Classical creativity: A functional magnetic resonance imaging (fMRI) investigation of pianist and improviser Gabriela Montero

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ARTICLE INFO

Keywords:
Case study
Musical creativity
Improvisation
Memory
Neural imaging
Functional connectivity

ABSTRACT

Improvisation is sometimes described as instant composition and offers a glimpse into real-time musical creativity. Over the last decade, researchers have built up our understanding of the core neural activity patterns associated with musical improvisation by investigating cohorts of professional musicians. However, since creative behavior calls on the unique individuality of an artist, averaging data across musicians may dilute important aspects of the creative process. By performing case study investigations of world-class artists, we may gain insight into their unique creative abilities and achieve a deeper understanding of the biological basis of musical creativity.

In this experiment, functional magnetic resonance imaging and functional connectivity were used to study the neural correlates of improvisation in famed Classical music performer and improviser, Gabriela Montero. GM completed two control tasks of varying musical complexity; for the Scale condition she repeatedly played a chromatic scale and for the Memory condition she performed a given composition by memory. For the experimental improvisation condition, she performed improvisations. Thus, we were able to compare the neural activity that underlies a generative musical task like improvisation to ‘rote’ musical tasks of playing pre-learned and pre-memorized music. In GM, improvisation was largely associated with activation of auditory, frontal/cognitive, motor, parietal, occipital, and limbic areas, suggesting that improvisation is a multimodal activity for her. Functional connectivity analysis suggests that the visual network, default mode network, and subcortical networks are involved in improvisation as well. While these findings should not be generalized to other samples or populations, results here shed insight into the brain activity that underlies GM’s unique abilities to perform Classical-style musical improvisations.

1. Introduction

The performing arts, which include the domains of theater, dance, music, and poetry, are inherently creative activities, with artists generating novel material or interpreting material with artistic expression. Within the domain of music, improvisation — the extemporaneous creation of melodies and rhythms — is a particularly complex process. Musical improvisers generate ideas and realize them immediately in an aesthetic manner that fits within a given musical context. For this reason, improvisation is regarded as “instant composition” (Dobbins, 1980). Over the last decade, neuroscientists have used neural imaging techniques such as functional magnetic resonance imaging (fMRI) to better understand the brain activity that underlies improvisation by comparing activity patterns when participants perform improvisations as opposed to pre-learned music (Bengtsson et al., 2007; Berkowitz and Ansari, 2010; Donnay et al., 2014; Limb and Braun, 2008; Pinho et al., 2014). Thus,
scientists are able to contrast the neural activity associated with generating novel musical material in comparison to ‘rote’ musical activity. However, these group experiments looking at improvising vs. memorized fMRI contrasts have used different experimental setups, tasks, and participants and thus a wide diversity of methods have been used to study the neuroscience of creativity.

Nevertheless, group experiments performed on a variety of musicians with varying levels of expertise in improvisation have identified several core brain structures associated with improvisation. Currently, it is believed that structures such as the medial prefrontal cortex (MPFC) and cingulate cortex, the dorsolateral prefrontal cortex (DLPFC), inferior frontal cortices (e.g. inferior frontal gyrus), dorsal premotor areas (for motor planning and sequencing), and pre-supplementary and supplementary motor areas are associated with improvisation (Bashwiner, 2018; McPherson and Limb, 2018; Pinho et al., 2016). The brain structures active during improvisation span multiple functional networks, including the default mode, executive, and salience networks, underlying the idea that improvisation is a highly engaged, unique brain state (Beaty, 2015; Loui, 2018). The executive network, including medial prefrontal regions like the MPFC and cingulate cortex, is often active during tasks that require cognitive control. By contrast, the default network, including cortical midline and posterior parietal areas (Beaty et al., 2015; Loui, 2018). The executive network, including medial and posterior parietal areas (Beaty et al., 2015; Loui, 2018). The executive network, including medial and posterior parietal areas (Beaty et al., 2015; Loui, 2018). The executive network, including medial and posterior parietal areas (Beaty et al., 2015; Loui, 2018). The executive network, including medial and posterior parietal areas (Beaty et al., 2015; Loui, 2018).

