Keyboard Psychohaptics:

A Nexus of Multidisciplinary Research into Kinesthetics, Gesture, and Expression

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All one has to do is hit the right notes at the right time, and the instrument plays itself.
Johann Sebastian Bach

ONE MAY AT FIRST DISMISS this famous quote attributed to Bach as merely an expression of modesty in response to admiration for his unparalleled mastery of the keyboard.[1] After all, we've all been taught that command of the notes is only the beginning. What of expression, of emotion, of meaning, of all the intangibles that make music more than a mere string of notes in time? Are these not the elements that make music *music*? On the other hand, we must admit Bach's aphorism does hold a kernel of truth. More than just about any other instrument, the keyboard is basically a device for generating a string of tones. Pitch is preset with no variable for control during performance, unlike the infinite micro-tuning, and hence expressive, possibilities on an unfretted string. Most keyboard instruments offer very little control over timbre or tone envelope. The organ in particular might be regarded as the ultimate digital instrument: the key goes down and the pipe sounds, the key comes up and the pitch ceases. In a sense, one might argue that playing the organ is indeed all about hitting the right keys at the right time—but what about expressive timing, hierarchies of note length, and shaping of the phrase? In the case of the organ, arguably, all of these parameters of expression, of making *music*, are merely matters of hitting and releasing the keys "at the right time."

However, as an experienced performer might attest, it is not possible to directly control the lengths and timing of all notes at all times. We do not think in terms of strings of individual notes. Rather, we chunk groups of notes together into motives, gestures, and phrases. The micro-timing of notes within gestures is something that comes about from years of experience and hours of practice,

[1] The quote does not stem directly from Bach, but from an anecdote, dating later than 1776, by Johann Friedrich Köhler. See Hans T. David, Arthur Mendel, and Christoph Wolff, eds., *The New Bach Reader* (New York: W. W. Norton, 1998), 412.

but is hardly a conscious process executed during performance. In other words, we don't merely hit the right keys at the right time, but rather direct actions in our hands and arms to shape music at a variety of conceptual levels: from ingrained note-to-note micro-timing, to gestures and phrases associated with metaphorical shapes and forces, to the larger structural architecture of the work. And these actions do not even begin to address the potential for control over key velocity and pipe speech apparent to varying degrees in mechanical action organs. So, what does it mean to master the art of keyboard performance? If it is more than merely directing the correct fingers to play the correct keys at the correct time, how can we begin to untangle the rich cognitive web weaving together our control over directed kinesthetic activity, the physical and tonal affordances of a keyboard instrument, and our multi-level conceptions of musical shape, structure, and expression?[2] The field of empirical research into this question has been termed "keyboard psychohaptics." Though the questions it addresses are old and the multi-disciplinary lines of intersecting research are substantial and well established, the field of keyboard psychohaptics is relatively new and holds promise for advancing our empirical understanding of the art of keyboard performance. This essay will present the recent emergence of keyboard psychohaptics as a defined field of research, discuss preliminary work in this field, give an overview of intersecting research in music cognition, expression, and performance, and discuss avenues and methodologies for future keyboard psychohaptics research and its potential applications.

Haptics and Psychohaptics

In February 2009, the University of Rochester (New York) hosted a three-day symposium titled, "Haptics in Music: Key Touch Characteristics in Organ Action." The gathering was initiated by Hans Davidsson, then Professor of Organ at the Eastman School of Music, and Jack Mottley, Associate Professor of Computer and Electrical Engineering and Biomedical Engineering at the Hajim School of Engineering and Applied Sciences. The multidisciplinary symposium featured presentations and discussions addressing key touch and organ actions by experts in the fields of pipe organ construction and design (John Brombaugh, Steve Dieck, Paul Fritts, and Munetaka Yokota), research into keyboard actions (Anne Acker, Carl-Johan Bergsten, Stephen Birkett, Mendel Kleiner, Joel Speerstra, and Alan Woolley), and keyboard performance (Davidsson, Mottley, and Speerstra). Topics

[2] Throughout this paper I use the term "kinesthetics" to refer collectively to both the fine motor control of the hand and fingers as well as the larger motions of the arm and body.

of discussion included the materials and design of actions based on historical models, how to define and model the physical parameters of an action, techniques to quantifiably characterize the actions of specific instruments, and to what degree actions influence performance. There was much discussion around Woolley's research which found that organists cannot possibly control the opening of the pallet from the key, and thus cannot affect the transient speech of a pipe—a finding which runs contrary to the collective wisdom of many organ builders and first-hand experiences of performers on historic organs.[3]

While Woolley's research results were indisputable, at least with regards to the modern, albeit historically inspired, actions of the three organs measured in his study—an Ahrend, a Lammermuir, and a Hill, Norman, and Beard—questions remained. Do these results hold for heavier historic organ actions? To what degree does an organist's control over key/pallet motion versus control over key onset timing convey musical expression? How do our physical gestures and actions at the keyboard shape our control over these parameters? Such questions offered topics for discussion at subsequent organ haptics symposia in Sweden (GOArt International Organ Academy, 2009), Rochester (EROI Festival, 2009 and 2010), and Ithaca (Cornell University, 2011). My 2009 papers at GOArt and EROI sought to problematize some of these issues. Through the use of a "feedback loop" metaphor connecting our cognition of musical structure and expression with kinesthetic action and aural perception, I sought to link issues of keyboard haptics with the kinesthetics of performance, all mediated by our physically grounded cognition and conceptualizations of music.[4] Our haptic interactions with the instrument are inexorably linked with our conceptions of musical gesture, structure, and even performance practice. Regarding the latter, in the context of baroque *figuren* and clavichord technique, Joel Speerstra has demonstrated that for a meaningful understanding of baroque keyboard aesthetics, one cannot separate the rhetorical figure from the physical gesture at the keyboard.[5] Consequently, one cannot separate physical gesture at the keyboard from the resulting musical rhetoric. Together, our cognitive models of musical structure, motion, and meaning form a feedback loop with our directed kinesthetic action, constrained

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[3] Alan Woolley, "Can the Organist Control the Movement of the Pallet in a Mechanical Action?" *Journal of American Organ Building* 21, no. 4 (December 2006): 4–8.

[4] Randall Harlow, "Haptic Technology for Organ Performance: Reimagining the Reciprocal Relationship between the Kinesthetic and Aural Domains" (Göteborg International Organ Academy, Göteborg, Sweden, August, 2009).

