# Musical improvisation reveals the fine-grained foraging dynamics of collective innovation

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## Abstract

Collective innovation is key to the global success of the human species. However, the moment-to-moment details of how creative innovation is accomplished by a collective remain unclear. One challenge is that while creative products (e.g., scientific breakthroughs, technological inventions, rehearsed performances) may be public, the creative processes that generated those products are often private. Here we introduce collective musical improvisation as a model system for the fine-grained study of *in vivo* collective innovation. In free jazz improvisation, the creative product *is* the creative process, offering a unique real-time window into the creative process. Using a corpus of free jazz recordings, we embedded each track as a trajectory through a high-dimensional "sonic space" and then analyzed the strategies by which musicians moved collectively through this space of sonic possibility. Despite the cognitive sophistication and cultural richness of musical improvisation, we find that musical ensembles spontaneously adopt a search strategy, Area Restricted Search, with deep evolutionary roots, previously identified in animal foraging. This convergence between behavioral ecology, cognition, and culture suggests deep evolutionary origins of the human capacity for collective innovation.

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# Introduction

Collective innovation is a cornerstone of our species' global success [1, 2]. This capacity is manifest in activities as varied as technological invention [3], crisis problem solving [4], scientific collaboration [5], and even interpersonal conversation [6], all of which require the coordination of creative behaviors distributed among multiple actors. Understanding the moment-to-moment dynamics of collective innovation remains a grand challenge. One major stumbling block to the scientific study of collective innovation is the inherent opacity of the creative process: while creative products like scientific publications or rehearsed musical performances are visible as the public "frontstage" of innovation, the crucial "backstage" of real-time collaborative creation often remains hidden [7]. The opacity of the creative process has severely limited our understanding of the fine-grained dynamics of real-world collective innovation.

To penetrate this observational barrier, we turned to a unusual group of creative professionals notorious for engaging publicly in the process of collective innovation: free jazz musicians. Improvising musicians must coordinate continuously, make constant decisions on the timescale of milliseconds, and select their moment-to-moment activity from a huge space of acoustic possibility [9]. In stark contrast to domains where the creative process is hidden behind its product, in musical improvisation the process of creation *is* the publicly observable product. This immediacy distinguishes it from, say, musical composition or scientific research, where creative products like musical scores or scientific publications are the polished outcomes of often protracted and private generative processes. Crucially, among improvisational practices, free jazz is especially well suited for studying truly *collective* creativity. Unlike genres that focus on individual soloists with harmonic or rhythmic accompaniment, in free jazz all ensemble members participate simultaneously in the improvisational process [10, 11]. Free jazz ensembles perform without established leaders, preexisting musical scores, predetermined chord changes, planned solo intervals, established harmonies, or canonical musical phrases. Instead, they make it up on the fly, collectively creating novel sounds as they navigate a space of possible sounds that is largely unconstrained [12]. Likewise, collaboratively improvising musicians rapidly and mutually adapt to their improvising partners to create optimal musical performances [13, 14]. Collective free jazz improvisation thus provides a unique real-world laboratory for studying the unscripted, fine-grained, moment-to-moment dynamics of collective innovation *in vivo*.

