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Towards a Cognitive–Scientific Research Program for Improvisation: Theory and an Experiment

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Despite often being conceived as a spontaneous and creative mode of performance, improvisation is predicated on prior knowledge. What characterizes this knowledge, and how is it represented or recalled differently as compared with other modes of music making? Asking about knowledge and trying to distinguish improvisation as a distinct performance process can locate research questions within the theoretical frameworks of cognitive science, but it is not clear how to make such questions experimentally accessible. Differences arising from music–analytical versus cognitive conceptions of improvisation are explored to provide a theoretical framework compatible with experimentation. Experimental research could concern itself with how the embodied interface between performer and instrument, when manipulated, invokes different cognitive processes of music making, helping to describe the cognitive characteristics of various modes of music performance. Here, an experiment is reported that synthesizes previous techniques used to analyze improvisations with experimental strategies from the neuroscientific literature aimed at differentiating performance processes within a given improviser. Jazz pianists improvised monophonically over backing tracks in a familiar and unfamiliar key as well as with their right and left hands. Among other findings, in some of the less familiar performance situations, participants relied more on diatonic pitches and produced more predictable improvisations as measured by entropy and conditional entropy. The nature of the different underlying processes and knowledge at play under these different conditions is explored, and future research directions to better describe them are identified, including incorporating motor theories of perception.

Keywords: improvisation, cognition, musical performance, music analysis

Despite often being considered a creative and spontaneous activity, musical improvisation is predicated on acquired knowledge (Ashley, 2009; Pressing, 1988). Improvisers may be creating something that is new or unplanned according to a particular set of structural–analytic criteria (e.g., the notes are new or the chords were not chosen beforehand), but they also have prior knowledge that enables their music making. How can what improvisers know be characterized? How might the nature or use of such knowledge differ when the same musician is improvising as compared with playing from memory, or when the same improviser plays in different performance contexts? Asking questions about a musician's knowledge can locate the topic of improvisation within the theoretical frameworks of cognitive science, but it is not clear how one might frame these questions so as to make them experimentally accessible. If improvisation is, by its definition, free, how could experimentation help to systematize its processes?

Previous research has approached these questions in few different ways. Many analytical methods have been used to examine transcribed and recorded improvisations to infer properties of their style and the underlying cognition of the processes that created them (e.g., Järvinen, 1995; Järvinen & Toiviainen, 2000; Pfleiderer & Frieler, 2010). These studies provide valuable insight into the processes of improvisation, but could go further by examining improvisations produced in the laboratory under a set of experimentally designed systematically varying conditions. Functional neuroimaging studies have had musicians produce improvisations in the laboratory to assess differences in performance process (memorized performance vs. improvisation) through measuring differences in brain activation (Bengtsson, Csíkszentmihályi, & Ullén, 2007; Berkowitz & Ansari, 2008, 2010; Limb & Braun, 2008), but could go further by not treating improvisation as a single kind of process. These two approaches could be usefully combined to form an experimental program in which improvisations are produced within the laboratory under experimentally varying conditions to reveal differences in process. With the goal to differentiate process from the neuroscience literature and the modes of inference that can identify differences in process through musical structures from the analytical literature, a more developed cognitive–scientific experimental program could access questions

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This article includes an experiment previously described and published in conference proceedings (Goldman, 2012). Additional analyses on the same data set are provided here as well as an expanded discussion and theoretical contextualization.

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about improvisational processes and help describe the nature of its underlying knowledge.

There are thus two goals in this article. The first is to arrive at a set of appropriate cognitive–scientific questions by reframing common conceptions of improvisation from the literature—which often focus on structural and analytical characteristics of improvisation—to a cognitive–scientific conception compatible with experimentation. In-laboratory improvisational experiments do not have an established approach and a somewhat broad theoretical context is thus necessary to construct a set of appropriate questions. Second, based on this reconsideration, an experiment is reported that has participants improvise in the laboratory under a set of varying experimental conditions and uses established analytical techniques to reveal differences in performance process and help describe the cognition of different improvisatory processes.

Reframing Conceptions of Improvisation

This first section presents an overview of how improvisation has been defined in previous theoretical literature. It focuses on a few key features common to many definitions of improvisation and considers whether they are compatible with a cognitive–scientific conception of improvisation. Such reconsideration is necessary to further develop an experimental approach.

The features in the definition of improvisation produced by Nettl et al. (2013) are present in many other definitions and so they serve well the purposes of this discussion:

> The creation of a musical work, or the final form of a musical work, as it is being performed. It may involve the work's immediate composition by its performers, or the elaboration or adjustment of an existing framework, or anything in between. To some extent every performance involves elements of improvisation, although its degree varies according to period and place, and to some extent every improvisation rests on a series of conventions or implicit rules.

There are four features of this definition that I wish to consider: First, the relationship between improvisation and the musical work; second, the notion that this work or composition is created immediately; third, the notion of frameworks, conventions, and rules; and fourth, the notion of "anything in between." My treatment of Nettl's definition is meant to address common themes in discussions of improvisation and is not meant to be a direct response to his particular definition. It is cited merely as a platform from which to launch a discussion of what the important issues of defining improvisation are as far as a cognitive approach is concerned.

Improvisation and the Musical Work

Alperson (1984) raises a useful distinction between two senses of the term "improvisation." One sense is improvisation as the act of improvising, and the other is improvisation as the thing-improvised. Nettl's definition would seem to be concerned with improvisation insofar as it creates an end product rather than focusing on the features of the process. One could interpret "the creation of a musical work" as "the process of creating a musical work," and in this sense, the definition could be read as concerning both process and product. But, why is a musical work mentioned at all? Whether Nettl meant to focus on process or product, a conception of improvisation as creating a musical work raises problems for a cognitive approach.