[5] Joel Speerstra, *Bach and the Pedal Clavichord: an Organist's Guide* (Rochester, NY: University of Rochester Press, 2004).

by the haptic properties of the instrument at hand. Though the workings of this feedback loop need elucidation, the metaphor provides us with a means to theorize at a level beyond basic haptics, linking the discussions started at the Rochester symposium with scientifically established topics in music cognition. During a panel discussion at the GOArt conference, Mendel Kleiner, Professor of Applied Acoustics at Chalmers University of Technology, suggested the term "psychohaptics" for the field of research linking kinesthetics and touch with its underlying psychology. Unbeknownst at the time, the term had already been in use for medical research studying the effects of touch on patient psychology and physical recovery. In a sense our use of the term, and my use of the more focused term, keyboard psychohaptics, reverses this paradigm, driving the feedback loop in the other direction, from the mind to the act of touch. While a goal of keyboard haptics research, emerging from the first Rochester conference, might be to develop a comprehensive "characterization" of the instrument action, the goal of keyboard psychohaptics research could be said to be a comprehensive characterization of the keyboard performer.[6]

Initial Empirical Research

Woolley's experiments up to 2009 had effectively measured a performer's actions under laboratory conditions, asking the organist to play one key repeatedly and attempt to control the opening speed of the pallet. As had been suggested in the 2009 conferences, Woolley devised a new series of experiments, this time on organs considered to offer substantial transient control, measuring the performer in his or her "natural habitat" and using realistic musical examples. A set of experiments on the North German organ in Örgryte New Church in Göteborg measured the key motion and pressure in the key channel while Joel Speerstra performed a variety of baroque musical rhetorical figures. The results show some variation in key motion and wind pressure between diverse technical approaches. The key motions in Speerstra's performances of rhetorical figures tended to group into two categories: slow anticipatory key motion with delayed onset, and fast continuous key motion.[7] Similarly, wind pressure profiles grouped

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6 Randall Harlow, "The Psychohaptics of Organ Performance: Toward a Comprehensive Characterization of the Organist" (Festival of the Eastman Rochester Organ Initiative, Rochester, NY, October, 2009).

7 Alan Woolley, "Mechanical Pipe Organ Actions and Why Expression is Achieved with Rhythmic Variation Rather than Transient Control," in *Proceedings of the International Symposium on Music Acoustics 2010* (Sydney: Australian Acoustical Society, 2010), 4.

into two corresponding categories: a slow increase with immediate stabilization, and rapid increase followed by pressure oscillations.

Later experiments using different performers on the GOArt-Yokota Casparini copy organ in Christ Church, Rochester, showed similar results, though with less distinct grouping patterns.[8] Though Woolley did not perform a detailed spectral analysis of the resulting pipe speech on the Örgryte and Christ Church organs, his preliminary results indicated potential for variation in transient speech. Furthermore, they demonstrated that performers can aurally distinguish diverse key touch styles, though he suggested that pronounced action noise may account for this perception. Woolley found the clearest evidence for transient speech control on the Italian baroque organ in the Memorial Art Gallery, Rochester. On this instrument, a fast attack clearly results in pipe speech initially at the octave partial, whereas a slow attack generates speech at the fundamental.[9] Woolley also documented slight delays in key onset correlating to the slow key motion groupings at Örgryte and Christ Church. He hypothesized that these variations may be due to anticipatory finger motion on the key, resting against the spring resistance of the action.[10]

From a psychohaptics perspective, what is interesting about Woolley's later results is how the performers vary the key motion, tone onset timing, and possibly transient speech without focusing control over the specific finger in question. Rather, the key and finger variations resulted from context within varied musical rhetorical figures, as part of larger kinesthetic gestural action. The heavy, inertia-laden actions of the Örgryte and Christ Church organs presented specific haptic affordances with which the performer could translate physical gesture into aural shaping, both spectrally and temporally, illustrating the cognitive-aural-kinesthetic feedback loop model of keyboard psychohaptics.

In 2010, concurrently with Woolley's later experiments, Jack Mottley and I devised a very different experiment on the Rochester Christ Church organ to gain further insight into what parameters of the organ action and sound the performer can effectively control, and how these parameters are controlled in the context of musical performance. In order to measure transient pipe speech and note length, we set up a microphone at the mouth of the façade 8' Principal pipe corresponding to the key in question (Figure 1).

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8 Alan Woolley, "How Mechanical Pipe Organ Actions Work Against Transient Control," in *Proceedings of the Acoustics 2012 Nantes Conference* (Nantes, France: 2012), 1979.

9 Ibid., 1980.

10 Woolley, "Mechanical Pipe Organ Actions," 6.

Figure 1 *Lobar microphone focused on Principal 8'.*

Eastman School of Music organ faculty and doctoral student subjects were asked to perform a series of musical examples which present a single key/pipe in question in a wide variety of musical and gestural contexts indicative of German baroque *figuren*.[11] Subjects were unaware of the nature of the experiment and the fact that measurements were being collected from one specific key and pipe. They were simply instructed to perform the examples as musically as possible, shaping the musical gestures as they would baroque rhetorical figures. In the

[11] It should be explained that the pitches used did not fit common baroque melodic and harmonic paradigms. Rather, in order to isolate the pipe being measured, all other notes in the musical examples had to be drawn from pipes on the opposite side of the organ case. In short, the examples conform to "whole-tone plus one" pitch space.

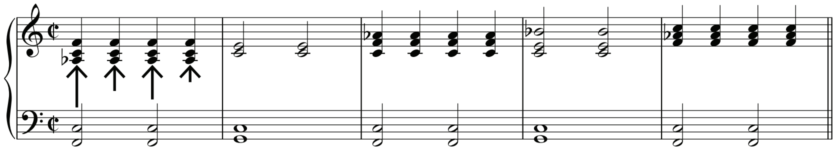

Figure 2 *The key f¹ in repeated chords.*

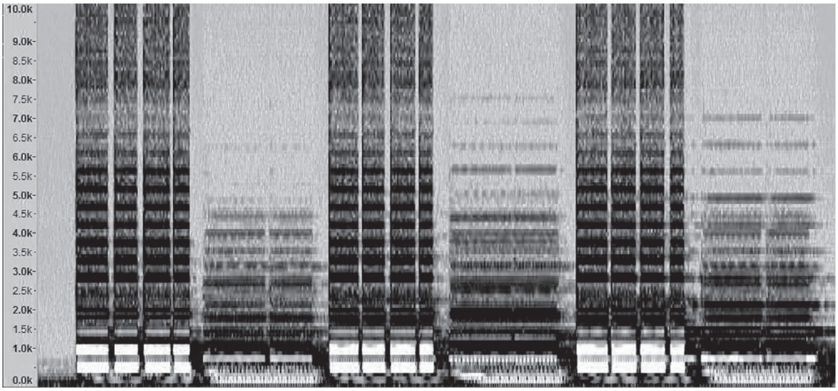

Figure 3 *Note lengths of f¹ corresponding to Figure 2.*

first musical example, subjects played a series of chords, featuring the note in question (f¹) in fingers five, three, and one, respectively (Figure 2).