Here, to quantify the fine-grained dynamics of collective innovation, we analyze the improvisational process as a kind of *foraging*, a search for rewards in an uncertain landscape. More mundane forms of individual creativity have been characterized as foraging processes, including searching through semantic memory [15], creating interesting visual patterns [16, 17, 18], and solving insight puzzles [19]. Similarly, free improvisation can be thought of as a *collective* foraging process, in which musical ensembles must move through an abstract space of sonic possibility with the goal of discovering sounds that are novel, interesting, or otherwise rewarding. From this perspective, locations within the sonic space correspond to complex sounds produced by the musical ensemble, which could be sounds that the musicians have produced before (analogous to locations that a foraging organism has visited previously) or entirely novel
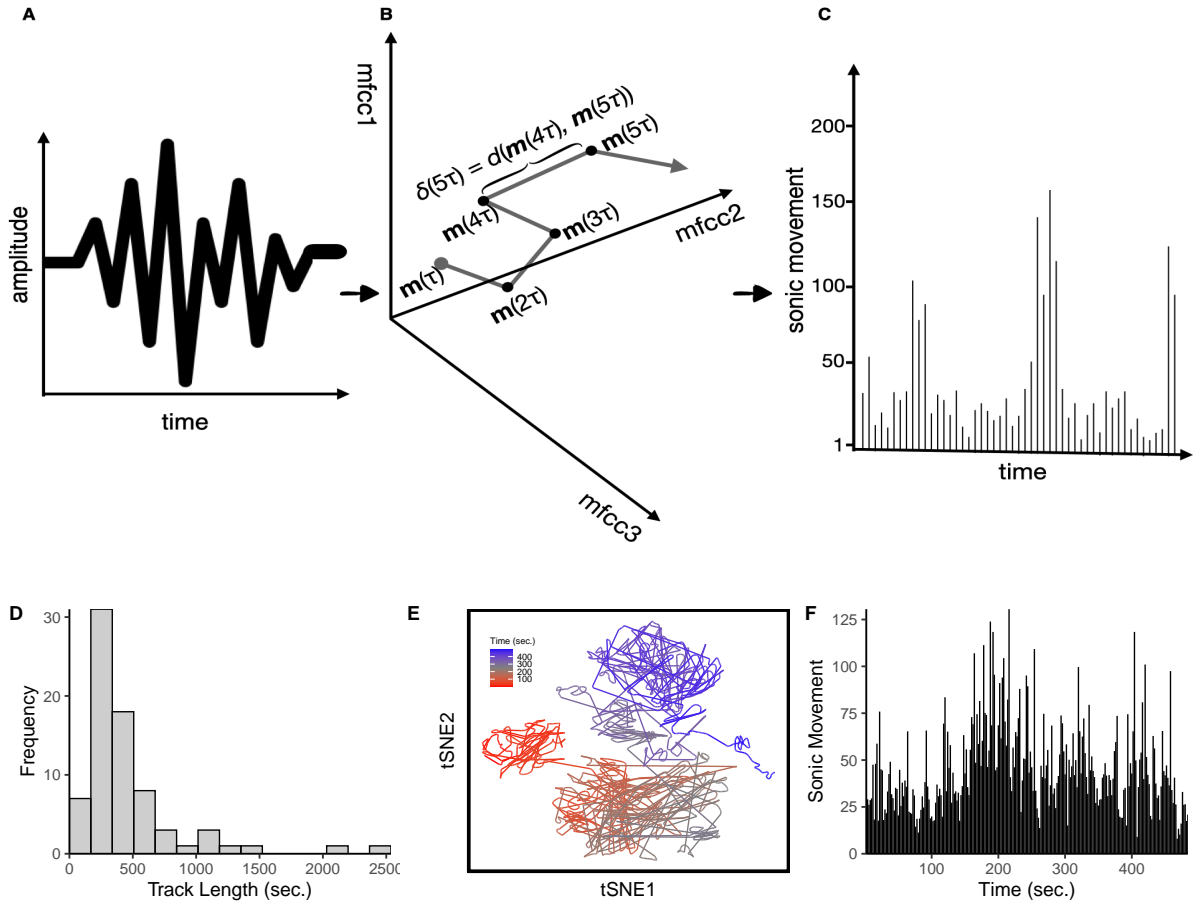
2

Figure 1: **Quantifying the sonic trajectories of improvised musical performances. (A-C)** Graphical illustration of the analysis pipeline. Single-track audio recordings of improvised free jazz, illustrated in (A), were transformed into trajectories through a 'sonic space,' illustrated in (B), that captured timbral features using Mel Frequency Cepstral Coefficients (MFCC). The trajectory for each recording consisted of consecutive sonic embeddings, $m(t)$, of brief, non-overlapping "moments" of duration $\tau$. To quantify the moment-to-moment dynamics of these trajectories, we calculated the sonic movement at time $t$ as the Euclidean distance between consecutive sonic embeddings, $\delta(t) = d(m(t - \tau), m(t))$. This generated a time series of moment-to-moment sonic movements, illustrated in (C). **(D)** Empirical distribution of track durations in the corpus of free jazz recordings. **(E)** Trajectory through sonic space of one illustrative track. For visualization, the trajectory's 20 dimensions were reduced to 2 using t-SNE, a dimension-reduction technique [8]. Color indicates time within the recording, from start (red) to end (blue). **(F)** Time series of moment-to-moment sonic movements for the track in (E).

60 sounds that have never been created (analogous to locations that a foraging organism has yet to
61 visit). Below, we explain how computational methods can formalize this foraging perspective

3

on musical improvisation (Fig. 1, A-C).

What foraging strategies might musical ensembles use to improvise? Across a wide range of environmental conditions where resources cluster together in patches, a highly effective foraging strategy is to move through the space using a Lévy flight random walk [20]. In a Lévy flight, the length of each step is drawn randomly from a heavy-tailed distribution, with frequent small steps and infrequent large steps [21]. Despite their randomness and lack of any plan or memory, Lévy flights can generate search trajectories that appear patchy, with extended periods spent within local regions, interspersed with large jumps to new regions. The spatial foraging behavior of a wide variety of organisms has been characterized as Lévy flights, including albatrosses [22], sharks [23], mussels [24], deer [25], humans [26, 27, 28], and even entire sports teams [29], although subsequent reanalyses have cast doubt on some of these claims [30, 31]. While a random walk may seem an overly simplistic account of collective innovation, random walks have been used to model a range of high-level cognitive processes, including decision making [32, 33], memory retrieval [34], individual creativity [35], curiosity [36], and even scientific productivity [37], and some have argued that they are optimal in a wide range of conditions [20]. In the context of improvised music, novel and interesting sounds are distributed unevenly and unpredictably throughout the space of sonic possibility, so musicians could perform an abstract form of a Lévy flight to increase their odds of encountering particularly novel or interesting sounds.

