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Professional Jazz Musicians Explore and Exploit a Space of Sounds

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Abstract

Collective improvisation is remarkable. When people improvise—whether dancing, making music, or conversing—they coordinate their behavior while exploring abstract spaces of movements, sounds, and ideas. How do improvisers navigate these abstract spaces? One possibility is that improvisation builds on foraging strategies used to search the physical world. Here, we investigate the dynamics of an especially complex and abstract form of collective improvisation: free jazz. We quantify how professional jazz ensembles navigate a space of sounds and show that it resembles a foraging strategy known as Area Restricted Search. In particular, ensembles change their playing dynamics in response to encounters with novel 'soundworlds.' Before encountering a new soundworld, ensembles engage in widespread exploration; immediately after, they shift to focused exploitation of the new sound. While collective improvisation pushes at our cognitive limits and is a paradigm of human creativity, it may build on evolutionarily-ancient strategies for searching space.

Keywords: creativity, music improvisation, foraging, collective cognition

Introduction

Collective improvisation is a remarkable achievement. From modern dancers developing spontaneous choreography in response to the movement of other dancers, to improv comedians creating entire scenes on the spot to tell impromptu collective stories, to free jazz musicians crafting entirely new sounds on the fly, collective improvisation requires real-time interaction, coordination, and creativity. High-level creative improvisation is thus a paragon of complex human cognition.

Here we focus on an especially remarkable instance of collective improvisation: collectively improvised music, where musicians create complex sounds without any prior score. Music improvisation is of particular interest because it requires real-time and coherent expression of musical ideas from an infinite number of potential combinations (Berkowitz, 2010). Although similar to more mundane forms of interaction such as conversation (Wheatley, Thornton, Stolk, & Chang, 2023), musical improvisation is extreme in the demands it places on real-time creativity, coordination, and interaction, all in the service of creating an interesting musical performance for an audience. A successful performance requires improvisation, collaboration, and emergence (Sawyer, 2006). These musicians are not just producing creative products in isolation, but instead trying to create a collective product that is greater than the sum of its parts. In doing so, musicians need to search for new, complex sounds in real time. How do they do this? What are the strategies that collectively improvising musical ensembles adopt to move effectively through a space of potential sounds?

Searching for sounds... or foraging for food?

One speculative proposal is that collective improvisation shares strategies with a far more mundane activity: foraging in the physical world for food or other resources. A foraging organism can deploy multiple strategies to search for food or other high-value resources. Mental search (Todd & Hills, 2020) an individual creativity (Malaie, Spivey, & Marghetis, in press) have been found to make use of foraging-like strategies.

What kinds of strategies are used to forage in space? One strategy that is especially effective for search in patchy environments is known as a Levy flight. A Levy flight is characterized by a heavy-tailed (specifically, a power-law) distribution of step lengths (Viswanathan et al., 1996): many small steps and infrequent large steps. For instance, marine predators may use a Levy flight search strategy to hunt for prey, taking heavy-tailed steps in random directions ("The Lévy flight paradigm: random search patterns and mechanisms", 2009).

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If at each moment an organism moves in a random direction but travels a distance drawn from a heavy-tailed distribution, it will spend extended periods of time searching one region and then every once in a while jump to an entirely new region, thus giving rise to a “patchy” style of search without any plan or memory.

An alternative foraging strategy is known as Area Restricted Search. In Area Restricted Search, the organism does not just take random steps. Instead, the organism keeps track of recent successes— e.g., discoveries of food—-and adjusts its search pattern accordingly (Dorfman, Hills, & Scharf, 2022). Whenever an organism finds a resource, it continues to search in that region on the assumption that more resources are likely to be nearby, thus ‘exploiting’ that particular patch. Eventually, once that region has been depleted of resources, the organism switches to ‘explore’ mode and searches widely for a new patch of clustered rewards. For instance, ladybugs use Area Restricted Search to hunt for aphids, exploring widely until they encounters a potential prey and then continuing to exploit that region after an encounter (Dorfman et al., 2022).