Nettl is probably using the term "work" as a placeholder to find a word to refer to the content of what is improvised. In this way of thinking, a composer creates a work as well through a different generational process. In fact, improvisations have often been compared with compositions, differing subtly in the process of their creation (e.g., Larson, 2005). To refer to a thing-improvised as a composition or work is to define what is produced in structural terms. The *thing* that is improvised must be defined somehow (with some structural criteria) if one wishes to refer to it as a distinct ontological entity. It is to say that an improvisation, like a composition, has structures that can be identified and described within the context of a theory such as a tonal theory (e.g., Järvinen, 1995), or a Schenkerian theory (e.g., Larson, 1998). This conception of an improvisation as a work might lead to questions about what structures there are and how they work together, as in an analysis of a composition. There is no problem with this in itself—the process of improvisation does produce *something*, and can thus be understood in terms of structures. In fact, analyzing structures can also help infer the performer's process as in the literature mentioned above and the experiment suggested below. One just needs to be careful in choosing an appropriate theoretical approach and concomitant technique of analysis. In other words, which structures does one examine, and why those? One of the goals of a definition of improvisation, presumably, is to distinguish it from other modes of performance. From a slightly different angle, another goal might be to speak to what is different about music that is produced by improvisation as compared with composition. Either way, the analytical technique chosen would need to support a theory aimed at understanding the improviser's performance process and not just to understand structural relationships in themselves. Because there is only a work when viewed after the act of creation, then during the performance, if one wants to distinguish improvisation from the act of a rehearsed performance or the act of composing, the question of process is central. What is different about the *way* the music is produced? One can develop ways to infer this from examining the work, but as far as a definition of improvisation is concerned, the focus should be on the "creation" and not the "work."

Immediacy

The second element in Nettl's definition to consider is immediacy. This could be construed in two senses. In the first sense, it could refer to music produced "in real time" (e.g., Ashley, 2009). Time is said to place pressures on an improviser with all of the listening, monitoring, synthesizing, and moving that has to be done online, and thus places constraints on how knowledge can be recalled and executed during performance. A composer can take as much time as necessary to work out a retrograde inversion of a tone row while an improviser must calculate more quickly in order to play it, and thus might tend to play different musical ideas that are able to be generated in real time. Sometimes a compose-able idea is not an improvise-able idea even if coming from the same musician.

Notably, needing to distinguish improvisation from composition in terms of time only becomes an issue when conceiving of a musical product, a work. A musical product is conceived as having a kind of timeline; a composer can jump around on the timeline while creating a work whereas an improviser must progress linearly. Without considering a musical product, however, the consideration of time becomes less important—composing, improvising, and playing from memory, at least in cognitive terms, are all "in real time." What differ are the circumstances of the recall and representations of the musical ideas. What makes some musical knowledge improvise-able? What about the interface between the musician and the instrument enables the improvisatory performance of musical ideas? How is improvise-able musical knowledge represented and recalled and how does that compare to compositionally generated ideas, or the way ideas are recalled during a rehearsed performance? Again, this might be asked structurally: what sorts of structures are present, or more present, in improvisations as compared with compositions, or compared with rehearsed performance, and why it would be *those* structures. For instance, some empirical studies have searched for cues present in improvisatory music that may not be in rehearsed performances (e.g., Lehmann & Kopiez, 2010). Also, what about a particular performer–instrument interface would lead to the prevalence of certain musical structures? The experiment described below attempts to distinguish between different processes of recalling ideas by examining structural differences in improvisations produced under different experimental conditions. Discussions of "real-time" raise important questions about how knowledge is represented and recalled, but to distinguish between modes of musical production and different modes of musical improvisation, it is not *time*, exactly, that is the primary question.

In the second sense, immediate might mean that improvisation is not mediated. However, improvisation is indeed mediated. It is mediated by physical things like the body and instruments, cognitive things like the ways sounds and movements are represented and executed, and social things like group interactions and societal constructs of performance practices. Hogg (2011) describes various aspects of this embodied knowledge. All of these mediated sources of knowledge change what is possible and what is more likely to be played. Nettl is aware of these sources of knowledge considering his reference to constraints and frameworks (discussed below), but the point is that as far as a cognitive approach is concerned, the term "immediate" in terms of time could be refocused to questions of differences in the representation and recall of musical knowledge, and its use in the sense of mediation may discourage the examination of important sources of knowledge.

Frameworks and Rules

The constraints placed on music by frameworks or rules is well noted (e.g., Ashley, 2009), and is present in Nettl's definition. These frameworks are understood to be constraints on what an improviser is able to play or chooses to play. It might be something like a chord progression that limits the notes an improviser can play, or a more abstract rule like to trade four-bar sections of a solo with another improviser. It could also be cultural norms that are gradually acquired in training (see Pressing, 1998, p. 57).

The idea of musical constraints must be carefully considered if it is to be made compatible with a cognitive–scientific approach. First, it is useful to distinguish between music–theoretical constraints and cognitive constraints. Music–theoretical constraints include patterns that arise from the analysis of improvisations. It might be noted that improvisations in a particular style emphasize certain scale degrees more than others. It could show that a certain performance must conform to a particular harmonic progression or set of scales. Such constraints could group styles on the basis of these features and make predictions about which formal structures will occur in which performance contexts. Johnson-Laird (1991) takes these kinds of constraints to computationally model improvisation. He points out, however, in the tradition of Marr's (1982) computational account of vision, that a computational implementation may recreate *what* a human produces, but will not necessarily explain *how* it is produced. Further, it should be noted that music–theoretical constraints are also sometimes explicitly known by the improvisers. Berliner (1994), for example, examines how improvisers describe their own processes of playing on existing structures (frameworks) while improvising (p. 222). Improvisers know they are using chord progressions, for instance. On being asked, improvisers can adopt the role of an analyst and describe their own performance in such music–theoretical terms. Similar to Johnson-Laird's methodological limitation, being self-aware of such constraints is not necessarily knowledge of *how* the music is produced.

Generally speaking, the recurrence of music–theoretical patterns (like a particular key's set of pitch classes) only becomes a "constraint" by virtue of the existence of other similar patterns. For example, playing music in C major is "constraining" if one accepts the existence of the alternative possibility of E*b* major. The categories chosen by a particular music theory thus dictate which things can be called constraints. A different music theory could identify different constraints in the same improvisation after it was produced. In this way, music–theoretical constraints are a description of the product after a performance process has been executed and is not necessarily an explanation of that process.