Alternatively, instead of moving randomly as in a Lévy flight, foragers may respond strategically to resource encounters [38]. In Area Restricted Search, for instance, resource encounters prompt the forager to search nearby, thus 'exploiting' the local region. As resource encounters become less frequent, the organism becomes more likely to abandon that region to 'explore' widely for a new patch of clustered rewards. Much like Lévy flights, Area-Restricted Search has been documented widely in the natural world [38], including in ladybugs foraging for aphids [39], seabirds foraging for fish [40], and humans foraging for mushrooms [41]. Since resources are often clustered spatially, Area Restricted Search can generate patchy trajectories that resemble those of a Lévy flight. After encountering an interesting sound, for instance, improvising musicians may decide collectively to persist in exploiting the similar sounds within a sonic patch or "soundworld," only switching to explore for a new soundworld when they have exhausted the current soundworld's novelty or interest.

As accounts of foraging, Lévy flights and Area Restricted Search are difficult to distinguish because both can generate search patterns that are patchy, with periods of sustained search within a focal region punctuated by leaps to a new region. A key difference, however, is the role of memory in the transition between patches [42, 43]. In a Lévy flight, the organism does not adjust its behavior on the basis of recent resource encounters; it just draws randomly from a heavy-tailed distribution of steps. An organism engaged in Area Restricted Search, by contrast, will transition from exploring to exploiting when it encounters a new resource, and it may then persist in exploiting that region based on the memory of that resource encounter. Area-Restricted Search and Lévy flights are thus distinguished by whether or not the organism adjusts its foraging behavior before and after a resource encounter. As a consequence, when an

4

organism uses Area Restricted Search to forage in a patchy landscape, large exploratory steps should cluster together temporally within periods of sustained exploration; in a Lévy flight, by contrast, the temporal distribution of large steps is random.

Using a corpus of audio recordings of professional musicians engaged in collective improvisation — a model system for the fine-grained study of *in vivo* collective innovation — we investigated the foraging strategies adopted collectively as the ensembles engaged in free improvisation (Fig. 1, A, D). We converted each track ($N = 75$, ranging from 1 min. to over 40 min.) into a trajectory through a space of sonic possibility by embedding consecutive moments in a high-dimensional "sonic space" (Fig. 1B, E). We quantified the dynamics of these trajectories by analyzing the moment-to-moment movements through this sonic space (Fig. 1C, F). We then asked whether the dynamics of collective improvisation instantiate classic foraging strategies from behavioral ecology.

# Results

## Sonic foraging exploits local patches of sound

We first characterized the overall dynamics of musicians' sonic foraging. We calculated the pairwise distance between sounds produced throughout each track, using Euclidean distance between sonic embeddings (see Methods). In more structured genres of music, including so-called "straight-ahead" jazz in which improvised solos are interleaved with composed sections, songs will often return repeatedly to the same region of sonic space (e.g., the refrain or chorus in a pop song). In free improvised music, on the other hand, the sound may wander without returning. (In Figure S1, we visualize this difference between a more structured jazz standard and a free jazz performance.) As a result, freely improvised music should gradually diverge from past sounds. As expected, in the corpus, sounds that were performed around the same time in a track were highly similar, and mean sonic distance increased monotonically for sounds that were produced at increasingly distant moments (Fig. 2A). On the long timescale of the entire track, therefore, musicians explored widely in the the sonic space.