Although existing literature has established some basic knowledge of core substrates involved in musical improvisation, it is unknown how creativity manifests in an individual artist. Key insight about the neuroscience of creativity may be gained not only from studying groups of artists and averaging their data together, but instead performing case study research on individual artists. Eminent musicians are often creative outliers, as they have a degree of talent or modes of expression that distinguishes them from other high-caliber, professional artists (Barrett and Limb, 2019). While generalizing data from cohorts of musicians is fundamental to a basic understanding of improvisation, case-studies of unique musicians provide an opportunity to identify novel patterns of neural activity that underlie their highly individualistic creative behavior and ability (Barrett and Limb, 2019). It is possible, for example, that averaging artists together in group experimental studies may be eliminating key neural variability that contributes to an artist’s unique creative abilities. Thus, in the present experiment we used the case study approach to investigate the creative processes of a standout Classical pianist who is a gifted performer of Classical concert repertoire as well as an amazing improviser, making her remarkable and unusual even among high-caliber, touring Classical pianists.

Here we present a neuroimaging case study of famed Venezuelan Classical pianist Gabriela Montero (GM, see Fig. 1). Montero was a child prodigy who began playing melodies on the piano before she could speak, took formal classical piano lessons throughout her adolescence, and began playing concerts solo and with professional orchestras from age 5 onwards. She developed an early skill in improvising around the age of 18 months old, when she would start to play the themes of songs that her mother would sing to her at night and improvise on them using a toy keyboard (Segal, 2006). Today, Montero is recognized worldwide for her unique concerts that include both performances of core piano repertoire as well as her improvisations. When improvising, Montero composes and plays new works in real time, often basing her improvisations on themes or musical ideas suggested by the audience in attendance. Montero has won a wide variety of awards including Grammy awards, 2 Echo Klassik Awards, as well as having albums remain on the top spots of Billboard Classical Charts for months. She has released numerous critically acclaimed albums containing interpretations of standard Western art music repertoire and her own improvisations and is shown that the salience network comprised of the bilateral insula and anterior cingulate cortex may serve as a functional link between the default mode and executive networks, identifying ideas generated during improvisation by the default network and forwarding this information to executive systems for higher order processing such as evaluation or revision (Beaty et al., 2018). Indeed, highly creative people (as assessed by a verbal divergent thinking creativity task) show dense functional connections between the default, executive, and salience brain networks (Beaty et al., 2018).

Fig. 2. Graphical representation of musical structure used in some of GM’s improvisation trials. A) Each row represents a different trial; each color represents a theme or motif, and the dark lines separate musical phrases. Cross-hatch indicates merging themes. GM improvises thematic, structured compositions that return to and embellish upon musical ideas. B) Highlight of theme and its embellishment from improvisation trial IB3. Note the significant rhythmic variations. See Supplementary Materials for audio sound files of these improvisation trials (IA1, IA4, and IB3).
known for using her improvisations to do social justice work.4

Monteiro’s abilities are unique as she is both a Classical concert performer as well as a gifted improviser, a combination which is not

whole compositions (Gjerdingen, 2007; Sanguinetti, 2012). Cognitively, internalization of these schemata in the minds, ears, and fingers of improvisers allowed them to draw upon them rapidly when improvising (see further discussion in Berkowitz, 2010). During the later Classical period of the late 18th and early 19th century, concert performers spontaneously invented cadenzas—virtuoso solo passages where a musician developed motivic material from the written sections of the movement—in solo concerti (Berkowitz, 2010). It has been proposed that this improvisatory, aural tradition declined, however, with the increased dissemination of written scores and reliance on written notation (Dobbs, 1980) as well as several other sociocultural factors (Moore, 1992). Currently, Western Classical performance practice features highly trained musicians performing repertoire rather than improvising novel compositions.

While Jazz musicians often have Classical musical training, they increasingly perform jazz improvisations as they progress through their formal training. Until now, most of the group experiments on the

4 See https://www.gabrielamontero.com/biography.

Table 1

Minima and Maxima Table showing activation (top) and deactivation (bottom) clusters and locations for contrast comparison of Improvisation vs Scale.