Arrows are drawn to length according to the expected hierarchy of strong versus weak beats. In performance, the relative note lengths consistently fulfilled the expectations represented by the arrows (Figure 3). The fourth musical example presents a chain of *transitus* figures such that the pipe being measured appears in all rhythmic positions of the four-note group (Figure 4). Even though the notes being measured were not adjacent, being a part of three separate musical and physical gestures, their relative note lengths again consistently fulfilled the expectations represented by the arrows.

It is important to note that in Figures 4 and 5 the gestures each use the same fingering with only slight variations in natural versus sharp note position within the hand. This begs the question, would we find the same note-length consistency if the note appears in different gestural contexts? Another musical example features the note F again in each hierarchical rhythmic position, but this time among a variety of gestures (Figure 6). In performance, the pitch lengths did not fulfill expectations. While the first and second notes held their respective positions in the hierarchy, the fourth note was longer than the third, contrary to

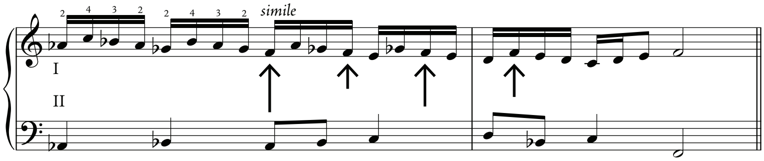

***Figure 4** The key f^1 in a* transitus *chain.*

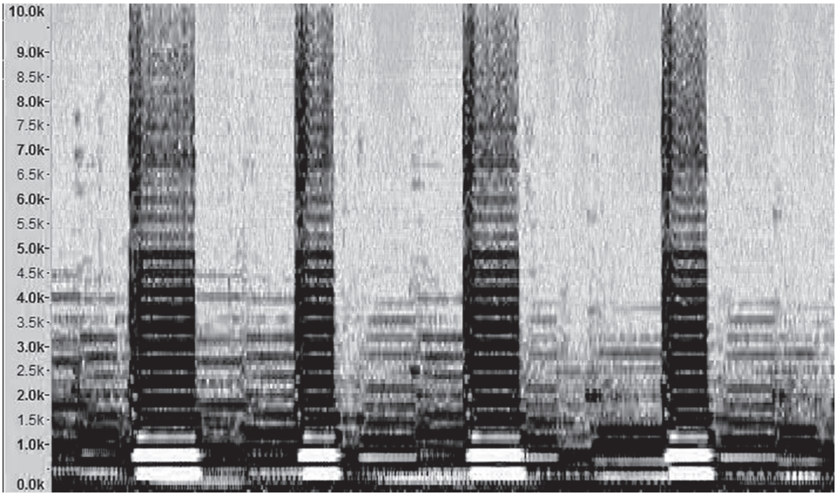

***Figure 5** Note lengths of f^1 corresponding to Figure 4.*

its position at the bottom of the hierarchy (Figure 7). This result was consistent among most subjects.

This discrepancy might be attributed to the fact that the fourth note was played with the thumb, necessitating a shift in weight and hand position which may overemphasize this particular pitch. Should one wish to rectify this situation and secure the fourth note's proper place in the note-length hierarchy, one could use the index finger, followed by a position shift to finger three or four on the following E. On the other hand, perhaps performers consistently emphasize this particular note within such a falling gesture. One could conceivably devise a similar musical example wherein the note on the fourth sixteenth occurs on a sharp, necessitating a finger other than the thumb. Would the note regain its place in the hierarchy, or would it remain strong and thus confirm note length primacy within this category of gesture? More empirical research would help clarify these and similar questions. One additional example illustrates further subjugation of note length hierarchical expectation as the result of gestural circumstance. This musical example features repeated notes in various gestural contexts (Figure 8).

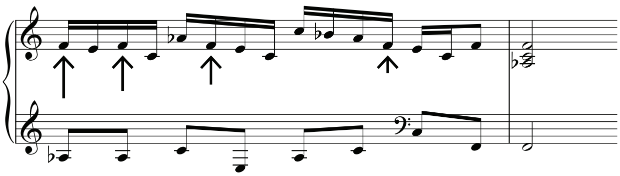

__Figure 6__ The key f^1 in all positions, among diverse gestures.

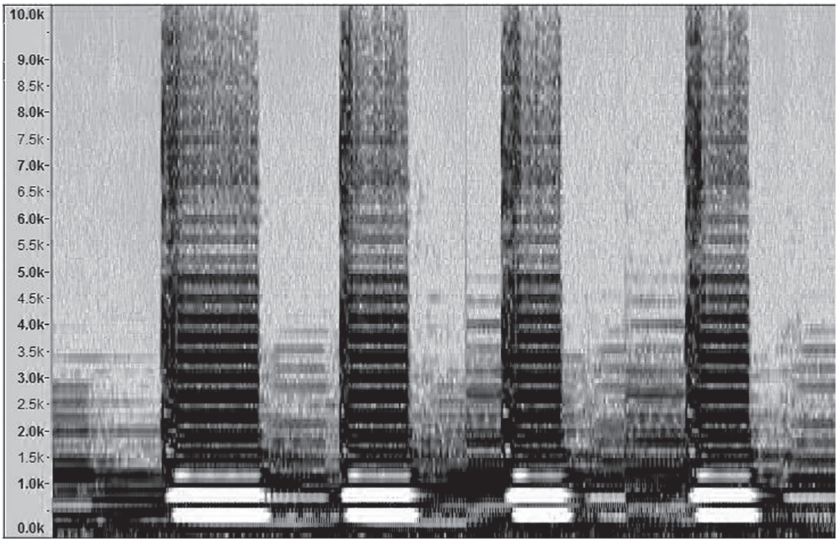

__Figure 7__ Note lengths of f^1 corresponding to Figure 6.

The arrows show f^1 at the same hierarchical rhythmic position within three different gestures: first as the beginning of a fourth ascent, second as the middle of a descending gesture, and third as the beginning of a descending fifth. Note that the F in each case could be played with the same finger, and was by most subjects. In performance these hierarchically identical pitches elicited widely differing note lengths (Figure 9).