By contrast, one can think of cognitive constraints as a kind of embodied situation arising from the way the mind and body interface with an instrument. In the course of learning to improvise, a musician acquires knowledge of how to create certain sounds with certain movements at an instrument. It could be thought to be constraining in the sense that a 10-fingered human can only play 10-fingered music, that the human brain can only process so quickly, or that a given instrument has a certain physical structure that affords many musical possibilities, but not every musical possibility. The relationship between the brain, body, and instrument creates a situation that requires an improviser to possess a kind of embodied knowledge. Pressing (1998) casts such knowledge in cognitive terms with his ideas of "referents" and the "knowledge base." The ability to play a given music–theoretical structure has cognitive correlates (such as motor programs and auditory images) dependent on the brain, body, and instrument. It may be misleading, however, to think of this kind of embodied knowledge as constraining. The boundaries between these cognitive referents do not necessarily align with music–theoretical boundaries. There may not be a completely distinct referent for C major and E*b* major. Because of this asymmetry, this kind of knowledge arising from the embodied situation between the performer and the instrument is perhaps better characterized as enabling, not constraining. The ability to play in C major does not rely on the ability to play the music–theoretical alternative of E*b* major. The body has to interface with an instrument to do either.

Nothing is constrained by knowing or not knowing how to do the other.

Music–theoretical constraints are a particular description of what is produced; by contrast, embodied knowledge is an attempt to explain how music is enabled and produced by minds, bodies, and instruments. Again, understanding this *how* question may still need to rely in part on considering music–theoretical contexts through making inferences about the presence of certain patterns and structures. With an appropriate theory of which structures are notable and why, however, an understanding of this enabling embodied knowledge may be inferable. This is a goal of the experiment described below.

Everything in Between—Continuum

The final point in Nettl's definition is the notion of "anything in between." The amount of things that are constrained could be said to be varied, leading to ideas of a spectrum of how improvisatory something is. For example, perhaps the melody is fixed but the harmony is not. Some theorists suggest that no performance has everything completely determined and thus all performance is somewhat improvisatory. For example, Gould and Keaton (2000) suggest that because thoughts and intentions do not exactly match the movements we actually execute, performance of music, as performance of speech, inevitably must have some discrepancy from what is intended. To Gould and Keaton, improvisation is necessary to account for this gap. Merker (2006) suggests that improvisation in performance could be structural, expressive, or both. The classical pianist producing a rehearsed performance still improvises the expressive elements (such as the precise amount and placement of dynamic variation, articulation, etc.) whereas the harmonic and melodic structure may be fixed. On the other hand, a jazz pianist may improvise the harmonic and melodic content itself as well as the expressive elements. He notes that methods of improvisation around the world " . . . span the gamut from mild embellishment to de novo creation, though the extent to which genuine on-the-spot novelty is created even in genres that prize it is a question as important as it is difficult to answer" (p. 27). Similarly, Clarke (1988) distinguishes between structural and expressive improvisation.

Similar to the notion of constraints described above, this anything-in-between reasoning depends on a particular music–theoretical framework. One must be able to delineate and count such constraints before arriving at a conception of a continuum. Because the enabling cognitive mechanisms are not necessarily symmetrical with music theoretical constraints (see Clarke, 1989), there should be at least initial skepticism of a cognitive continuum. Separating expression from structure is a music–theoretical distinction, and it might have symmetrically dissociable cognitive analogues. Then again, it might not. Music theoretical categories can define improvisation according to a continuum, but it stands as an open question whether there are cognitive mechanisms that enable improvisatory abilities that are in any sense continuous.

Toward an Experiment

The first section of this article reconsidered some common elements of the definition of improvisation to raise questions compatible with cognitive–scientific experimentation. In summary, the cognitive approach should use the analysis of music–theoretical structures as a means to reveal process and not as a definition of improvisation in itself. To answer the *how* question, the cognitive approach should focus on how knowledge is differently accessible in different performance situations to describe the different ways musical knowledge is represented, and the different processes that underlie its recall and execution. These differences will help form a cognitive taxonomy of performance that can distinguish between not only rehearsed performance and improvisation, but also between different types of improvising. The second section of this article will identify a more specific experimental strategy that answers to the questions raised here.

Despite sensitivity in the literature to the plurality of different approaches to improvisation around the world (e.g., Nettl & Russell, 1998), the multiple improvisational processes within a single musician are less questioned. How the processes might differ within improvisers depending on a varying music–theoretical performance context (e.g., playing in different keys, or using different musical material) or between groups of musicians who have been trained by different pedagogical methods, such as Sudnow's (1978) "Ways of the Hand" method versus Haerle (1978) who advocates learning licks and chords in all 12 keys, are cognitive–scientific questions that could be compatible with experimentation.

Structural analysis still plays a role in this experimental approach. Any cognitive–scientific experiment trying to dissociate process and strategies in the laboratory based on what music participants produce would at some point need to cast certain musical features as data (e.g., pitch class distributions), and by doing so must use structural analysis. Previous empirical literature on the cognition of improvisation could be usefully synthesized to develop this approach. In particular, as mentioned above, two main strands of this research provide the basis for the experiment proposed below. First, many studies seek to understand something about the cognition of musical improvisation through analyzing improvisations that have been produced outside of the laboratory with various metrics to infer something about how the improvisations were produced. Järvinen (1995) and Järvinen and Toiviainen (2000) analyzed transcriptions of Charlie Parker solos to look for properties of their pitch class distributions and the relation between the use of pitch class and metrical placement. Engel and Keller (2011) noted that improvisations tended to have a greater variation of key-strike velocities (as measured with entropy) and correlated such variation with activation in the amygdala of listeners. The greater unpredictability of the intensity of the key strike was a notable formalized feature of improvisatory playing. Pfleiderer and Frieler (2010) examine improvisations with a number of analytical metrics including Markov chain analysis to seek out patterns and indicate differences in style between performers.

The other strand of research involves trying to compare performance processes within a single performer. Neuroscientists have looked for neural correlates of rehearsed and improvised performance to describe differences in the processes (Bengtsson et al., 2007; Berkowitz & Ansari, 2008, 2010; Limb & Braun, 2008). These studies are useful in their goal to dissociate between performers' processes, but, notably, they do not try to dissociate different improvisational strategies within a given performer. For instance, Berkowitz and Ansari define improvisation as "the spontaneous generation, selection, and execution of novel auditory—motor sequences" (p. 535). Improvisation may not be homogenously spontaneous or novel. With a more subtle understanding of how improvisation might differ between performance contexts in terms of process, and how that would change the music that is produced, the interpretation of such neuroscientific evidence could be enhanced. Improvisation is not a single kind of behavior. This approach can be usefully expanded with a consideration of differences in improvisatory process, and what kinds of bodily, instrumental, and cognitive factors would lead to such differences.