| Structure                          | BA | Left Hemisphere | Right Hemisphere |
|------------------------------------|----|----------------|------------------|
|                                    |    | t-score x y z          | Cluster Size   | t-score x y z          | Cluster Size   |
| Middle Frontal Gyrus               | 10.6 | 6.4 | 0.084 48 22 43 | 7.02 | 0.48 4 22 52 | 9857 |
| Superior Medial Gyrus              | 10.8 | 5.4 | 0.084 54 14 25 | 5.75 | 0.2 30 22 32 | 9857 |
| Superior Frontal Gyrus, medial     | 6   | 6.5 | 0.084 70 50 35 | 6.32 | 0.34 70 70 | 9857 |
| Posterior-Medial Frontal/SMA       | 6   | 12.8 | 0.002 60 9857 | 12.82 | 0.2 60 9857 |
| Precentral Gyrus                   | 6   | 7.7 | 0.002 12 32 58 | 10.38 | 0.56 70 44 | 9857 |
| Postcentral Gyrus                  | 1   | 6.6 | 0.002 54 35 54 | 325 | 0.93 60 36 | 9857 |
| IFG (p. Opercularis)/Broca         | 44  | 0.059 8 16 10 | 9.58 | 0.38 14 28 | 9857 |
| IFG (p. Triangularis)/Broca        | 45  | 0.067 32 4108 | 7.99 | 0.56 36 6 | 9857 |
| IFG (p. Orbitalis)                 | 47  | 0.5 | 0.062 24 6 328 | 6.62 | 0.30 24 12 | 9857 |
| ITG                                | 27  | 0.2 | 0.062 62 20 7123 | 5.81 | 0.54 44 | 9857 |
| MTG                                | 21  | 0.067 70 8 | 7123 | 9.84 | 0.48 36 2 | 9857 |
| STG/Wernicke                       | 22  | 0.2 | 0.067 64 14 | 7123 | 10.04 | 0.68 34 20 | 9857 |
| STG 41                             | 8.65 | 0.067 66 14 | 7123 | 9.75 | 0.68 8 | 9857 |
| Fusiform Gyrus                     | 19  | 0.054 | 62 20 7123 | 9.44 | 0.32 78 | 12 7123 |
| Temporal Pole                      | 38  | 0.154 | 16 16 328 | 6.66 | 0.52 24 14 | 9857 |
| SupraMarginal Gyrus                | 40  | 0.088 | 68 14 443 | 10.10 | 0.68 20 22 | 9857 |
| IPL 40                            | 0.86 | 0.066 | 28 50 325 | 8.39 | 0.46 | 56 9857 |
| Precuneus                          | 7   | 0.72 | 0.066 62 32 | 7123 | 0.56 | 18 78 | 48 9857 |
| SPL 7                             | 0.83 | 0.066 | 64 58 | 7123 | 0.89 | 0.44 | 46 58 | 9857 |
| MOG 19.18                         | 0.103 | 0.030 | 90 24 | 7123 | 0.53 | 0.34 | 80 4 | 64 |
| SOG 18.19                         | 0.519 | 0.14 | 0.94 14 | 14 | 0.16 | 0.30 | 84 26 | 7123 |
| Cuneus 19.18                      | 0.068 | 0.16 | 0.62 40 | 7123 | 0.65 | 0.8 | 92 22 | 7123 |
| LG 18                             | 0.725 | 0.10 | 0.62 14 | 7123 | 0.74 | 0.14 | 86 | 12 | 7123 |
| Calcarine Gyrus                    | 17  | 0.067 | 72 6 181 | 6.67 | 0.8 | 88 | 10 | 7123 |
| MCC 31.24                         | 0.566 | 0.12 | 0.42 36 | 7.67 | 0.0 | 4 | 50 | 9857 |
| ACC 32                            | 0.066 | 0.0 | 0.24 30 | 9857 | 0.56 | 0.24 | 28 | 9857 |
| Insula Lobe                        | 13  | 0.45 | 0.0 | 0.24 6 | 328 | 0.69 | 0.24 | 10 | 9857 |
| Rolandic Operculum                 | 44  | 0.065 | 0.0 | 0.24 | 328 | 0.93 | 0.24 | 12 | 9857 |
| Putamen                           | 49  | 0.517 | 0.0 | 0.2 | 10 | 9857 | 0.72 | 0.24 | 8 | 9857 |
| Pallidum                          | 51  | 0.64 | 0.0 | 0.2 | 2 | 9857 | 0.73 | 0.24 | 2 | 9857 |
| Thalamus                          | 50  | 0.555 | 0.0 | 0.14 | 6 | 9857 | 0.64 | 0.4 | 16 | 12 | 9857 |
| Cerebellum (VI)                    | 12.74 | 0.34 | 0.62 | 7123 | 0.96 | 0.28 | 52 | 22 | 9857 |
| Cerebellum (VIII)                  | 8.43 | 0.44 | 0.46 | 7123 | 0.80 | 0.32 | 80 | 20 | 7123 |