On the short timescale of moment-to-moment playing, however, the ensembles engaged primarily in *exploitation* of local regions of sonic space, as revealed by the size and direction of moment-to-moment sonic change. Musicians primarily made smaller adjustments to their sound, but infrequently made unusually large changes, generating a heavy-tailed distribution of sonic movements (i.e., sonic distannces between consecutive moments; Fig. 2B). This is consistent with both Area Restricted Search and Lévy flight foraging strategies. In the Supporting Information, we show that these sonic movements are well characterized by a log-normal distribution, which is typically generated by multiplicative processes [44], suggesting (unsurprisingly) that musical improvisation reflects complex interactions among the musicians rather than independent, additive contributions. (For context, in the Supporting Information we also plot the distribution of sonic movements for a structured jazz standard; movements in this track are
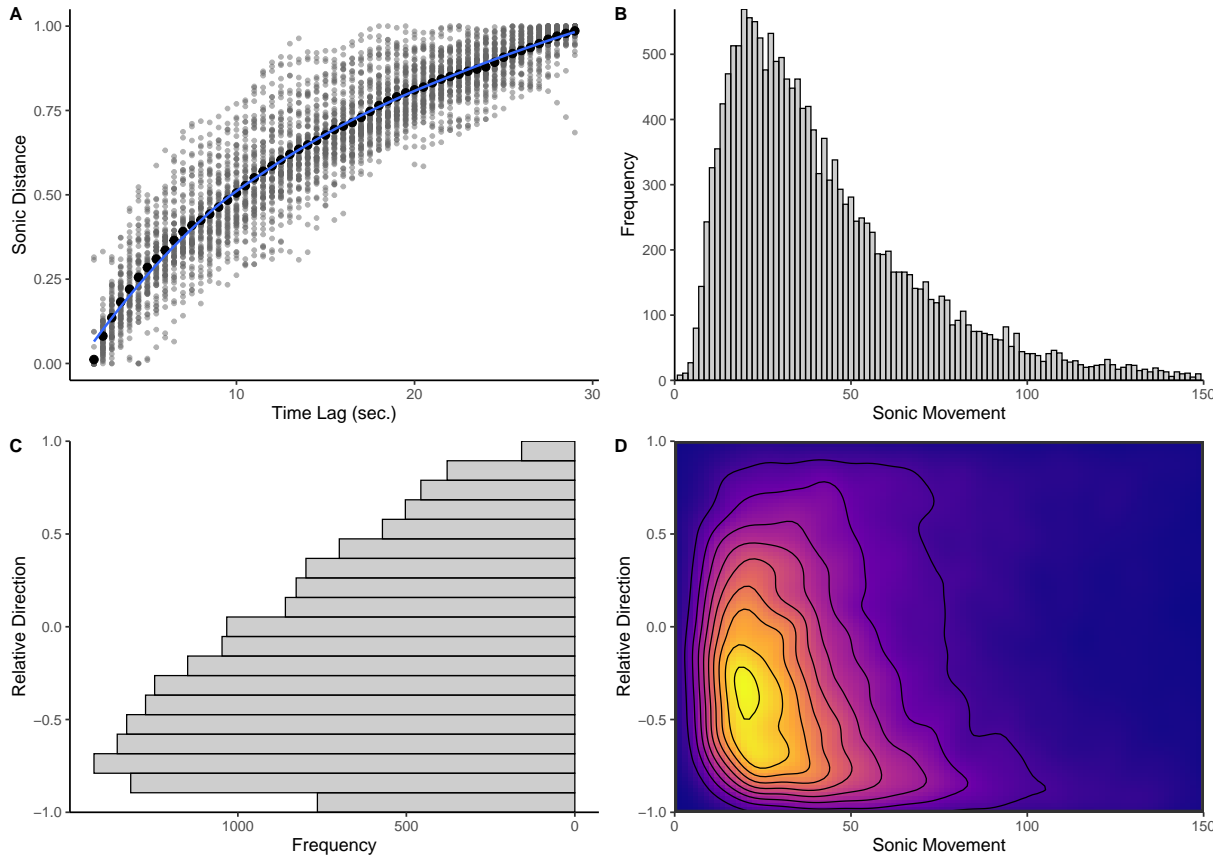
Figure 2: **Free improvised music consisted primarily of local exploitation of the sonic space.**
(**A**) Temporal decay of sonic similarity. Within each track, sounds were more dissimilar (vertical axis) if they were produced further apart temporally (horizontal axis). Smaller grey dots show the mean sonic distance between all pairs of moments within a particular track that were produced at a given temporal lag. Large black dots show means across all tracks. Sonic distance was rescaled within each track to range from 0 (maximally similar sounds) to 1 (maximally dissimilar sounds). (**B**) Heavy-tailed distribution of sonic movements (i.e., sonic distance between consecutive moments). (**C**) Distribution of relative directions across all tracks. Relative direction was measured using cosine similarity and thus ranges from $+1$ (continuing in the same direction), to $0$ (moving in an orthogonal direction), to $-1$ (reversing direction). Moment-to-moment movements more frequently involved reversing the direction of the previous movement (i.e., more negative relative direction). (**D**) Kernell density heatmap of moment-to-moment sonic movement (distance between consecutive moments) and relative direction. Most movements involved a smaller step that reversed the direction of the previous step, consistent with local exploitation of a limited region of sonic space. (Color indicates relative density: lighter yellow = higher density; darker purple = lower density)

considerably smaller, with fewer larger steps.) Notably, the relative direction of sonic change, which characterizes whether sonic movements continued or reversed direction, was less skewed and primarily negative ($M = -0.11$, $SD = 0.50$; Fig. 2C), indicating a tendency to turn back rather than continue in the same direction. This pattern of smaller sonic movements that tended to turn back on themselves is indicative of local exploitation, which is characteristic of both the 'exploit' phase of Area Restricted Search and the dominance of small steps in a Levy flight.