Both Levy flights and Area Restricted Search generate search patterns that appear ‘patchy,’ with periods of sustained search in one region, punctuated by leaps to a new region (e.g., Fig. 1). The two strategies, however, are distinguished by the role of memory in the transition between patches. In a Levy flight, the organism’s behavior is not informed by its memory of past discoveries; it just draws randomly from its heavy-tailed distribution of steps. An organism engaged in Area Restricted Search, by contrast, will transition from explore behavior to exploit behavior whenever it encounters a new resource, and then it will sustain that exploit behavior within that region based on the memory of the recent resource encounter. Levy flights and Area Restricted Search are thus distinguished by changes in foraging behavior before and after a resource encounter.

From foraging in space to foraging in mind?

The same foraging strategies that are used by non-human animals to search for food have been found to describe how humans search through more abstract spaces of ideas, words, or memories (Todd & Hills, 2020). One common example comes from searching for words in memory (Hills, Jones, & Todd, 2012; Rhodes & Turvey, 2007). For instance, when people are asked to name as many animals as possible, they exhibit patch-like search behavior, where they name animals in spurts of related species (e.g., farm animals) before jumping to a new ‘patch’ of animals (e.g., pets) (Hills et al., 2012; Rhodes & Turvey, 2007). When people search through their memory, therefore, the search process is ‘patchy’ in a way that resembles the way animals use Levy flights or Area Restricted Search to forage in physical space. This strategy makes sense given that words cluster semantically (Romney, Brewer, & Batchelder, 1993; Montez, Thompson, & Kello, 2015), much like rewards can cluster together in the physical world. Similar to how resources may be grouped together in physical space, words and ideas are often grouped together in an abstract space of meaning. In other instances, however, targets may not be clustered, as in divergent creativity where the goal is to generate as many as and varied solutions as possible. In that case, people may adopt a more exploratory foraging strategy, searching widely and divergently in a space of possible solutions (Malaie et al., in press).

Free musical improvisation as a case study in collective mental foraging

The current project seeks to better understand the process of collective creativity — particularly the way it operates as a kind of collective foraging — through a case study of ensemble improvisation. We focus on free jazz, a genre of improvised jazz that is a paradigmatic example of collective creative improvisation. In free jazz and other free improvised genres of music, musicians create music without a centralized controller or preexisting musical score (Borgo, 2022). This means that there is often no guiding path — no predetermined chord changes, for instance, or planned solo intervals. Instead, musicians collectively create novel sounds on the fly, without reliance on a score, with all participating instruments capable of taking the lead (Canonne & Garnier, 2015).

Free jazz is especially interesting as a case study in collective improvisation because musicians in this genre are not confined to a limited set of phrases, harmonies, or rhythms that are considered aesthetically pleasing (Pras, Schober, & Spiro, 2017). This distinguishes free jazz from other jazz traditions, such as straight-ahead jazz, in which musicians improvise over a composition. As a result, the space of possible sounds through which free jazz musicians must search is diverse and largely unconstrained, making it an especially good case study for a scientific investigation of collective improvisation.

The Current Study

The question, then, is whether collective improvisation can be characterized as a kind of sonic foraging, and, in particular, whether musical ensembles exhibit any of the foraging strategies that have been documented in other contexts.

Here, we leverage a corpus of recordings of professional jazz musicians to quantify how free jazz musicians traverse the space of possible sounds during improvised performances. In particular, we test whether these performances exhibit the hallmarks of a Levy flight (i.e., randomly sampled steps from a heavy-tailed distribution) or of Area Restricted Search (i.e., strategy switches from explore to exploit in response to encounters with a new patch of interesting sound).