A final point of reference is that of Hargreaves (2012) theoretical piece, which identifies several "sources of ideas" from which improvisers can draw, including strategy-generated ideas (e.g., deciding to use perfect fourths), audiation-generated ideas (e.g., getting ideas from what an improviser "hears" with mental imagery), and motor-generated ideas (unconscious procedural knowledge). This type of reasoning helps ground the experimental method proposed below. The performance situation may change which sources the improviser can access.

How, then, could music–theoretical performance contexts be varied to reveal differences in an improviser's use of or access to embodied knowledge? How can manipulating these contexts be shown to manipulate cognitive processes? What can be learned about the nature of the embodied knowledge through such an experiment? How can different improvisational strategies be characterized cognitively? The experiment reported below, initially discussed in Goldman (2012), begins to address these questions experimentally. It keeps the goal of the neuroscientific literature of distinguishing between an individual's different performance processes, expands it by considering different modes of improvisation, and combines it with analytical techniques used in previous improvisation literature. It offers a new synthesis of these by devising experimental conditions under which the same improviser's performances can be compared, and the effect of different performance context variables can thus be measured. It also offers a way to make inferences about differences in cognitive processes based on these measurements.

The task required jazz pianists to perform monophonic improvisations with one hand in a familiar music–theoretical context (playing over *Rhythm Changes*, the chord progression from Gershwin's song *I Got Rhythm*), but varied the situation between the performer and the instrument by varying the key signature between a common key (B*b* major) and a less familiar key (B major), and by varying which hand played which musical function (bass line or melody). B*b* is generally more familiar than B for jazz pianists in part because jazz standards are written and played in keys that accommodate horn and wind players playing on instruments that transpose to flat keys, and pianists play at concert pitch. Keys with many sharps, like B, are thus uncommon for pianists in jazz standards. To play the same musical idea in these different conditions would require a different set of movements. From a music–analytical point of view, all of these performance conditions are improvisational and could be said to follow the same (or a similar) framework. Cognitively speaking, however, the conditions were meant to force the improvisers to rely on different improvisational strategies and cognitive processes by changing the familiarity of their mind–body–instrument interface. Comparing the resultant improvisations could help characterize the cognition of these strategies.

The less familiar performance conditions were meant to take away access to familiar and overlearned motor patterns ("muscle memory") and require the performers to rely on an alternative strategy. Pressing (1998) describes a knowledge base for improvisers. Here, it may not be that different parts of a single knowledge base are accessed depending on the situation—it may be that several knowledge *bases*, distinguished on the basis of separate kinds of representations and processes of execution, are at play. Trying to understand whether there is such a difference and what its nature would be is a goal of this experiment.

Hypothetically, if improvisers are not able to use overlearned and practiced movements as would be available in the familiar keys, they would need to rely on a more explicit strategy to create improvisations appropriate for the musical style. Without this kind of procedural knowledge, improvisations should become less varied and more predictable. They would have a smaller repertoire of ideas in terms of their ability to use the range of tonal possibilities available to them in the key and in terms of more specific licks and patterns acquired over years of practice. In a less familiar situation, participants would be less familiar with how to move their hands at the instrument to get the sounds they would want. In the absence of this connection, they would still have to play something that worked over the harmonic progression. Without knowing how to create the more complex chromatic sounds, participants would likely rely on the use of more diatonic scale and chord tones to play something that, while less harmonically complex, would still work over the chord changes. The metrics used to test these hypotheses are described in detail below.

Experiment: Inferring and Describing Different Improvisational Processes Through Structural Analysis

Method

Participants. Ten jazz pianists (all male, nine right-handed) with an average age of 24.3 years ($SD = 4.9$) participated in the study. Eight were students or recent graduates of a jazz piano program at the Birmingham Conservatoire, one was a music student at the University of Cambridge, and one was a music student from a university in the United States. The participants had similar periods of formal musical study ($M = 17.3$ years, $SD = 4.22$) and similar periods of specifically improvisational training ($M = 8.0$ years, $SD = 4.88$). All participants volunteered to participate after receiving an invitation from the author.

Materials. Aebersold's (2000) backing track for *Rhythm Changes* from the Play-A-Long series was chosen to accompany the pianists. The track is a recording of a drummer playing a swing pattern, a walking bass line, and a pianist comping. The length of one chorus was extracted (~1 min long). The track was transposed from its original key of B*b* major to B major using Logic Pro's Time and Pitch Machine. A version in each case was also created without a bass line (the original tracks are recorded in stereo such that panning to one side eliminates the bass line). The backing tracks thus needed to be slightly altered to accommodate the experimental design and could potentially introduce additional variance. A strictly controlled MIDI backing track could have been used for the purpose of this experiment, but the Aebersold backing tracks are a more ecologically valid option. They were produced as practice aids for musicians. Such alterations to these recordings were deemed acceptable for the purposes of this experiment. Participants improvised on an 88-key weighted keyboard and listened through headphones. MIDI recordings were made through Logic Pro, which also was used to play the backing tracks. The keyboard was set to a generic piano sound.

Design. Eight conditions were chosen (three factors with two levels each). The factors were key (B or B*b*), hand (left or right), and function (melody or bass line). Each condition was repeated five times, totaling 40 MIDI file improvisations collected for each participant.

Procedure. Before the improvisational task, the participants filled in questionnaires about their demographic information including age, gender, handedness, and musical training. Participants were then instructed to improvise over the *Rhythm Changes* backing track on the MIDI keyboard. They were told which hand to use, which key to play in, and whether to play a melody or bass line via the recorded voice of the experimenter, depending on the condition. Trials were arranged in a pseudorandom order such that identical conditions did not occur consecutively. After 20 trials, participants took a short break before completing the remaining 20 trials. Participants were further instructed to play bass lines as a walking bass line and not a bass solo, and to consider the melodies as solo horn lines. Finally, for melodies, they were advised that they could use the whole keyboard with either hand and should adapt their sitting posture accordingly. Following the improvisational task, a postexperiment interview was conducted to discuss the task, practice methods, and any other comments participants had.