## Large-scale sonic exploration occurred in bursts

While the musicians engaged primarily in local exploitation — small steps that turned back on themselves — the heavy-tailed distribution of sonic steps reveals that they occasionally engaged in larger steps that allowed them to explore new sonic possibilities. In a Lévy flight these big steps occur at random, while in Area Restricted Search they arrive in bursts while the collective is engaged in sustained exploration for a new patch of interesting sounds. To quantify the burstiness of large sonic steps, we identified sonic movements that were unusually large and calculated whether these clustered together in bursts of sonic exploration (see Methods). In line with Area Restricted Search, and unlike a Lévy flight, the temporal distribution of large sonic steps was significantly bursty (Burstiness: $M = .15 \pm .02$ SE, $t(73) = 6.9$, $p < .001$, Fig. 3B). Large sonic movements thus occurred in temporal clusters.

To determine the foraging strategy that could have generated this pattern, we implemented minimal models of Lévy flight and Explore-Exploit foraging. The latter captures the outcome of Area Restricted Search in a patchy landscape of sonic resources. To test whether these models could recover the observed temporal distribution of sonic movements for each track, we fit the models to the empirical distribution of sonic movements and then generated synthetic time series of sonic movements.

First, the Lévy flight model was a memory-less, uncorrelated random walk. At each time step, the musical ensemble takes a sonic step of length $d$, with $d$ drawn from each track's empirical distribution of sonic movements (Fig. 3A, top). Note that here we use the heavy-tailed empirical distributions of sonic movements rather than a true Lévy distribution, although our results are robust to the choice of distribution.

Second, the Explore-Exploit model traded off between exploration and exploitation (Fig. 3A, top), the behavior generated by Area Restricted Search in a patchy landscape. Like the Lévy flight model, this minimal model generates sonic movements by drawing randomly from distributions estimated from the tracks in the corpus. Unlike a memory-less Lévy flight, the musical ensemble can be in one of two latent states, and the distribution from which the sonic movement is drawn depends on the latent state: smaller movements while *exploiting*, larger movements while *exploring*. For simplicity, we ignore the resource encounters that drive changes in behavior in Area Restricted Search, and instead allow the minimal model's latent state to switch stochastically. We implemented this process as a two-state Hidden Markov Model, fit to the empirical time series of each track's sonic movements. Since Hidden Markov Models estimate the distribution of observations associated with each latent state, they can capture processes
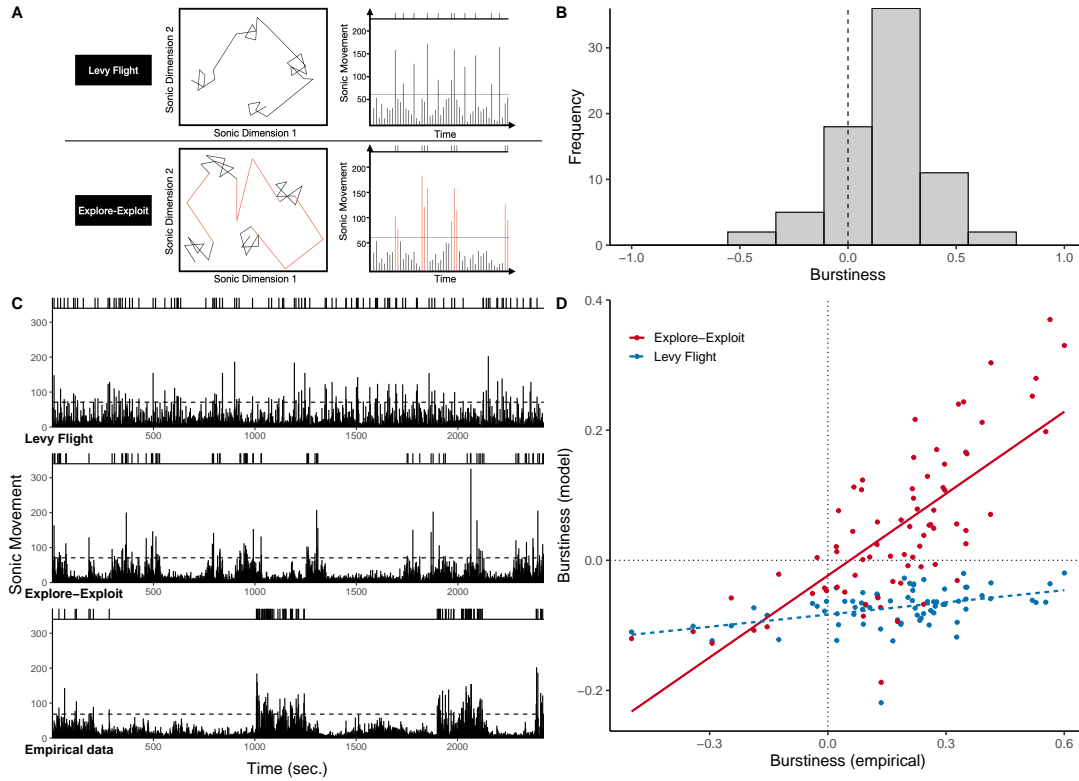
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Figure 3: **The burstiness of free improvisation was consistent with Explore-Exploit foraging, a pattern generated by Area Restricted Search in patchy environments. (A)** Graphical illustration of minimal models of foraging: Lévy flight (top) and Explore-Exploit (bottom). Left panels illustrate hypothetical trajectories through sonic space. Explore-Exploit alternates between exploitation (black) and exploration (red). Right panels illustrate hypothetical time series of sonic movements (i.e., sonic distance between consecutive moments) derived from these trajectories, with movements considered 'large' if they passed a threshold (dashed line). Raster plots atop each time series show the timing of large movements: random in the Lévy flight and in clustered bursts in the Explore-Exploit process. **(B)** Empirical distribution of burstiness of large sonic movements. Large movements typically occurred in clustered bursts (i.e., burstiness $> 0$), consistent with an Explore-Exploit process. **(C)** Time series of sonic movements from one representative free jazz performance (bottom) and minimal models fit to that recording: Explore-Exploit (middle) and Lévy flight (top). Raster plots atop each time series show the timing of large movements. **(D)** Burstiness of recordings in the free jazz corpus (x-axis) compared to the burstiness generated by minimal models of those recordings (y-axis): Explore-Exploit (red) and Lévy flight (blue). Lines show linear regressions between empirical burstiness and model burstiness. Only the Explore-Exploit model recovered the burstiness of the empirical recordings.