The examples illustrate the complex dynamics of note length relative to metric structure and musical and physical gesture. Regarding transient pipe speech, the results are inconclusive. More complex spectral analysis is warranted, but initial analysis does seem to support the aural and haptic feedback related by the subjects. When asked to play one pitch repeatedly and "vary the touch from one extreme to the other" (we purposely did not define "touch" or "extreme"), subjects reported perceiving pipe speech variation on key releases at the "soft" or "slow" extremes. Glancing at four progressively slower key releases filtered

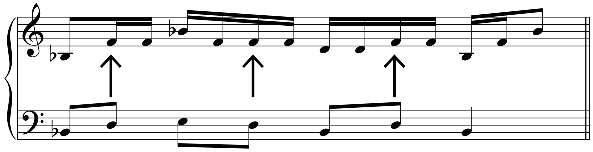

Figure 8 *The key f^1 as a repeated pitch in various contexts.*

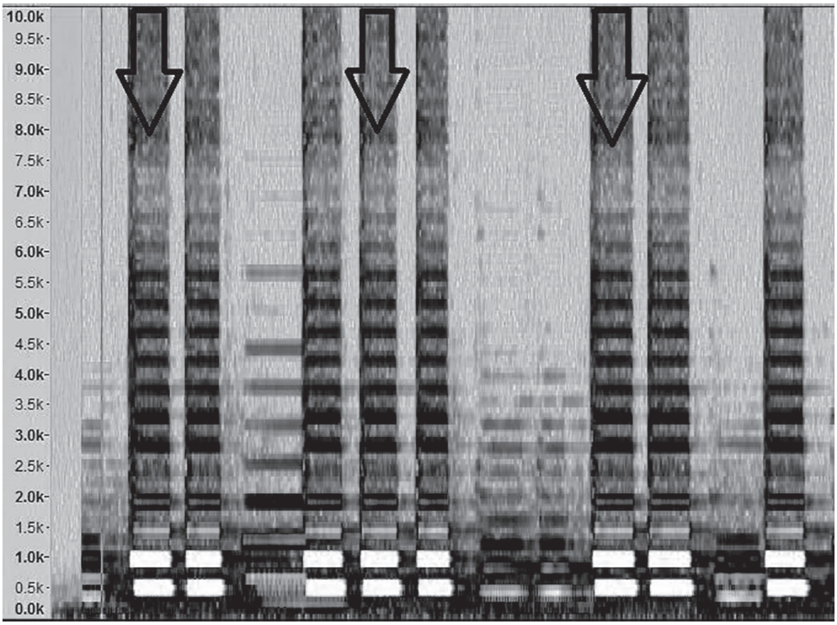

Figure 9 *Note lengths of f^1 corresponding to Figure 8.*

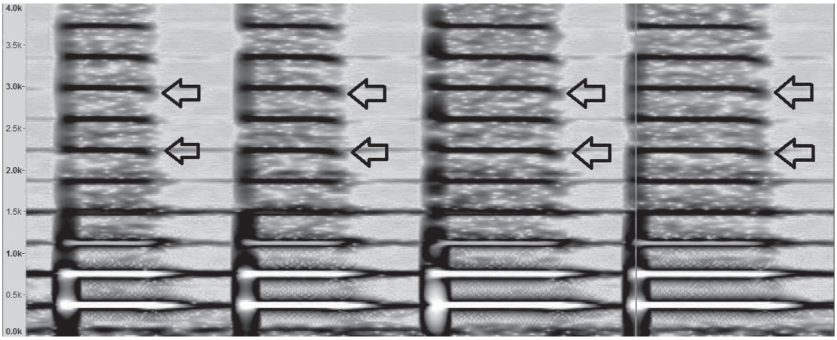

Figure 10 *Increasing pitch instability corresponding to slower key release.*

through a Fast Fourier Transform performed in Audacity, we see a corresponding progressive sinking of pitch and increase in instability among the higher partials, corroborating the subjects' aural perceptions (Figure 10).

It must be emphasized that this represents an informal and preliminary study, intended to test the methodology and data acquisition techniques necessary for more comprehensive empirical keyboard psychohaptics research. A more thorough study would feature a larger pool of subjects, formal statistical analyses of note-length deviations, and quantifiable spectral analyses of transient speech.

Multidisciplinary Intersections

The above studies illuminate some intriguing correlations between aspects of keyboard action, musical gesture, and the kinesthetics of performance, even though more sophisticated theorizing of the psychohaptics of keyboard performance must be founded upon greater scientific understanding of each of these aspects. Fortunately, the scientific and theoretical study of music cognition, expression, and the kinesthetics of performance has grown exponentially in the last half century. Today, psychologists, cognitive scientists, and music theorists are engaged in vast swaths of research which intersect and may inform the field of keyboard psychohaptics. While an exhaustive presentation of recent research into music cognition, perception, and performance is well beyond the scope of this paper, this next section will present some findings from recent empirical research and discuss their pertinence to this field.

The modern empirical study of music perception and cognition, emotion and meaning, and expressive performance can be traced back to two books published in the 1950s: Leonard B. Meyer's *Emotion and Meaning in Music* (1956) and Robert Francès's *La perception de la musique* (1958). Meyer and Francès were among the first to apply theories of perception and cognition drawn from the field of psychology to the discipline of music theory. Going beyond analyzing meaning through external cultural references and historicism, Meyer was interested in how we perceive meaning from music as a closed system, emerging from within the musical structure itself.[12] In the following decades, music theorists, psychologists, and cognitive scientists sought new means to formally analyze these more ineffable aspects in a musical composition, those which might otherwise be considered "beyond analysis." Robert Hatten applied the semiotic theories of Charles Sanders Peirce, grounded in research in sensory perception

[12] Leonard B. Meyer, *Emotion and Meaning in Music* (Chicago: University of Chicago Press, 1956).