Analysis

Data. A total of 400 MIDI files were collected. The data was processed using MATLAB and Eerola and Toiviainen's (2004) MIDI Toolbox. A total of five trials were excluded from analysis for various reasons such as the participants playing with the wrong hand for the condition or using both hands. Because one of the metrics described below incorporates conditional probabilities, additional trials were discarded for those analyses. Occasionally, for all of the trials, the participants would produce two note events very close in time (<10 ms). Sometimes these were grace notes, sometimes they appeared to be errors (such as playing two notes at once on accident), and sometimes they were deliberate uses of harmony. For conditional probability measures, it is necessary for the data to be monophonic, as the analysis is sequential in nature. However, because it is sometimes difficult to tell whether two notes in proximity are deliberate or not, discarding all instances of this could eliminate meaningful data. The events never occur simultaneously in time, so as far as the analysis is concerned, they are able to be treated as separate sequential events. Trials with a few of such instances were tolerated for this analysis, but some trials had a large number of them. Trials with more than five of such instances were discarded. Eleven of such trials were found. Therefore, a total of 16 trials were discarded in total for the conditional probability analysis. For the ANOVAs described below, the values for missing trials were replaced with the average value across all data within that condition. Also, for the purpose of analyses, notes were treated according to their pitch class and not their absolute MIDI note number.

Metrics. In designing a study such as this, some kind of formal analysis is needed to infer and describe differences in cognitive strategy from recorded MIDI data. For this study, two relatively gross measures were used initially, and followed up with a more specific metric. First, to test the hypothesis that less familiar conditions would lead to more predictable improvisations, the entropy of the pitch class distributions for the improvisations was measured. The entropy metric has a long precedent in the literature and has been interrogated for its musical relevance (Knopoff & Hutchinson, 1983; Margulis & Beatty, 2008; Meyer, 1957; Snyder, 1990; Youngblood, 1958). The equation for calculating entropy is

$$H = -\sum_{i}^{n} p_i * \log_2(p_i)$$

where H is the entropy in bits of a sample, n is the number of elements in the set (in this case, 12 different pitch classes), and $p(i)$ is the likelihood of a particular pitch class from the set occurring within the sample (the number of times a particular pitch occurs divided by the total number of notes for that sample). The highest possible entropy occurs when all pitch classes are used equally (≈3.58 bits). More predictable improvisations should have a lower entropy value, as they rely on some pitch classes more than others.

To refine the assessment of predictability in the improvisations, a conditional entropy metric was also used. An improvisation that, for instance, used many chromatic scales, would return a high entropy value because all possible pitch classes would be used more evenly, but would nevertheless be a predictable improvisation. For this study, a one-back measure was used, which considers each note within the context of the note immediately preceding it. For instance, in this case, an improvisation with many chromatic scales would return a low value because a given note would strongly predict the note that follows it. To calculate this value, Margulis and Beatty (2008) provide the equation

$$H_{x(y)} = \sum_{i,j} - p_{(i,j)} * \log_2 p_{i(j)}$$

where H is the conditional entropy in bits of a sample, $p_{(i,j)}$ represents the likelihood that a pair of successive events (x,y) will have the values i and j, respectively, and where $p_{i(j)}$ represents the likelihood that event y will have value j given that x has value i. A higher conditional entropy would mean it is generally harder to predict which pitch class will occur after an observed occurrence of a particular pitch class. It thus represents a more refined measure of unpredictability.

Also, the proportion of diatonic pitch classes was measured by dividing the total number of diatonic notes in a given improvisation by the total number of notes in that improvisation. In less familiar conditions, if improvisers are relying more on chord tones and diatonic scale tones as predicted, this metric should offer a relatively gross assessment of this effect. Each MIDI file thus had an associated entropy value, conditional entropy value, and diatonic proportion value.

Further, the improvisations all contained different numbers of notes (ranging from 64–384, $M = 167.6$, $SD = 46.4$). This presents a potential problem for assessing the entropy and conditional entropy values. After the entropy values were calculated, it was observed that the number of notes correlated significantly with the entropy value, $r(398) = .234$, $p < .001$. There were also significant correlations between the number of notes and the entropy value within the melody conditions, $r(198) = .157$, $p < .05$, and in the bass line conditions, $r(198) = .254$, $p < .001$. The number of notes also correlated with the conditional entropy values overall, $r(398) = .503$, $p < .001$, within the melody conditions, $r(198) = .396$, $p < .001$, and within the bass line conditions, $r(198) = .314$, $p < .001$. The number of notes thus introduced a potential confound. Knopoff and Hutchinson (1983) advise large sample sizes to ensure the entropy value is confidently estimated for a sample of music in question. As the number of notes increases, the entropy estimate becomes more accurate. In this experiment, there is assumed to be a true entropy value for each condition similar to the way previous research has assumed a true entropy value for styles of music (e.g., Youngblood, 1958). The longer improvisations may represent more accurate estimates of entropy and conditional entropy values. For this reason, a statistic is also reported that combines the individual MIDI files by factor so that a single entropy value for each factor was calculated rather than an average as would be calculated in an ANOVA. This dramatically increases the number of notes for a given calculation and thus more accurately estimates the true value. That being said, the number of notes in a given improvisation may not be a source of variance that should necessarily be eliminated for the purpose of this experiment. A given improvisation, regardless of how long, still has an entropy value that measures its predictability. Fewer notes may not necessarily mean more predictability according to entropy metrics.

Results

For each of the metrics, a three-way repeated measures ANOVA was conducted with the independent variables hand (two levels; right and left), key (two levels; B*b* and B), and function (two levels; bass line and melody). As described above, for the entropy and conditional entropy metrics, the improvisations were also pooled by factor to provide single values from a larger sample.

Entropy. There were no main effects of hand or function, but a highly statistically significant effect of key, $F(1, 9) = 40.194$, $p < .001$. The improvisations in the familiar key, B*b*, had higher entropy values than those in B (see Table 1). There were no significant interactions. Table 2 provides a set of entropy values calculated by combining the individual improvisations by factor. The entropy values calculated from this combination show that right-hand improvisations had a higher entropy value than left-hand improvisations, B*b* improvisations had a higher entropy value than B improvisations, and melody improvisations had a higher entropy value than bass line improvisations.

Table 1
Entropy Values by Key (in Bits)

Key	Mean	*SE*	95% Confidence interval	
			Lower bound	Upper bound
B	3.230	0.042	3.135	3.325
B*b*	3.318	0.039	3.229	3.408

Note. The mean value for improvisations in each key and standard error values are indicated.