8

where one latent state is associated with larger steps and the other with smaller steps, although this is estimated from the empirical time series for each track. Moreover, since Hidden Markov Models estimate the transition probabilities between latent states, they can capture persistent latent dynamics (i.e., the tendency to persist in *exploit* or *explore* modes), although once again this is estimated from the empirical time series. This model thus incrementally extends the Lévy flight model by allowing the musical ensemble to toggle between two latent regimes of sonic improvisation.

We used these minimal models to simulate time series of sonic movements. For each track, we used each of the two models to generate 100 simulated time series, with duration equal to the track's actual duration (Fig. 3C). Then, for each track, we calculated the mean burstiness of these simulated time series. As predicted, large sonic movements generated by the Lévy flight model were reliably anti-bursty (burstiness: $M = -.07 \pm .00$ SE, $t(74) = -19.03, p < .01$). Instead the temporal distribution of large steps ranged from random to periodic (Fig. 3D, blue dots). Conversely, the large sonic movements generated by the Explore-Exploit model clustered together in time and were thus consistently bursty ($M = .05 \pm .01$ SE, $t(74) = 3.47, p < .01$). The improvised tracks' true empirical values of burstiness were strongly associated with the burstiness values generated by the Explore-Exploit model (linear regression predicting empirical burstiness: $b = 1.30 \pm 0.17, p < .001$; Fig. 3D, red dots and line) but not the burstiness values generated by the Lèvy flight model ($b = -0.03 \pm 0.66, p = .96$; Fig. 3D, blue dots and line). Thus, the temporal clustering of large sonic movements in collectively improvised music is explained by a minimal model of Explore-Exploit foraging, but not by a model of Lévy flight foraging.

## Ensembles explore before and exploit after encountering a new soundworld

Finally, we examined whether musicians changed their foraging behavior before and after encountering a novel patch of sonic space or 'soundworld,' as predicted by Area Restricted Search but not Lévy flight foraging. We identified acoustic transitions between soundworlds as peaks in Foote novelty, a measure of change between stable periods of a time series (see Methods). These are moments when the musical ensemble changed its playing suddenly, going from one stable soundworld to a novel one. In the period immediately before transitioning to a new soundworld (i.e., the 10 second period before), musicians' sonic foraging was systematically more exploratory than moments away from a transition (Fig. 4A), with moment-to-moment sonic movements that were larger ($M = 53.5 \pm 2.4$ SEM; Fig. 4A) and changes in direction that were more orthogonal (i.e., closer to 0; $M = -0.10 \pm 0.03$ SEM; Fig. 4B). A shift toward exploratory foraging can thus serve as an early warning signal of an impending sonic transition. By contrast, in the period immediately after encountering a new soundworld (i.e., the 10 second period after), musicians' sonic foraging rapidly shifted from exploration to exploitation, with a sudden decrease in the size of sonic movements ($M = 47.4 \pm 2.3$ SEM) and relative directions that turned back on themselves ($M = -0.19 \pm 0.03$ SEM). This pattern was confirmed by multi-level Bayesian models of sonic movements and relative directions, with random effects by track

to account for between-track variation. These models confirmed that, compared to moments away from a transition, sonic foraging immediately before a transition involved significantly larger sonic movements ($\beta = 6.8$, 95% Bayesian Credible Interval = $[1.2, 12.3]$) and significantly more orthogonal turns ($\beta = 0.10$, 95% CI = $[0.03, 0.17]$). By contrast, sonic foraging immediately after a transition did not differ from baseline sonic exploitation (sonic movements: $\beta = -0.4$, 95% CI = $[-5.4, 4.5]$; relative directions: $\beta = 0.00$, 95% CI = $[-0.07, 0.07]$). Thus, transitions to a novel soundworld were prefigured by sonic exploration, while encounters with novel soundworlds were associated with a shift back to exploitation (Fig. 4C), as predicted by Area Restricted Search, but inconsistent with a memory-less Lévy flight process.