Methods

Corpus

Data come from a corpus of 75 audio recordings in a studio environment (as opposed to live performances with audiences). The corpus was limited to professional musicians performing in the genre of free jazz. Ensembles in the corpus consist mostly of small jazz combos (between 3 and five

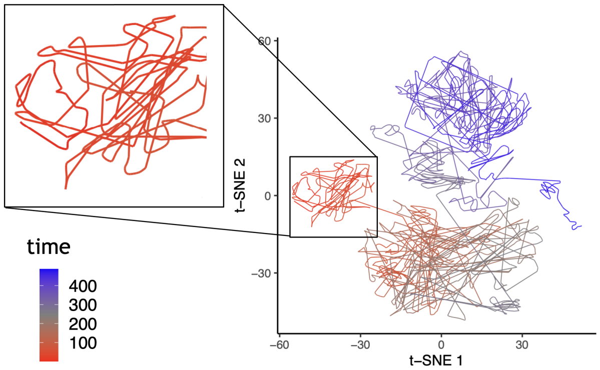

Figure 1: **Trajectory through MFCC sound-space of one improvised free jazz recording.** For visualization purposes, we reduce the high-dimensional MFCC trajectory to two dimensions using t-SNE, a dimension-reduction technique. Note that the trajectory is patchy. There are periods where sonic movements are small and the performance thus remains within the same local region of the sound space, punctuated by periods of rapid change. Both Levy flights and Area Restricted Search are consistent with patchy search patterns like the one seen here. The inset panel zooms in on one of these stable patches. (Color represents time elapsed within the track.)

musicians) with typical jazz instrumentation (percussion, piano/synthesizer, guitar, bass, horn, etc.). The corpus was built using a convenience sample of available recordings. Recordings range in duration from approximately 1 minute to 40 minutes in length.

Audio transformations

We embedded the raw audio recordings in a high dimensional 'sound space' using Mel-Frequency Cepstrum Coefficients (MFCC). MFCC is similar to semantic embeddings for words in that individual dimensions are difficult to interpret since they capture multiple features. These coefficients have been used previously to analyze and compare musical genres (Tzanetakis & Cook, 2002) and can capture subtle differences in timbre (e.g., the difference between two instruments playing the same note). The coefficients were calculated using a two-second sliding window. This MFCC transformation thus transformed each track into a trajectory through a 20-dimensional sound-space.

Quantifying the foraging dynamics of musical improvisation

The moment-to-moment dynamics of foraging can be characterized by two values: the length of the next sonic step ('step length') and the change in direction from the past step ('turn angle') (Fig. 2).

Step length was calculated as the Euclidean distance between subsequent values of the MFCC embedding.

Turn angle was calculated as the cosine similarity between subsequent change vectors. Cosine similarity is often used as a measure of similarity between word embeddings in natural language processing (Han, Kamber, & Pei, 2012). Turn angle values were thus bounded between -1 and $+1$. Values of -1 indicate that the current step is in the complete opposite direction of the previous step. Values of $+1$ indicate that the current step is in the exact same direction as the previous step. Values of 0 indicate that the current step is a direction