Conditional entropy. There were significant main effects of hand, $F(1, 9) = 19.97$, $p < .005$, and function, $F(1, 9) = 16.39$, $p < .005$ (see Table 3). The right-hand improvisations had higher conditional entropy values than the left-hand improvisations, and melody improvisations had higher conditional entropy values than bass line improvisations. There was no main effect for key and there were no significant interactions. Table 2 provides a set of conditional entropy values calculated by combining the individual improvisations by factor. The entropy values calculated from this combination show that right-hand improvisations had a higher conditional entropy value than left-hand improvisations, B*b* improvisations had a higher conditional entropy value than B improvisations, and melody improvisations had a higher conditional entropy value than bass line improvisations.

Diatonic proportion. There were no main effects of hand or function, but a highly statistically significant effect of key, $F(1, 9) = 124.47$, $p < .001$ (see Table 4). In the unfamiliar key, B, the improvisations had higher proportions of diatonic pitches than the B*b* improvisations.

There were two significant interactions. The interaction between key and function was highly significant, $F(1, 9) = 32.10$, $p < .001$ (see Table 5 and Figure 1). The key of the improvisations had a greater effect on melodies than on bass lines.

A three-way interaction between hand, key, and function was also significant, $F(1, 9) = 5.21$, $p = .048$ (See Table 6 and Figure 2). For bass lines, the left hand showed more of a difference between the keys than the right hand. For melodies, the left hand showed less of a difference between keys than the right hand.

Interview transcripts. Audio recordings of the participants' interviews were made and transcribed. Several potential issues with the method were raised by the participants and are addressed below. The interviews also served as further evidence that the experimental conditions indeed influenced participants to rely on different forms of knowledge. These findings are described below.

Discussion

Main effects for hand. No statistically significant differences in the entropy or diatonic proportion were found. This could be because the analysis was too blunt to detect a difference between the hands with regard to pitch class choices. The hand conditions may have produced equal values, but for different reasons. The left-hand improvisations could have simply been using different musical patterns than the right hand, resulting in the same diatonic proportion or entropy. For example, while the right hand may have been using a variety of musically appropriate nondiatonic pitch classes, the left hand may have been relying on chromatic scales, or guessing which notes to play.

The conditional entropy metric, however, did show a significant main effect, with right-hand improvisations returning a higher value than left-hand improvisations, which may help account for this missing effect for context-free entropy. This result suggests that the right-hand improvisations had a greater variety in their transitions between pitch classes. The more familiar and facile interface that improvisers could use when playing with their right hands demonstrated a wider variety of pitch-class transitions. They would seem to have access to a wider range of tonal possibilities.

Given that the number of pairs of notes used to calculate this value correlated significantly with it, it could be suggested that

Table 2
Entropy and Conditional Entropy Values by Factor

Metric	Left hand	Right hand	B	B*b*	Bass line	Melody
Entropy	3.438	3.460	3.415	3.473	3.424	3.459
Length of combined sample	30,498	33,618	30,777	33,339	25,932	38,184
Conditional entropy	3.220	3.268	3.217	3.256	3.114	3.210
Length of combined sample	30,304	33,428	30,583	33,149	25,738	37,994

Note. These values were obtained by combining the trials within the levels of a given factor and taking a single measurement of the entropy and conditional entropy values from that larger sample of notes. The higher number of notes in the sample reflects a more accurate estimate of the entropy values. All of the trials were transposed to the same key before making these calculations, so the entropy values use the distribution of scale degrees, not pitch classes. Entropy values are given in bits, and the length of the samples is given in the number of notes.

these improvisations only had a higher conditional entropy value because the right hand is more facile than the left and is thus able to play more notes. However, the ability to play more notes in itself would not necessarily correlate with a higher conditional entropy if they were the same combinations again and again. Not only were there more notes, but more variety in what was played, which could still be interpreted as having a wider range of tonal possibilities when playing with the right hand. A similar criticism is that the challenges in fingering between the hands are different. Parncutt, Sloboda, Clarke, & Raekallio (1997), for example, provide a model to determine ergonomic fingering possibilities. The challenges posed to the left hand would be different than the right to play the same passage, and the challenges would differ by key. This could cause a difference between the conditions. But again, this difference could still be interpreted in light of the experiment's premise. The way to execute a similar musical idea becomes different, and the same performer resorts to other sources of knowledge to perform. Either way, the tonal content changes, and the cognitive strategy changes. Improvisers could have taken their time and played less, but more varied musical phrases that were perfectly ergonomic.

Main effects for key. There were significant main effects between key conditions. The improvisations in the familiar key, B*b*, had significantly higher entropy and a significantly lower diatonic proportion than the unfamiliar key, B. Both of these findings support the hypotheses. The entropy metric shows that the overall variability of pitches used was greater in the familiar key, and thus the improvisations were less predictable with regard to pitch classes. This suggests that in familiar motor contexts, the pianists are able to rely on a greater and more varied repertoire of figurations and harmonic relationships. In the unfamiliar key, the pianists used more diatonic pitch classes. In this unfamiliar motor context, pianists would not have access to the procedural knowledge of complex chromatic lines they might use in the familiar key. They are replaced by a greater reliance on diatonic pitch classes, suggesting that pianists are relying on their explicit harmonic understanding of scale degrees and chord tones.

As for the conditional entropy metric, the absence of a main effect for key and the absence of a significant interaction between hand and function are notable. According to the hypotheses, there should have been a difference between keys as well as an interaction between hand and function because the hands are differently familiar with the musical functions. However such effects were not found. It could be that in the unfamiliar conditions (e.g., playing in B, or using a hand to play an unfamiliar function), the participants produced similarly varied material that was otherwise musically inappropriate. Wrong notes or guesses, in other words, could possibly account for the absence of this effect. A further analysis involving how subjectively stylistically consistent the improvisations were could potentially sort out this question.

Key interaction effects. There was a significant interaction between key and function for the diatonic proportion metric. The bass lines, overall, were less affected than the melodies, both of which had fewer diatonic pitches in the familiar key. This may be because bass lines are typically more limited in their note choices anyway, and are more likely, functionally speaking, to use chord tones and thus diatonic pitch classes.

There was a three-way significant interaction for the diatonic proportion metric. This observed finding is in line with the hypotheses. The right hand shows a difference between the familiar and unfamiliar keys for melody while as the left hand is unfamiliar with either key when playing a melody, it shows less of a difference. For bass lines, the reverse is true. The right hand is unfamiliar with either key, so it shows less of a difference while the left hand is familiar with one of the keys and not the other, so it shows a greater difference.