All coordinates are described according to the Montreal Neurological Institute system and Brodmann areas (BA) are given as well. Abbreviations: MFG = Middle Frontal Gyrus, SFG = Superior Frontal Gyrus, IFG = Inferior Frontal Gyrus, ITG = Inferior Temporal Gyrus, MTG = Middle Temporal Gyrus, STG = Superior Temporal Gyrus, SMA = Supplementary Motor Area, IPL = Inferior Parietal Lobule, SPL = Superior Parietal Lobule, MOG = Middle Occipital Gyrus, SOG = Superior Occipital Gyus, LG = Lingual Gyus, MCC = Middle Cingulate Cortex, ACC = Anterior Cingulate Cortex, AG = Angular Gyus.4

See https://www.gabrielamontero.com/biography.
neuroscience of creativity has focused on these jazz musicians for whom improvisation forms part of their core musical behavior. Gabriela Montero is unique because she is a world-class Classical pianist who not only perfects her performance of standard Western Classical art repertoire but is also equally active in generative musical activities like improvisation.

In light of Montero’s abilities as a Classical music improviser, the present study aimed to investigate neural correlates associated with improvisation. While lying in an fMRI scanner, GM performed several musical tasks: two different types of control tasks and one improvisatory experimental task. GM performed two controls at varying levels of musical complexity; GM either performed a chromatic scale (low complexity, ‘Scale’) or a pre-memorized composition (high complexity, ‘Rote performance’) or improvised upon that piece (‘Improvisation’). By contrast, in the experimental condition (‘Improvisation’), she improvised upon the composition used as a control. In addition to these functional neuroimaging tasks, functional connectivity data was also collected in a separate paradigm where GM performed a piece by memory (‘Rote performance’) or improvised upon that piece (‘Improvisation’). Functional connectivity data were collected in order to characterize potential unique signatures of improvisation in brain network modularity and integration. Given our current understanding of the neural mechanisms of improvisation, it was predicted that GM would show different brain activity in task-based measures and greater brain network modularity in functional connectivity measures when improvising vs. performing pre-composed music. However, this exploratory case study allowed us to see how her brain activity may differ from other musicians studied in group experiments to further our understanding of the neuroscience of creativity.

2. Methods

Participant: Participant (GM) was a 44-year old right-handed female with normal hearing and no history of neurological disorders. She contacted the senior author (C.J.L) in order to participate in this study, which was approved by the Institutional Review Board (IRB) at Johns Hopkins University School of Medicine. This project followed IRB guidelines. The participant gave written informed consent both to the experiment and to the release of the data. A film crew documented the experiment.

fMRI Scanning Procedure: The study was conducted at the F.M. Kirby Research Center for Functional Brain Imaging at the Kennedy Krieger Institute of Johns Hopkins University. Prior to starting the experiment, GM performed a training session in the lab where she heard the auditory cues for the experiment, familiarizing herself with the protocol. She then continued her training in a mock fMRI scanner where she was able to lay supine playing with the keyboard held on her lap, thereby allowing her to grow comfortable with the body positioning. When she was accustomed to both the paradigm and the experimental setup, she entered the fMRI scanner to complete the experiment. Blood oxygen level dependent imaging (BOLD) data were acquired using a 3-Tesla whole-body scanner (Philips 3T Achieva Multix X-Series, Philips Electronics, Andover, MA) using a 32-channel sense head coil and a gradient-echo EPI sequence. The following scanning parameters were used: TR = 2000 ms, TE = 30 ms, flip-angle = 70, 64 × 64 mm matrix, FOV = 192 × 143 × 168 mm, 36 slices covering the whole brain, 3 mm thickness, 1 mm gap. 436 vol were acquired. A hi-resolution T-1 weighted MPRAGE scan (voxel size = 1 × 1 × 1) was acquired at the end of the session.