and cognitive theories of embodied mind, to formalize the layers of signification and meaning within a musical work, as well as identify the semiotic constraints on musical interpretation. Psychologist Carol Krumhansl established new means of applying empirical techniques from cognitive psychology to the study of the perception of musical structure and organization. By finding common ground among music theory and cognitive psychology, one can bridge the gap between these respective humanistic and scientific disciplines, and explore how one can inform the other.[13] Other publications from the past fifteen years have collected the results of empirical research from across diverse disciplines to project a deeper understanding of music from the perspectives of embodied mind and conceptual metaphor; ecological psychology; the biological, psychological, and cultural manifestations of gesture; probabilistic modeling of performance; the psychology of anticipation and musical meaning; and the perception and expression of emotion through music from the perspectives of psychology, neuroscience, anthropology, sociology, and cognitive linguistics.[14]

While these large-scale works present broad theoretical frameworks, which

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[13] Edward T. Cone, "Beyond Analysis," *Perspectives of New Music* 6, no. 1 (1967): 33–51, also: Robert S. Hatten, "A New Frontier for Music Theorists," *Intégral* 14/15 (2000/2001): 68–72; Robert S. Hatten, *Musical Meaning in Beethoven: Markedness, Correlation, and Interpretation* (Bloomington: Indiana University Press, 1994); Robert S. Hatten, "Response to Peter Burkholder," *The Journal of Musicology* 11, no. 1 (Winter 1993): 24–31; Carol L. Krumhansl, "Perceiving Tonal Structure in Music: The complex mental activity by which listeners distinguish subtle relations among tones, chords, and keys in Western tonal music offers new territory for cognitive psychology," *American Scientist* 73, no. 4 (July–August 1985): 371–78; Eugene Narmour, "Our Varying Histories and Future Potential: Models and Maps in Science, the Humanities, and in Music Theory," *Music Perception: An Interdisciplinary Journal* 29, no. 1 (September 2011): 1–21; and Carol L. Krumhansl, "Music Psychology and Music Theory: Problems and Prospects," *Music Theory Spectrum* 17, no. 1 (Spring 1995): 53–80.

[14] Naomi Cumming, *The Sonic Self: Musical Subjectivity and Signification* (Bloomington: Indiana University Press, 2000); Lawrence M. Zbikowski, *Conceptualizing Music: Cognitive Structure, Theory, and Analysis* (Oxford: Oxford University Press, 2005); Steve Larson, *Musical Forces: Musical Meaning and Interpretation* (Bloomington: Indiana University Press, 2012); Eric F. Clarke, *Ways of Listening: an Ecological Approach to the Perception of Musical Meaning* (Oxford and New York: Oxford University Press, 2005); Robert S. Hatten, *Interpreting Musical Gestures, Topics, and Tropes: Mozart, Beethoven, Schubert* (Bloomington: Indiana University Press, 2004); David Temperley, *Music and Probability* (Cambridge, MA: MIT Press, 2007); David Huron, *Sweet Anticipation: Music and Psychology of Expectation* (Cambridge, MA: MIT Press, 2006); Daniel J. Levitin, *This is Your Brain on Music: The Science of a Human Obsession* (New York: Dutton, 2006); Patrik N. Juslin and John A. Sloboda, eds., *Music and Emotion: Theory and Research* (Oxford: Oxford University Press, 2001); W. Jay Dowling, review of Patrik N. Juslin and John A. Sloboda, eds., *Handbook of Music and Emotion*, *Music Perception: An Interdisciplinary Journal* 29, no. 3 (February 2012): 319–21; and Lawrence M. Zbikowski, "Music, Language, and What Falls in Between," *Ethnomusicology* 56, no. 1 (Winter 2012): 125–31.

may serve as models for future theories of keyboard psychohaptics, a closer look at a number of focused studies offers immediate insight into the cognitive-aural-kinesthetic feedback loop of keyboard performance described earlier.

One question that has intrigued music theorists and philosophers for centuries is: how do we perceive organized sound as meaningful expression? Are there innate temperaments and meanings in certain tunings and scales that are grounded in our physiology, as the Greeks postulated? Does music function as a language, with a learned syntax and grammar for semantic expression? Is music intuited as a series of internal visual representations, as moving pictures in time? A vast body of research has emerged examining the ways listeners perceive and interpret musical sound. To a great extent, music cognition is shaped by the metaphorical mapping of physical and kinesthetic motion, both through internal "conceptual metaphor" and external gesture. We not only speak of music as a complex interaction of metaphorical forces, rising and falling, pulling and pushing, overcoming and releasing; we literally *feel* these forces and gestures activating the same parts of the brain as when we encounter them in the physical world. Spitzer documents the historical use of metaphor in the human understanding and description of music. Neurobiological mechanisms have been proposed to account for the sense of motion in music from perspectives of both dynamic force and gesture. Marc Leman and Luiz Naveda demonstrate how dance gestures are embodied in musical cues, while Carol Krumhansl examines parallels between music and dance in the mapping of structure and emotion. Rolf Godøy examines spontaneous hand gestures to gain insight into motormimetic cognition: the theory that motor imagery runs in parallel with listening to or imagining musical sound. Subjects were asked to make spontaneous hand gestures or draw gestures on paper. Godøy found that hand gestures have a "privileged role in motormimetic cognition of musical sound," and that hand gestures "trace the *geometry* (i.e., elements such as pitch contour, pitch spread, rhythmic patterns, textures, timbral features), as well as convey sensations of *effort* of musical sound."[15]

[15] Zbikowski, *Conceptualizing Music*; Larson, *Musical Forces*; Michael Spitzer, *Metaphor and Musical Thought* (Chicago: University of Chicago Press, 2004); Neil P. McAngus Todd, "Motion in Music: A Neurobiological Perspective," *Music Perception: An Interdisciplinary Journal* 17, no. 1 (Fall 1999): 115–26; Marc Leman and Luiz Naveda, "Basic Gestures as Spatiotemporal Reference Frames for Repetitive Dance/Music Patterns in Samba and Charleston," *Music Perception: An Interdisciplinary Journal* 28, no. 1 (September 2010): 71–91; Carol L. Krumhansl, "Music: A Link Between Cognition and Emotion," *Current Directions in Psychological Science* 11, no. 2 (April 2002): 45–50; and Rolf Inge Godøy, "Geometry and Effort in Gestural Renderings of Musical Sound," in Miguel Dias et al., eds., *Gesture-Based Human-Computer Interaction and Simulation*, 205–15 (Berlin: Springer, 2009).