Function effects. Melodies had a higher conditional entropy measure than bass lines. Bass lines are typically more constricted

Table 3
Conditional Entropy Values

Factor	Level	Mean	*SE*	95% Confidence interval Lower bound	95% Confidence interval Upper bound
Hand	Left hand	2.359	0.036	2.278	2.439
	Right hand	2.442	0.032	2.370	2.515
Function	Bass line	2.287	0.058	2.157	2.418
	Melody	2.514	0.019	2.472	2.557

Note. The mean value for improvisations produced with each hand and in each musical function as well as standard error values are indicated.

Table 4
Diatonic Proportion by Key

Key	Mean	*SE*	95% Confidence interval Lower bound	95% Confidence interval Upper bound
B	0.803	0.016	0.767	0.840
B*b*	0.750	0.016	0.714	0.786

Note. The mean value for improvisations in each key and standard error values are indicated.

Table 5
Diatonic Proportion Interaction Between Key and Function

Key	Function	Mean	*SE*	95% Confidence interval Lower bound	95% Confidence interval Upper bound
B	Bass line	0.796	0.019	0.754	0.838
	Melody	0.811	0.018	0.771	0.850
B*b*	Bass line	0.756	0.018	0.715	0.796
	Melody	0.744	0.019	0.700	0.787

Note. Mean values and standard error values are indicated.

Table 6
Diatonic Proportion Interaction Between Hand, Key, and Function

Hand	Key	Function	Mean	*SE*	95% Confidence interval Lower bound	95% Confidence interval Upper bound
Left hand	B	Bass line	0.802	0.018	0.763	0.842
		Melody	0.809	0.018	0.769	0.849
	B*b*	Bass line	0.752	0.018	0.710	0.793
		Melody	0.751	0.017	0.712	0.790
Right hand	B	Bass line	0.79	0.021	0.743	0.836
		Melody	0.812	0.018	0.772	0.852
	B*b*	Bass line	0.760	0.019	0.717	0.803
		Melody	0.736	0.023	0.685	0.787

Note. Mean values and standard error values are indicated.

in their use of pitch classes, as they more often use chord tones. The context-free entropy metric, however, did not show a difference between bass lines and melodies. The bass lines still used the pitch classes as evenly distributed as in melodies, but there may have been simply less opportunities to show variety in their transitions both because there were fewer notes in bass lines, and because they need to stick to certain note transitions to outline the appropriate harmony.

Trials pooled by factor. Table 2 provides a set of entropy values and conditional entropy values calculated by combining the individual improvisations by factor. These were calculated using a far larger amount of notes. Pooling these is analogous to searching for an entropy value of a style by combining multiple separate pieces of music. This is another way to compare values between conditions that can begin to account for the difference in the number of notes between the improvisations. The predicted differences emerge here for both metrics (right hand is greater than left hand, Bb is greater than B, and melody is greater than bass line). The more familiar motor contexts result in a more even use of pitch classes and a more varied use of transitions from one pitch class to the next. In addition, melodies are more varied than bass lines, which makes sense in light of the musical function of each.

Interview transcripts. In the debriefing interviews conducted with the participants in this study, some described what seemed

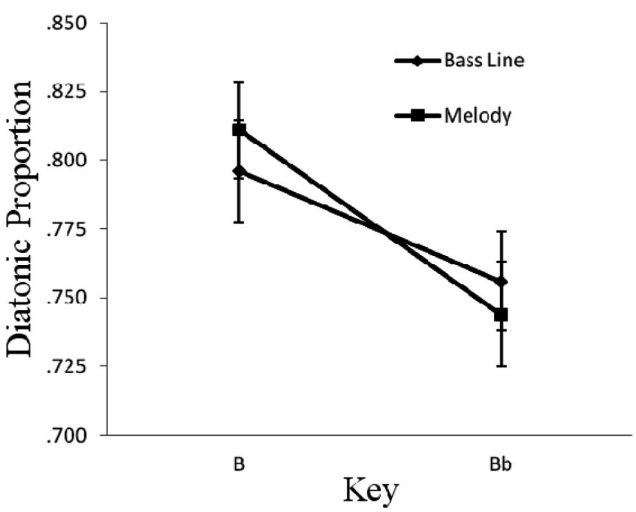

Figure 1. Graph of diatonic proportion interaction between key and function. Diatonic proportion is showed as a function of key and function. Error bars display one standard error in either direction.

different about their strategies when the interface with the keyboard became less familiar. One participant reflects on his performance in the experiment:

> In the right hand you're doing things because you can hear the notes and you play them. Whereas in the left hand, it's almost like you're trying to follow the rules of how to jazz improvise. Like, these are the chord tones, and this is how I'm going to work around them. Whereas when you're improvising with the right hand, you're just thinking, well this is how this, you hear notes, and you play them.

Another participant also describes a difference:

> But, because it's in B, there's a lot of thought involved, just trying to, remembering what the chords are and that kind of thing. When you're in B*b*, more of it gets to the subconscious. The process of, you know, oh yeah, c minor 7, F 7, that kind of thing. In B, you have to transpose a bit more. It's more of a conscious process. It's more difficult, I would say.

These comments reaffirm the validity of the experiment and point to further research possibilities to more precisely describe the differences in process underlying the different performance conditions. Such differences in what one "hears" while playing and what is "subconscious" may be a further route to describe differences in modes of improvisation that use different cognitive processes. These ideas are explored below. In the interviews, the participants also raised concerns about the experimental design, which are also discussed below.

Problems with the experimental design. Some participants complained that because the backing track was the same every time, they were not able to interact with it. This is not the most ecologically valid circumstance, but it was judged to be appropriate for the theoretical premise of this experiment.

Another problem with ecological validity is that it may not be fair to assess motor familiarity with a key when improvisers are only using one hand at a time. The knowledge pianists acquire to play certain musical phrases or ideas may well be distributed across both hands. That being said, it is not a wholly unfamiliar task to improvise one hand at a time, or one note at a time. It was necessary for the analysis of this study to ask the improvisers to play monophonically, but it may not need to be included in future studies depending on the metrics used to analyze the music.