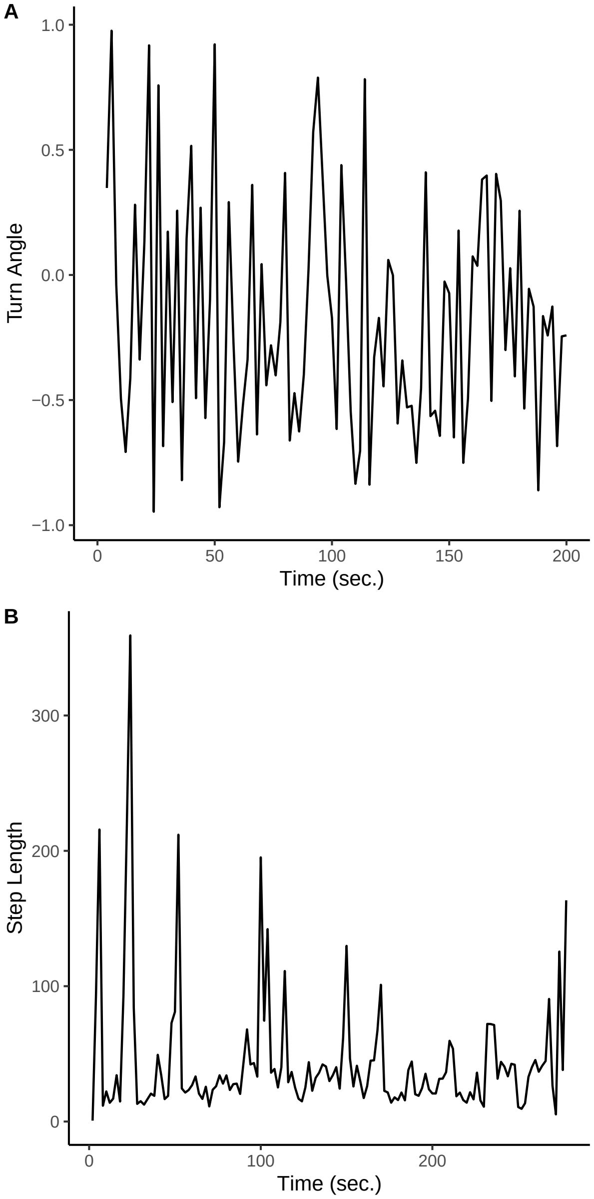

Figure 2: **Moment-to-moment dynamics of foraging in one illustrative track.** (A) Time-course of turn angles, calculated as the cosine similarity between sequential steps in sonic space. (+1 = movement continued in same direction; 0 = movement in an orthogonal direction; -1 = movement reversed direction.) (B) Time course of length of sonic steps for the same song. (Length was calculated using Euclidean distance from one location in MFCC space to the next.)

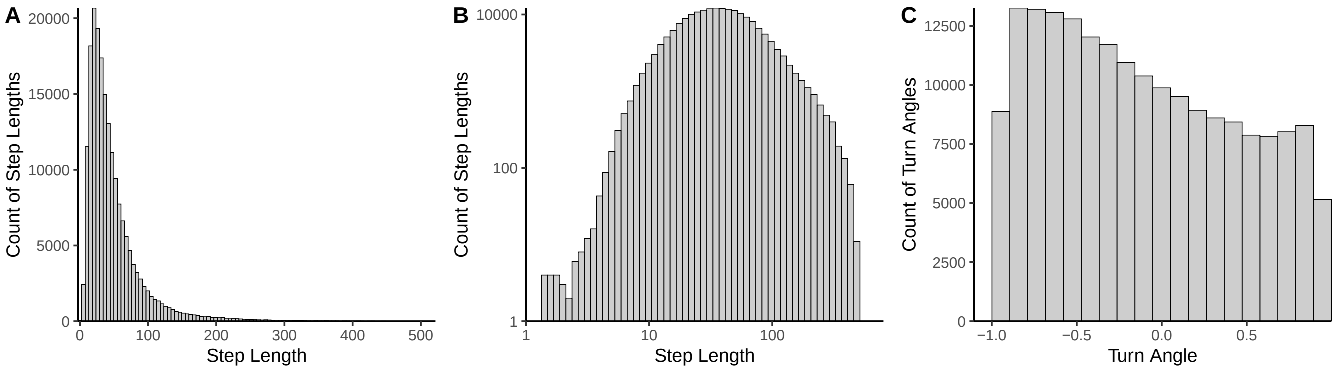

Figure 3: **Distribution of sonic step lengths and sonic turn angles** (A) The distribution of sonic step lengths is heavy tailed. This is consistent with both Area Restricted Search and Levy flight foraging. (B) Distribution of sonic step lengths on a log-log plot, with both step length and frequency log-transformed. (C) Distribution of sonic turn angles. Note that values were more often less than 0, which indicates a tendency to turn back, reversing the previous sonic movement.

orthogonal to the previous step.