Other studies more directly link musical gesture with the expression of emotion. Sofia Dahl and Anders Friberg asked subjects to rate the emotional intentions of performers on marimba, saxophone, and bassoon. Subjects were provided full and partial views of the performers. Though the specific gestures differed greatly between the performers, on account of the varied geometries of the instruments, Sad was consistently associated with slow and smooth motion, Anger with jerky movements, and Happy with broad, fast movements. Additionally, motion of the head proved important only in the expression of Sad. Schacher and Stoecklin demonstrate how inertia within dance gestures is a greater carrier of emotion than absolute spatial position. The importance of gesture in cognition as a "kinematic capturing device" has even been demonstrated in relation to mathematical diagrams. Several researchers have developed sophisticated analytical means to measure and analyze physical gesture using mathematical topology, applying analyses of the geometry of gesture to collaborative improvisation.[16] Others have developed sophisticated computer models to generate simulations of parameters of expressive performance. Some scholars acknowledge the value of models, but warn that such models can only be meaningfully evaluated in tandem with empirical performance data from human subjects. Phillips-Silver, Aktipis, and Bryant offer an evolutionary account for what appears to be our hardwired propensity for conveying meaning through embodied physical and metaphorical gesture.[17]

Other research into music performance shows how our metaphorical-kinesthetic conceptualizations of music and its means for expression shape its creation and practice. A study by Bruno Repp sought to define the constraints

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[16] Sofia Dahl and Anders Friberg, "Visual Perception of Expressiveness in Musicians' Body Movements," *Music Perception: An Interdisciplinary Journal*, 24, no. 5 (June 2007): 433–54; Jan C. Schacher and Angela Stoecklin, "Traces—Body, Motion and Sound," *Proceedings of the 2011 International Conference on New Interfaces for Musical Expression*, (Oslo, Norway), 155-60; Elizabeth de Freitas and Nathalie Sinclair, "Diagram, gesture, agency: Theorizing embodiment in the mathematics classroom," *Educational Studies in Mathematics* 80, nos. 1–2 (May 2012): 133–52; Luiz Neveda and Marc Leman, "The Spatiotemporal Representation of Dance and Music Gestures using Topological Gesture Analysis (TGA)," *Music Perception: An Interdisciplinary Journal* 28, no. 1 (September 2010): 93–111; and Guerino Mazzola, *Flow, Gesture, and Spaces in Free Jazz: Towards a Theory of Collaboration* (Berlin: Springer, 2009).

[17] Anders Friberg, "pDM: An Expressive Sequencer with Real-Time Control of the KTH Music-Performance Rules," *Computer Music Journal* 30, no. 1 (Spring 2006): 37–48; Peter Desain, Henkjan Honing, Huub Vanthienen, and Luke Windsor. "Computational Modeling of Music Cognition: Problem or Solution?" *Music Perception: An Interdisciplinary Journal* 16, no. 1 (Fall 1998): 151–66; and Jessica Phillips-Silver, C. Athena Aktipis, and Gregory A. Bryant, "The Ecology of Entrainment: Foundations of Coordinated Rhythmic Movement," *Music Perception: An Interdisciplinary Journal*, 28, no. 1 (September 2010): 3–14.

of expressive timing. Asked to rate the expressive timing of a specific gesture in Schumann's *Träumerei,* trained listeners gave the highest ratings to parabolic temporal shapes,[18] suggesting a certain optimal "energetic shaping through time," to borrow Robert Hatten's general definition of human gesture.[19] While only a certain minority of gestures may have parabolic optimal shapes, Repp suggests that musical gestures could be classified by shape, providing flexible constraints for artistic freedom.[20] Such formalization may provide an empirical anchor for analysis of performance practice through historic recordings. Additionally, it may prove useful for pedagogical purposes. A recent substantial study generated a model to determine the most efficient piano fingerings for any given situation, although without taking into account the possibility of "position fingering," such as when the same finger plays two adjacent or distant notes to convey a specific gesture.[21] Such research into the categories and geometries of keyboard gesture may redefine the "most efficient" fingering not as those which connect pitches with the least physical motion, but rather which lead to the optimal shaping of gesture.

Of course expressive timing is only one parameter of gesture and means for musical expression. How do parameters of dynamics and articulation shape musical expression at the keyboard, and to what degree are they interdependent? A study by Carol Krumhansl examines how dynamic and tempo fluctuations influence the perception of segmentation and the structure of tension and release in a performance of a Mozart piano sonata. As it turns out, dynamics play only a small role. For the most part, "tension is conveyed by the pitch and durational patterns in the music," rather than dynamics.[22] In another study, pianists recognized their own performances months later, even when general tempo and dynamics, both overall and nuanced, were equalized, leaving only

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[18] Bruno Repp, "A Constraint on the Expression Timing of a Melodic Gesture: Evidence from Performance and Aesthetic Judgment," *Music Perception: An Interdisciplinary Journal* 10, no. 2 (Winter 1992): 221–41.

[19] Hatten, *Interpreting Musical Gestures, Topics, and Tropes*.

[20] Repp, "A Constraint on the Expression Timing of a Melodic Gesture," 236.

[21] Richard Parncutt et al., "An Ergonomic Model of Keyboard Fingering for Melodic Fragments," *Music Perception: An Interdisciplinary Journal* 14, no. 4 (Summer 1997): 341–82; Pieter J. Jacobs, "Refinements to the Ergonomic Model for Keyboard Fingering of Parncutt, Sloboda, Clarke, Raekallio, and Desain," *Music Perception: An Interdisciplinary Journal* 18, no. 4 (Summer 2001): 505–11.

[22] Carol L. Krumhansl, "A Perceptual Analysis of Mozart's Piano Sonata K. 282: Segmentation, Tension, and Musical Ideas," *Music Perception: An Interdisciplinary Journal* 13, no. 3 (Spring 1996): 401–32.

expressive timing and articulation. Even performances on silent keyboards were identifiable (MIDI data was recorded for a reconstructed "performance" later). Repp and Knoblich suggest this result supports an "action-identity hypothesis," strongly linking auditory perception with motor output.[23] This link between the auditory perception and motor control segment of the psychohaptic feedback loop is further illuminated by a later study from the same researchers. When experienced and novice pianists were asked to play a sequence of tones on an electric keyboard and computer keyboard, experienced pianists were far more likely than novices to falsely report the direction of pitch motion when inconsistent with the motor gesture.[24] That is, embodied motor action and gesture can override experienced keyboard players' perception of the resulting sound. But how does music perception shape motor control? In another study by Bruno Repp, skilled pianists were able to reproduce patterns of expressive timing and dynamic variation from expert recordings, demonstrating that performers possess individual cognitive schemas for expression that affect perception, memory, and reproduction.[25] Repp's study also illustrates that dynamic variation greatly influences variation in timing, whereas variation in timing does not induce dynamic variation. This last finding has deep implications for organists, who have no control over dynamic variation and rely on expressive timing: perhaps attempting to vary dynamics with arm weight while playing the organ will result in greater control over expressive timing through gestural shaping.