# Discussion

By analyzing the moment-to-moment creative decisions of free jazz musicians, we have shown that their collective improvisation reflects a process of collective foraging through sonic space. Their sonic movements were heavy-tailed, with many small sonic movements and few large ones. Large sonic movements tended to cluster together in time, a bursty pattern that is consistent with the regime switching of Area Restricted Search but not the random draws of a Lévy flight. To further distinguish between these two foraging strategies, we examined the musicians' behavior before and after they encountered a novel 'patch' of the sonic space. Ten seconds before transitioning to a new patch, the musicians' playing became more exploratory, with larger sonic movements in more orthogonal directions. After arriving in the new sonic region, their playing reverted to more exploitative foraging, with smaller sonic movements and more reversals. This responsiveness to new sonic encounters is consistent with Area Restricted Search but not a memory-less Lévy flight. Thus, despite the cognitive sophistication and cultural richness of musical improvisation, we find that musical ensembles spontaneously adopted a search strategy, Area Restricted Search, with deep evolutionary roots, previously identified in animals foraging for food [38, 39, 40, 41, 42, 43]. This suggests that collective improvisation — a model system for studying collective innovation — involves the kind of distributed sensing and collective memory that is required for Area Restricted Search.

The collective sonic dynamics analyzed here complement accounts of the individual-level cognitive and physical processes involved in musical improvisation. One model of the cognitive processes underlying individual musical creativity, for instance, posits that musicians improvise in clusters of events that are either associated or interrupted [45]. Associated clusters seek continuity, consistent with the periods of collective sonic exploitation described here. Interrupted clusters differ from the preceding sound, consistent with bursts collective sonic exploration. Here we've shown quantitatively that the fine-grained dynamics of collective improvisation follow a similar pattern of stasis and transformation, association and interruption, exploitation and exploration. Other approaches have focused on the microdynamics of musician-musician interaction. Musicians are known to couple both their high-level playing (e.g., harmony, [13, 14]) and their low-level physical movements (e.g., swaying to and fro; [46, 47]). Dyadic coupling
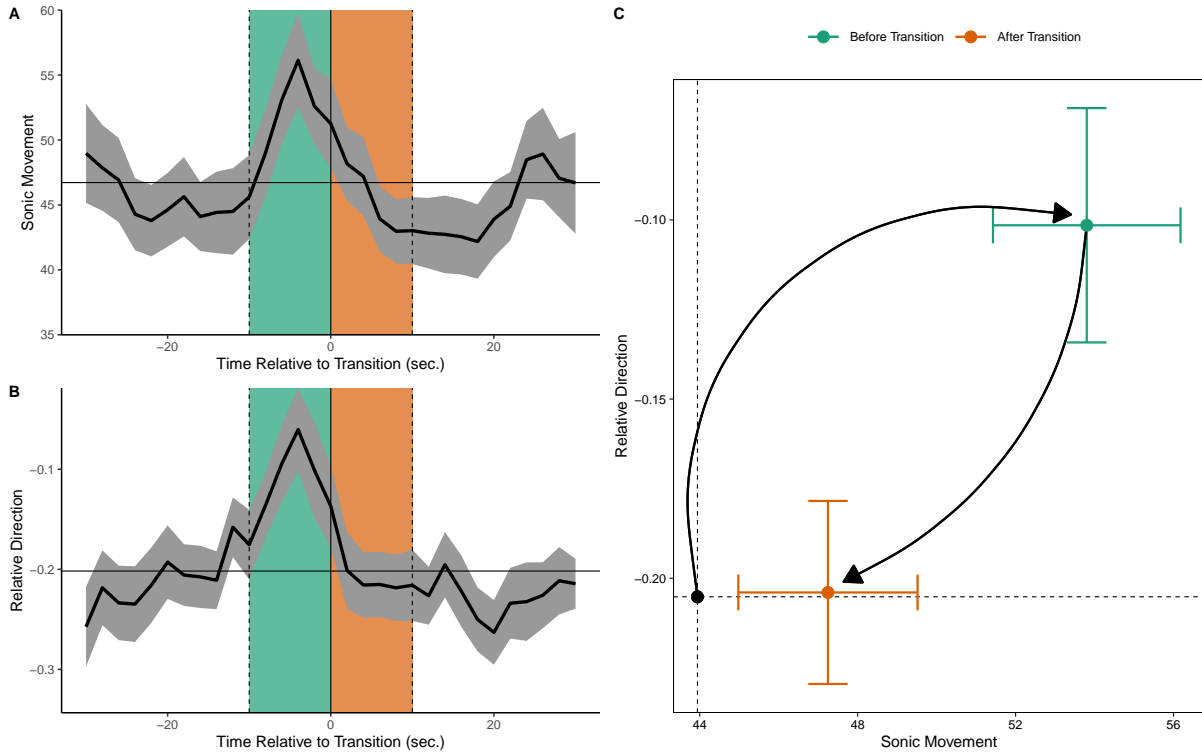
Figure 4: **Sonic foraging was more exploratory before sonic transitions.** **(A)** Time series of sonic movements in the period around major sonic transitions. In the 10 seconds before a transition (green), sonic movements became systematically larger than average (solid horizontal line), consistent with exploration. Sonic movements dipped rapidly in the 10 seconds following a transition (orange), consistent with a return to exploitation. (thick black line = mean; grey ribbon = standard error) **(B)** Time series of relative direction in the period around major sonic transitions. In the 10 seconds before a transition, relative direction approached 0, indicating that consecutive movements were in orthogonal directions, consistent with exploration. In the 10 seconds following a transition, relative direction become more negative, indicating consecutive movements that reversed direction, consistent with a return to exploitation. (thick black line = mean; grey ribbon = standard error) **(C)** Phase plot of relative direction and sonic movement before and after major sonic transitions. Arrows illustrate the transition from baseline foraging (all moments away from a major transition; black dot) to foraging in the 10 seconds before a major transition (green dot), to foraging in the 10 seconds after a major transition (orange dot). Before a transition, sonic foraging became more exploratory, with larger sonic movements in more orthogonal directions. Immediately after the transition, sonic foraging returned to a baseline of exploitation, with smaller sonic movements that turned back on themselves to stay in the same patch of sonic space. (points = means; error bars = standard errors.)