The temporal dynamics of these two values can distinguish between Levy flights and Area Restricted Search (Hills, Kalff, & Wiener, 2013). Levy flights are characterized by random draws from a heavy-tailed distribution of step lengths. Since Levy flights are memoryless, the probability of taking a large or small step is independent of the size of recent steps. Area Restricted Search, by contrast, is characterized by two distinct regimes: an 'explore' regime with larger steps that go off in orthogonal directions (i.e., turn angles close to 0); and an 'exploit' regime, triggered by an encounter with something rewarding (e.g., a novel, interesting sound), with many small steps that turn back on themselves (i.e., turn angles close to -1. Thus, while Levy flights are memory-less and thus do not change when a new patch is encountered, Area Restricted Search switches from explore to exploit when a new patch is encountered.

Identifying 'patches' of improvised sound

To identify moments of large sonic transition — that is, jumps from one sonic patch to another — we used Foote novelty, a measure of novelty in a time series (Foote, 2000). Foote novelty is a common multivariate metric of change well suited for time series data that has recently been extended to analyze human cultural activity (Leroi et al., 2020). Large values of Foote novelty indicate a moment between two periods that are highly different from each other yet highly similar within each period. The measure works by comparing moment-to-moment pairwise similarity within the periods on either side of a temporal boundary, to moment-to-moment pairwise similarity across the temporal boundary.

Results

Quantifying trajectories through sound space. We first investigated musicians' trajectories through sound space. Analyses of sound similarity revealed that, over the course of improvised performances, musicians moved from one region of sound space to another (Fig. 4). Sounds that were performed around the same time in a track were more similar than sounds that were performed farther apart in time. This suggests that the collectively improvised sound changed over the course of each track.

Next, we examined the distributions of step length to determine if they followed a heavy tailed distribution. As stated earlier, a heavy tailed distribution of step lengths is common to both Area Restricted Search and Levy flight search patterns. Figure 3A shows the distribution of step lengths which indeed indicate a heavy tailed distribution with step lengths ranging from 0 to 389 ($M = 44.21$, $SD = 32.75$). We also plotted a log transformed distribution of step length values (Fig. 3B) due to the heavy tailed distribution of step lengths. This distribution does not appear to be power-law distributed, and instead bears some resemblance to a log-normal distribution, suggesting the possibility of multiplicative processes. Next, we examined the distribution of turn angles. (Fig. 3C). The distribution of turn angles is more uniformly distributed from -0.99 to 0.99 ($M = -0.11$, $SD = 0.50$). However, this distribution of turn angles has a positive skew, which indicates that musicians spent more time turning back in sound space than continuing in the same direction.

These distributions are congruent with both Area Restricted Search and Levy flight search behavior. Thus, we next investigated whether search behavior changed before and after an encounter with a new 'patch' of interesting sound, a hallmark of Area Restricted Search.

Stable sound regimes punctuated by large acoustic changes. To analyze the searching behavior before and after acoustic transitions (i.e., periods of major sonic change), we used Foote novelty. For the current analysis we focused on large acoustic transitions which consisted of Foote novelty scores that were 1.5 standard deviations above the mean.[1]

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[1] Preliminary sensitivity analyses found that the patterns reported in this section are most pronounced for large sonic shifts (i.e., when

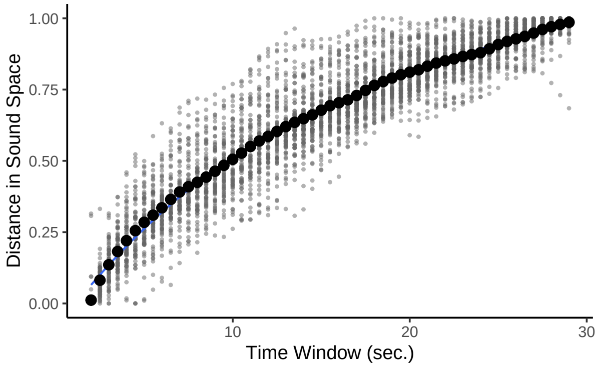

Figure 4: Musicians change sonic location over the course of improvised performances. Sounds were more different (vertical axis) if they were farther apart temporally within a track (horizontal axis). Large black dots show the mean sonic distance across all tracks; smaller grey dots show the mean sonic distance for a single track. Distance in sound space is normalized within each track to range from 0 (maximally similar sounds) to 1 (maximally different sounds).