In the postexperimental interviews, participants reported getting fatigued toward the end of the experiment. This may have differ-

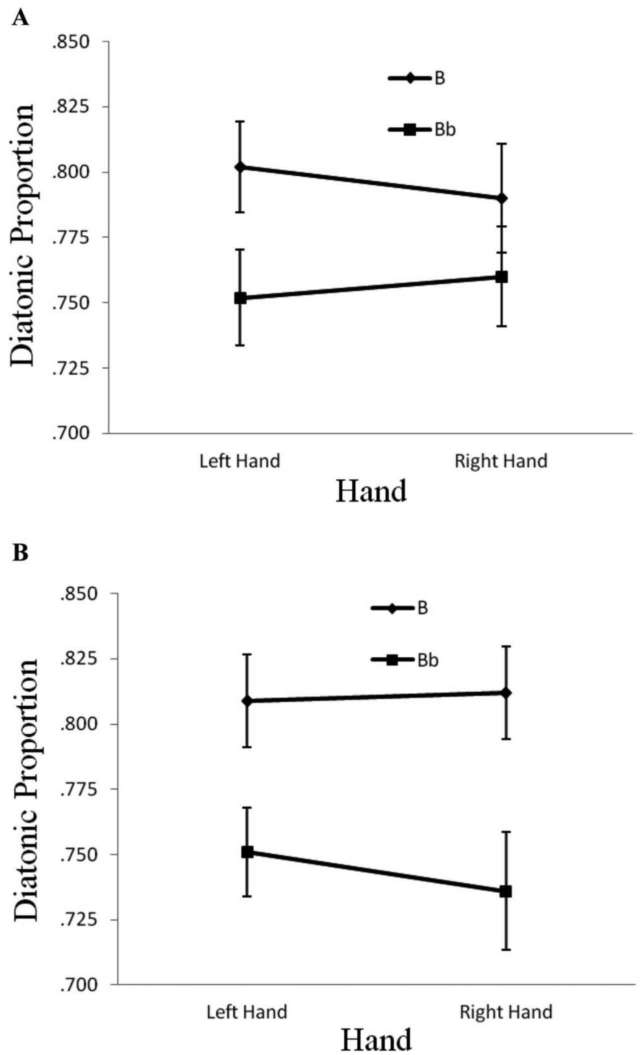

Figure 2. Graphs of diatonic proportion interaction between hand, key, and function. Diatonic proportion is shown as a function of hand, key, and function. (A) Function = bass line, (B) function = melody. Error bars display one standard error in either direction.

entially affected their improvising over the course of the experiment. It is difficult to anticipate, however, how such fatigue would affect metrics based on pitch class distributions.

Perhaps more of a problem is the possibility that participants learned things from themselves. Improvising melodies with the left hand is not something the participants normally practice, according to their interviews. Between trials, they may have tried to mimic what one hand played with the other hand. This may have introduced confounding variance in the data, but it is also in itself an interesting possibility. If this were indeed the case, it would be another way to consider how access to musical knowledge differs in different performance circumstances. Finding instances of this transfer would be a valuable possibility for a future study.

One could imagine that an improvisation, regardless of how the metrics used here assess it, could possibly use different improvisational processes. Procedural knowledge can perfectly well produce low entropy improvisations and the explicit strategies could produce highly variable improvisations. Given the specific nature of the task for this study (to improvise over Rhythm Changes), and because the style was familiar to the participants, it is still likely that the use of different strategies explain the differences in the metrics. Future research, as suggested below, may be designed differently to more confidently characterize and identify instances of such differences in process.

Finally, generally speaking, the statistics in this study did not consistently support the hypotheses that unfamiliar motor contexts would result in less variance between the use of different pitch classes and less predictability. However, many of the hypothesized effects are present, and the study can still be seen to demonstrate what happens when the situation between the performer and the instrument is made more unfamiliar. With the same music–theoretical knowledge but a different situation between a performer and an instrument, the playability of ideas changes. This describes a difference in improvisational and cognitive process. The best way for future experiments to follow from this one should involve methods to more precisely characterize what about the difference in the interface makes ideas more or less playable (not just in terms of the ergonomics of fingering, but also in the cognitive representations of musical knowledge) to further characterize the nature of the knowledge used in the multiple different processes of improvisation.

Further Research

This study has begun to characterize different improvisatory strategies and some of their structural correlates, but precisely characterizing how the cognition differs is still an open question. What makes different ideas playable depending on the performance situation? As some of the participants noted, the connection between hearing and moving may be crucial. Sometimes the connection would seem to be more fluent than others leading to differences in structural characteristics and subjective reports of performance strategies. This difference could be further understood within the context of motor theories of perception. Such theories, including ideomotor theory (for a review, see Shin, Proctor, & Capaldi, 2010), simulation theory (for a review, see Hesslow, 2012), and the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), generally suggest that actions and their perceptual correlates share a common representational domain. These theories combine research from sensory mental imagery (see Finke, 1989) and motor mental imagery (see Jeannerod & Decety, 1995) to demonstrate how they may be related. Musical knowledge may be represented in this way for improvisers under familiar conditions. Hearing something in your head can easily be translated into playing something with your hands. In unfamiliar performance conditions, however, a different cognitive process may be at play. It could be that what is heard with auditory imagery cannot be linked to any motor output because the motor context is different (e.g., an abnormal key layout). It could also be that what is played is not simulated and heard with auditory image at all, and the musician only knows what it sounds like after playing it. The jazz pianist and pedagogue Lennie Tristano reportedly criticized students when he thought they were not “hearing” (mentally) what they were playing (Shim, 2007).

Motor theories of perception provide a potential way to explain why sensory feedback (tactile and auditory) may be more or less important under certain performance conditions. Altered auditory feedback (both delayed feedback and altered pitch) has been explored with musicians playing and singing (Pfordresher, 2006), but not as it pertains to understanding improvisation. It may be that altered auditory feedback may affect improvisation differently under different conditions as well as differently affect improvisation as compared with rehearsed performance or sight reading, helping to further construct theoretical differences between cognitive modes of performance. For instance, it may be less disruptive to have altered pitch feedback if the musicians do not have an idea of what sounds their finger movements will make before making them, as was perhaps the case when the jazz pianists here played in B major or with their left hands. These theories may also help describe differences in other musical skills. Kopiez and Lee (2008) have identified mental imagery ability as an important predictor of sight-reading ability, for instance. The same cognitive capacities might also correlate with improvisation experience.

There are several ways forward to advance the research program proposed above. Trying to differentiate between cognitive representations and processes of different modes of performance can help develop a cognitive–scientific taxonomy of performance that diverges from a definition stemming from music theory and structural analysis. Music analysis can instead be used in tandem with cognitive theories to build an understanding of such modes of performance.

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