among musicians is one simple, local mechanism that could give rise to the sophisticated collective coordination analyzed here, similar to the collective synchronization that can emerge in coupled non-linear oscillators [48, 49].

Analyses similar to the ones performed here may shed light on other forms of collective search through acoustic, semantic, or physical space. Collectively improvised dance, for instance, could be analyzed as a search through "movement space" using motion tracking hardware [50] or pose estimation models from computer vision [51], while collective conversation could be analyzed as a search through semantic space [52]. We suspect that an unscripted free-wheeling conversation, for example, may resemble an Area Restricted Search for juicy topics in semantic space. And while we have focused on the short-timescale dynamics of improvisation within a single musical track, this rapid process of mutual adaptation and coordination is nested within much slower processes of lifelong learning and rehearsal [53]. Since the short-timescale dynamics of engagement and struggle can give rise to qualitatively different long-timescale dynamics of learning [53], it remains unclear how the short-timescale foraging dynamics analyzed here might develop and change over the course of a sustained creative collaboration or an entire musical career.

In seeking to understand collective innovation, Area Restricted Search can serve as metaphor, model, or mechanism. As a metaphor, Area Restricted Search can offer a framework — strategic (non-random) foraging — for thinking qualitatively about the patterns of behavior exhibited by innovative groups. As a model, Area Restricted Search can offer formal tools to quantify those patterns. And as a mechanism, Area Restricted Search can designate an evolutionarily conserved capacity, exapted to navigate figurative rather than literal spaces. We think Area Restricted Search is undeniably a fruitful metaphor. And the current results add to a larger movement to use Area Restricted Search as a model for analyzing a range of foraging-like cognitive phenomena in individuals [54, 16, 17, 18, 55, 19]. Finally, in terms of mechanism, the spontaneous emergence of Area Restricted Search in improvising musicians suggests a deep evolutionary origin of the human capacity for collective innovation. For instance, varied foraging processes — from searching for food to collective improvisation — may rely on conserved, evolutionarily-ancient mechanisms for goal-directed behavior [56]. But we hesitate to conclude that Area Restricted Search as a foraging strategy is innately specified. In addition to evolutionarily-conserved neural mechanisms, the repeated emergence of Area Restricted Search may reflect a recurring solution to a common problem — namely, searching for exhaustible resources in patchy environments. More speculatively, the ubiquity of Area Restricted Search may reflect a kind of universality [57], wherein systems that differ in their microscale details exhibit the same qualitative behavior at a more coarse-grained scale. Strategic tradeoffs between local, intensive exploitation and global, extensive exploration may emerge in a wide range of systems that differ radically in size, timescale, and content.

## Open data and analyses

Data and analysis scripts required to reproduce all results are available through the Open Science Framework: https://osf.io/6krg8/?view$_o nly = 14701b4bf32647d6ab354397c25588a9$

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