There were 98 acoustic transitions ($M = 1.3$/recording) ranging from 1 to 9 transitions across all tracks.

Evidence of Area Restricted Search in sonic foraging. Finally, we investigated whether musicians strategically and systematically changed their sound-foraging behavior before and after a major sound transition, which is consistent with Area Restricted Search but not with a Levy flight.

We examined the sound trajectories in the period immediately before and after moments of large acoustic transition (Fig. 5). We analyzed the 10 second windows before and after each acoustic transition. Sensitivity analyses, not reported here due to limitations of space, confirmed that our analyses are not highly sensitive to the choice of window duration. Before major acoustic transitions, musicians' sound trajectories were highly exploratory (Fig. 5, red cross). Turns were significantly more orthogonal than at other times ($M = -0.10$, $SD = 0.47$) and moment-to-moment acoustic steps were significantly larger ($M = 53.80$, $SD = 26.28$). By contrast, after large acoustic transitions, musicians rapidly returned to a more exploitative regime (Fig. 5, green cross), similar to the acoustic trajectories at other times. Turn angles were more negative (more reversed) in comparison to before the transition ($M = -0.20$, $SD = 0.47$). Moreover, step lengths decreased (returning near baseline) after a transition ($M = 47.25.80$, $SD = 20.24$).

This pattern was confirmed by multilevel Bayesian models of acoustic step length and turn angle. The first model contained step length as the outcome variable with the predictor variable being 10 seconds before and after each acoustic transition allowing the intercept to vary by each audio track. This model confirmed that step lengths after the transition were indeed smaller then before the transition ($\beta = -14.32 \pm 6.27$ SE, Bayesian Credible Intervals $= [-26.47 - -2.17]$). The second model contained turn angle as the outcome variable, again with the predictor variable being 10 seconds before and after acoustic transitions and intercepts varying by audio track. This model also confirmed that turn angles were more negative after acoustic transitions compared to the period before ($\beta = -0.30 \pm 0.10$ SE, Bayesian Credible Intervals $= [-0.49 - -0.09]$).

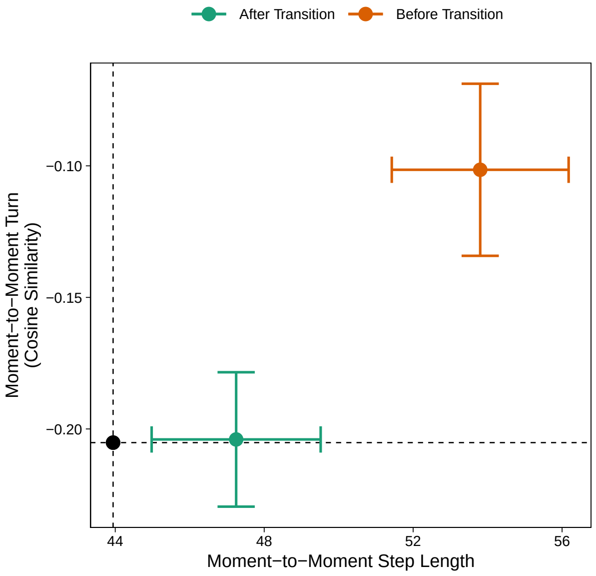

Figure 5: Turn angles and step lengths before and after transitions. Dotted line represents average step length and turn angles for all recordings. Black dot represents the mean across all tracks. Red dotted cross represents the mean with error bars for all tracks 10 seconds before a transition. Green cross represents the mean with error bars for all tracks 10 seconds after a transition.