Further studies examine the relationship between tempo, timing, and motor action. Meyer and Palmer tested how quickly subjects could perform a test example modified from the practice example through meter, rhythm, or motor movement, illuminating distinctions between temporal and motor representations of performance.[26] Repp demonstrates how the dimensions of tempo and expressive timing are interdependent. Both listeners and performers preferred reduced variation in expressive timing as tempo increased, and more variation at

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[23] Bruno Repp and Günther Knoblich, "Perceiving Action Identity: How Pianists Recognize Their Own Performances," *Psychological Science* 15, no. 9 (September 2004): 604–9.

[24] Bruno Repp and Günther Knoblich, "Action Can Affect Auditory Perception," *Psychological Science* 18, no. 1 (January 2007): 6–7.

[25] Bruno Repp, "Pattern Typicality and Dimensional Interactions in Pianists' Imitation of Expressive Timing and Dynamics," *Music Perception: An Interdisciplinary Journal* 18, no. 2 (Winter 2000): 173–211. Also: Caroline Palmer, "Sequence Memory in Music Performance," *Current Directions in Psychological Science* 14, no. 5 (October 2005): 247–50.

[26] Rosalee Meyer and Caroline Palmer, "Temporal and Motor Transfer in Music Performance," *Music Perception: An Interdisciplinary Journal* 21, no. 1 (Fall 2003): 81–104.

slow tempi.[27] Additionally, Repp shows that expectations of variation in expressive timing among listeners are substantially smaller than such variations in practice during performance.[28] Regarding the control of timing during performance on a keyboard instrument, Palmer demonstrates how sensory (haptic) feedback at finger-key contact increases temporal accuracy of performance.[29] Such results confirm anecdotal accounts from some organists that heavier, inertia laden organ actions afford greater control over musical expression. Furthermore, as auditory feedback is reduced, keyboard players increasingly rely on haptic feedback, utilizing higher finger motion to retain synchronization.[30] Modeling note onset and overlap timing from a neuromotor perspective, Jacobs and Bullock bridge the gap between the kinesthetics of performance at the motor level and more abstract performance and pedagogy issues.[31] Such studies serve to further illustrate the cognitive depth of the psychohaptic feedback loop of keyboard performance.

A number of other studies help draw a broader picture of keyboard psychohaptics. Alf Gabrielsson had subjects listen to violin, saxophone and voice performances of "What shall we do with a drunken sailor" according to the following expressions: Happy, Sad, Angry, Tender, Fearful, Solemn, and No Expression. Listeners were able to accurately identify the expressive category. Based on these results, Gabrielsson lists the performance characteristics most successfully associated with each. Zielona Fyk documents the use of "expressive intonation" in violin playing. While keyboard instruments have fixed intonations, one could use a similar approach to study how performers vary expressive timing in different temperaments (for example, playing an elevation toccata on an Italian meantone organ versus an instrument in equal temperament). Manfred Clynes examines our perception of microstructure and its influence on performance choices, while Krumhansl explores the degree to which our perception of musical

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27 Bruno Repp, "Quantitative Effects of Global Tempo on Expressive Timing in Music Performance: Some Perceptual Evidence," *Music Perception: An Interdisciplinary Journal* 13, no. 1 (Fall 1995): 39–57.

28 Bruno Repp, "The Detectability of Local Deviations from a Typical Expressive Timing Pattern," *Music Perception: An Interdisciplinary Journal* 15, no. 3 (Spring 1998): 265–89.

29 Caroline Palmer et al., "Movement-Related Feedback and Temporal Accuracy in Clarinet Performance," *Music Perception: An Interdisciplinary Journal* 26, no. 5 (June 2009): 439–49.

30 Werner Goebl and Caroline Palmer, "Synchronization of Timing and Motion Among Performing Musicians," *Music Perception: An Interdisciplinary Journal* 26, no. 5 (June 2009): 427–38.

31 Pieter J. Jacobs and Daniel Bullock, "A Two-Process Model for Control of Legato Articulation Across a Wide Range of Tempos During Piano Performance," *Music Perception: An Interdisciplinary Journal* 16, no. 2 (Winter 1998): 169–99.

structure is innate.[32] Caroline Palmer shows how editorial markings in different editions affect performance, including global timing and performer-specific patterns (cadence timing and use of pedal, ornaments).[33] One study particularly relevant to organists shows how pitch and timing have "separable effects on musical performance."[34] Subjects played an electronic keyboard with various degrees of pitch and timing feedback, or no feedback at all. Lack of feedback showed little impairment, whereas delay showed much. Pitch alteration showed little impairment, and when combined with delay lessened the impairment from delay. Highben and Palmer demonstrate how an accurate "auditory image" is critical for performance.[35] Pianists with strong aural skills were least affected by lack of auditory feedback. They argue the importance of strong aural skills for creating robust auditory images.

A number of researchers address the purely cognitive segment of the psycho-haptic feedback loop. Eugene Narmour theorizes how listeners construct rules which guide expectation, and how denial of expectation is used as a compositional strategy for musical affect.[36] John Sloboda demonstrates that while perception of emotionality among listeners corresponds well with specifically intended emotionality among performers, increases in emotionality are strongly correlated with high degrees of local deviation of performance characteristics from the average.[37] Palmer and Meyer postulate that with advanced performers, conceptual

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[32] Alf Gabrielsson, "Studying Emotional Expression in Music Performance," *Bulletin of the Council for Research in Music Education* 141 (Summer 1999): 47–53; Zielona Fyk, *Melodic Intonation, Psychoacoustics, and the Violin* (Gora, Poland: Organon, 1995); Manfred Clynes, "What a musician can learn about music performance from newly discovered microstructure principles (P.M. and P.A.S.)," in *Action and Perception in Rhythm and Music,* ed. Alf Gabrielsson (Stockholm: Royal Swedish Academy of Music, 1987), 201–33. Also: Bruno Repp, "Composers' Pulses: Science or Art?" *Music Perception: An Interdisciplinary Journal* 7, no. 4 (Summer 1990): 423–34; and Carol L. Krumhansl, "Infants' Perception of Phrase Structure in Music," *Psychological Science* 1, no. 1 (January 1990): 70–73.

