse (SP) is shown at the bottom. (Reproduced from Clynes & Walker, 1982: 211, with permission of the publisher.)**

Concerning the tempo variations in performances, Todd (1992a, 1992d) has presented evidence that they are a linear function of real time. In other words, expressive timing consists of alternating phases of constant acceleration and deceleration, one cycle typically corresponding to a musical group or phrase. Listeners also seem to prefer performances whose timing follows this rule, although more extensive perceptual tests remain to be done. Constant acceleration or deceleration seems to characterize various forms of physical and biological motion, so that music having this property would seem an optimal stimulus for the perception and induction of motion. Todd (1992a) has also begun to investigate the way in which changes in musical dynamics go along with changes in timing and has devised a system for the automatic extraction of hierarchical rhythmic structure from the amplitude envelope of the acoustic signal (Todd, 1994). This is exciting work at the cutting edge of contemporary research on music performance.

Research on Biological Motion

Evidence for constraints on natural motion comes from research on human motor control. There is one body of research that seems particularly relevant to me, which is due to Paolo Viviani and his collaborators (see Viviani, 1990; Viviani & Laissard, 1991). Over the last decade, they have investigated the constraints that link the geometry and the kinematics of guided hand movements. The movements in question involved the drawing or tracking of ellipses or of more complex curvilinear paths. The consistent finding has been that, within a single coherent movement, velocity varies as a power function of trajectory curvature (Viviani & Terzuolo, 1982; Viviani & Cenzato, 1985; Viviani & Schneider, 1991). In other words, the greater the local curvature, the slower the movement. Viviani, Campadelli, and Mounod (1987) have demonstrated that subjects are unable to track accurately a light point moving at a constant velocity around an elliptic path, whereas the task is easy when the target velocity changes with curvature according to the power function. It has also been shown that dynamic visual stimuli of the latter kind are judged by observers to represent constant velocity, whereas elliptic stimuli exhibiting constant velocity seem to vary in velocity (Viviani & Stucchi, 1992).

The *spatio-temporal coupling* described in this research on biological movement enhances considerably the scientific respectability of the technique of "accompanying movements" developed by Sievers, Becking, and particularly by Truslit. If spatial trajectory determines the velocity profile, then a particular velocity profile also implies a spatial trajectory of a particular kind. What Truslit evidently did was to convert the velocity information available in the temporal and dynamic microstructure of music into arm movements with a matching spatial trajectory whose direction also took the melodic pitch contour into account. In his book he describes how, with practice, a close subjective match between the spatial trajectory and the auditory information can be achieved. What seemed like a highly idiosyncratic method at first may in fact have a solid foundation in the constraints of biological motion.

Conclusions

I conclude from this very limited survey that music, by virtue of its temporal and dynamic microstructure, has the potential to represent forms of natural motion and to elicit corresponding movements in a human listener. While a rigid rhythm may elicit only foot tapping or finger snapping, an expressively modulated structure can specify movements with complex spatial trajectories that, for the purpose of demonstration and analysis, can be realized as guided movements of the limbs or the whole body. However, execution of such movements is not necessary to appreciate the motion information: Experienced listeners, at least, can judge by ear whether the musical motion is natural or awkward, and they can move along with the music inwardly, as it were. An aesthetically satisfying performance presumably is one whose microstructure satisfies basic constraints of biological motion while also being responsive to the structural and stylistic requirements of the composition.

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FOOTNOTE

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