Discussion

The purpose of the current study was to determine if humans engage in patterns similar to Area Restricted Search during abstract creative improvisation. To examine this question, we analyzed the sound trajectory of free jazz musicians as they improvised by embedding each recording in high dimensional 'sound space.' We indeed found that displacements in this sound space were heavy-tailed, with many small steps and few large ones, a distribution that is consistent with both Area Restricted Search and Levy flights. To distinguish between these two foraging strategies, examined the search behavior before and after encounters with a novel 'patch' of sound. Before musicians transitioned to an especially novel region of the sound-space, they reliably exhibited more exploratory search behavior, with greater step lengths and turn angles that

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the threshold for Foote novelty is set higher), which correspond to cases where the new 'patch' of sound is most different from the previous one.

were more orthogonal in the moments leading up to a transition. After transitioning to the new sound, they switched back to a more exploitative search behavior, with smaller step lengths and turn angles that were more oriented toward turning backwards. This is consistent with Area Restricted Search behavior but not with Levy flight foraging. The free improvising musicians in our corpus, therefore, appear to engage collectively in the sonic equivalent of Area Restricted Search through an abstract space of spaces.

Here, we have used free jazz improvisation as a case study of abstract human "foraging" during collective improvisation. We have focused on free jazz for a number of reasons. For one, unlike non-musical forms of collective creativity, during free jazz the process of collective improvisation is measurable as it unfolds acoustically in real time. Furthermore, unlike most other forms of musical improvisation, in free jazz all musicians participate in the improvisational process rather than merely providing harmonic or rhythmic support to an individual soloist. This makes free jazz a paradigmatic example of *collective* rather than individual improvisation. The current project thus offers a proof-of-concept that collective improvisation can be analyzed as a kind of abstract foraging, using free jazz as a paradigmatic example of collective creativity. Similar analyses may extend our results to other forms of collective search through acoustic, semantic, or physical space. For instance, completing similar analyses on other genres of music — both improvised and composed — may provide further insight into how collective foraging strategies vary across contexts.

Implications for the study of collective behavior

Although the current study focused on collective search within the context of free jazz, the results could be used as a guide to analyse other forms of collective behavior. Similar to analysing improvisation, Area Restricted Search is often used to categorize the behavior of an individual, however here we find that the entire group seems to exhibit Area Restricted Search. Applying this type of analysis to other types of collective human behavior such as team sports or collective problem solving may find that this same process is recycled across various types of group phenomena.

Implications for high-level creative improvisation

Similarly, using this same approach to analyse other types of creative improvisation could further clarify the strength of the current findings. Within free jazz, the improvisation process is moment to moment, however analysing the search process of longer time scale improvisation such as creative story telling, improvised comedy, or visual art could also be helpful. Moreover, analysing the same type of improvisation at various time scales could check for nested behavior to this search process. For example, analyzing the trajectory of an entire free jazz album could help determine if musicians search between tracks in the same way they search within tracks.

Future Directions

While the current study is primarily interested in free jazz as a case study for creative improvisation, future research can expand the analyses used in this study to other genres of music, as well as other forms of creative improvisation. Finding similar patterns of Area Restricted Search behavior in more traditional forms of jazz could provide insight into how improvisation with more structure could use similar methods of search. Conversely, it could be that added structure of traditional jazz improvisation could diminish processes that resemble Area Restricted Search. Furthermore, a comparison to non-improvised music with predetermined structure would ensure that current findings are unique to improvised genres given that we do not find the same or similar results. Lastly, future work could use these analyses in congruence with analytical approaches from musicology that emphasize the perspectives of the musicians, as discussed in Pinheiro (2023). This would provide musicologist who are knowledgeable about a genre's sociocultural and musical context with an additional objective approach for analysing musical pieces.

Conclusion

High level creative improvisation seems to be one of the features unique to human cognition. However, innovation during improvisation may arrive from broader evolutionary mechanisms for search and discovery. The current research has demonstrated that in the case of free jazz improvisation, the Area Restricted Search patterns present in animal foraging strategies also seem to be a part of highly creative improvisation.

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