[33] Caroline Palmer, "Anatomy of a Performance: Sources of Musical Expression," *Music Perception: An Interdisciplinary Journal* 13, no. 3 (Spring 1996): 433–53.

[34] Steven A. Finney, "Auditory Feedback and Musical Keyboard Performance," *Music Perception: An Interdisciplinary Journal* 15, no. 2 (Winter 1997): 170.

[35] Zebulon Highben and Caroline Palmer, "Effects of Auditory and Motor Mental Practice in Memorized Piano Performance," *Bulletin of the Council for Research in Music Education* 159 (Winter 2004): 58–65.

[36] Eugene Narmour, "Music Expectation by Cognitive Rule-Mapping," *Music Perception: An Interdisciplinary Journal* 17, no. 3 (Spring 2000): 329–98.

[37] John A. Sloboda, "Tracking Performance Correlates of Changes in Perceived Intensity of Emotion During Different Interpretations of a Chopin Piano Prelude," *Music Perception: An Interdisciplin-*

plans become independent of and influence new learning more strongly than motor action. Pianists were asked to practice a certain passage, and then play a new passage similar in conceptual dimension, motor skill, or both. Advanced subjects learned the new piece better if it was similar in concept rather than in motor action. Child pianists did better with motor similarity, "indicating that mental plans for behaviors such as music performance become increasingly abstract and decreasingly motoric as skill increases."[38] Julian Hellaby theorizes how an informed listener arranges performance-related categories hierarchically into an "interpretive tower."[39] Finally, Masato Yako describes music as belonging to one of four "language games" according to definitions from Ludwig Wittgenstein, philosophically tying our experience of musical expression to our physical manifestations of these expressions, further underlying the importance of the body in music cognition.[40]

Future Prospects

What does the future hold for keyboard psychohaptics? Informed by past and ongoing intersecting research, future rigorous and focused studies will provide a greater understanding of the psychohaptics of performance. The key word here is "focused." Though we like to talk about broad theories connecting the cognitive and kinesthetic aspects of performance, such as the feedback loop metaphor presented earlier, theories must be built on evidence. When pursuing empirical psychohaptics research, the first challenge will be to break down the broad questions we wish to address into discrete, testable hypotheses. As seen in the studies presented above, it is these types of carefully constructed experiments which provide small windows into the greater depths of the subject. As experimental results are evaluated, verified, and published, we will be able to advance more comprehensive theories.

The above studies illustrate how the field of keyboard psychohaptics, or performance psychohaptics in general, functions as a nexus for multidisciplinary research. As such, experimental study in this field often necessitates collabora-

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ary Journal 19, no. 1 (Fall 2001): 87–120.

38 Caroline Palmer and Rasalee K. Meyer, "Conceptual and Motor Learning in Music Performance," *Psychological Science* 11, no. 1 (January 2000): 63–68.

39 Julian Hellaby, *Reading Musical Interpretation: Case Studies in Solo Piano Performance* (Farnham, UK: Ashgate, 2009).

40 Masato Yako, "Recognition of Music and Beauty by the Language Game," *International Review of the Aesthetics and Sociology of Music* 38, no. 1 (June 2007): 3–21.

tion between scholars of diverse disciplines. Professional performers often do not have the skills necessary to construct sound scientific experiments, nor the necessary statistical expertise to evaluate the results. On the other hand, trained scientists often do not have the years of professional performance experience necessary to ask the right questions and generate meaningful hypotheses. In addition, engineering expertise may be necessary to construct equipment for data acquisition, and historians and theorists in the humanities may be best suited to evaluate experimental goals and results in context. Due to its inherently multidisciplinary methodology, the study of the psychohaptics of performance may yield rich results, informing many fields at once.

I will conclude by pointing out one specific future avenue of psychohaptics research and its potential applications. With the dramatic and ongoing increases in computing power, the analysis of "big data" has been championed as a potentially disruptive force in nearly every imaginable field. How can one collect massive amounts of real-time keyboard performance data, and what might the results of this data hold for keyboard psychohaptics? One answer to the first half of this question may be a "smart" practice room.

Imagine a room equipped with a keyboard instrument and capable of recording and analyzing nearly every facet of performers' actions: high-speed cameras generate three-dimensional plots of the moving body, arms, and fingers; sensors embedded in the keys measure micro-fluctuations in timing, touch force, finger position, and contact area;[41] microphones capture every detail of attack and decay; and discrete sensors record performers' biometrics, all without disturbing the "natural habitat" of the performer, as would be the case in sterile laboratory conditions. Such a room would of course be a researcher's dream, providing the ability to capture nearly every detail of the kinesthetic segment of the psychohaptic feedback loop. Perception and cognition experiments performed in the room would rapidly paint an ever clearer picture of the psychohaptics of keyboard performance.

Furthermore, through the results of such research, the room could be equipped to provide informative feedback to the performer in real time. Using motion analysis techniques similar to those employed by sports researchers, the room could report slouching, tense shoulders, too much or too little arm motion, sinking wrists, or protruding fingers. It could track and chart students' changes in technique and posture over time, or using visual overlays to compare a student's

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[41] Such a sensor was recently developed by Andrew McPherson of Queen Mary University, London, minus the ability to measure key touch force.

hand and arm gestures to those of her teacher. Novel means could be developed to generate real-time isomorphic representations of various parameters of performance. For example, key sensors could map precise timing information directly onto a digital score. The music would turn deeper shades of red or blue as the tempo increases and decreases, respectively, allowing the student to compare her expressive timing with that of her teacher or the practice of a past, historically important artist. The act of devising such representations would itself be a major research project: performance informing research, and research informing performance. The technology for this "smart" practice room exists today, and these ideas and projected applications draw from current research. Such a performance research laboratory could either confirm or upend the folk wisdom common to many performers and schools of pedagogy. An empirically tested, theoretically sophisticated field of keyboard psychohaptics holds the potential to shed light on formerly intangible aspects of keyboard performance, those once considered beyond analysis. In doing so, we will gain a new understanding of the inherently human foundations underlying every act of keyboard performance, an act infinitely richer and more meaningful than merely hitting the right keys as the right time.