During scanning, the participant used a custom-built non-
ferromagnetic piano keyboard (MagDesign, Redwood, CA) with thirty-five full-size plastic piano keys and played with both hands. The keyboard had Musical Instrument Digital Interface (MIDI) output, which was sent to a Macintosh Macbook Pro laptop computer running the Logic Pro 9 sequencing environment (Apple Inc., Cupertino, CA). The MIDI input triggered high-quality piano samples using the Logic EXS24 sampler plug-in. Piano sound output was routed back to the subject input triggered high-quality piano samples using the Logic EXS24.

In the scanner, the piano keyboard was placed on the participant’s lap in supine position while her knees were elevated with a bolster. A double mirror placed above the subject monitored visually to ensure that she did not move her head, trunk, or other extremities during performance.

Stimuli: A block design was used to assess the neural activity during the three conditions: Scale (low musical complexity control condition), Memory (high musical complexity control condition), and Improvise (the experimental condition). The experiment consisted of three 14.5 min sessions. The 3 conditions were presented in a random order consisting of 10 blocks: 5 Improvisation blocks, 3 Memory blocks, and 2 Scale blocks. Each active block lasted 60 s and was immediately followed by a rest block of 28, 30, or 32 s (mean = 30 s). This portion of the experiment was approximately 60 min in duration (3 sessions + anatomical scan).

For the Scale blocks, the participant played the ascending and descending chromatic scale with both hands repeatedly. For the Memory condition, the participant performed a piece provided by the experimenters prior to the experiment: the Minuet in G major, BWV ANH 114 by J.S. Bach. For the Improvise condition, the participant was instructed to improvise in the style of the composition used in the Memory condition.

Functional Connectivity Procedure: To gather functional connectivity data, GM completed a different, separate 15-min performance task prior to the experiment: the Minuet in G major, BWV ANH 114 by J.S. Bach. For the Improvise condition, the participant was instructed to improvise in the style of the composition used in the Memory condition.

| Structure BA | Left Hemisphere | Right Hemisphere |
|-------------|-----------------|------------------|
|             | t-score | x | y | z | Cluster Size | t-score | x | y | z | Cluster Size |
| Superior Frontal Gyrus, Medial 6 | 5.56 | −30 | −8 | 72 | 41 | 5.45 | 22 | −10 | 74 | 45 |
| Posterior-Medial Frontal/SMA | 6 | 8.57 | 2 | −2 | 56 | 971 | 8.57 | 2 | −2 | 56 | 971 |
| Precentral Gyrus | 6 | 6.45 | −58 | 6 | 44 | 122 | 5.98 | 50 | 4 | 44 | 240 |
| Postcentral Gyrus | 1 | 7.65 | −52 | −30 | 58 | 460 | 6.53 | 54 | −24 | 46 | 565 |
| IFG (p. Opercularis)/Broca | 44 | 5.93 | −62 | 12 | 32 | 122 | 7.31 | 52 | 14 | −2 | 344 |
| IFG (p. Triangularis)/Broca | 45 | 5.36 | −54 | 30 | 2 | 38 | 6.08 | 54 | 36 | 6 | 344 |
| IFG (p. Orbitalis) | 47 | 5.66 | −40 | 28 | −6 | 321 | 5.21 | 52 | 18 | −6 | 344 |
| ITG | 37 | 5.92 | −48 | −46 | −28 | 11 | 4.81 | 60 | −56 | −4 | 5265 |
| MTG | 19 | 4.80 | −50 | −66 | 8 | 146 | 6.83 | 48 | −70 | 8 | 5265 |
| STG/Wernicke | 22 | 6.16 | −66 | −44 | 16 | 156 | 5.05 | 50 | −34 | 4 | 5265 |
| STG | 41 | 5.40 | −68 | −24 | 10 | 5265 | 5.27 | 64 | −4 | 4 | 99 |
| Fusiform Gyrus | 19 | 7.03 | −22 | −80 | −18 | 5265 | 10.05 | 32 | −78 | −18 | 5265 |
| Superior Temporal Gyrus, SMA | 6 | 6.65 | −68 | −20 | 38 | 460 | 6.36 | 42 | −34 | 44 | 565 |
| IPL | 40 | 7.66 | −58 | −28 | 50 | 460 | 6.19 | 46 | −38 | 56 | 565 |
| Precuneus | 7 | 7.10 | −14 | −54 | 66 | 526 | 5.52 | 6 | −52 | 66 | 51 |
| SPL | 7 | 6.09 | −20 | −62 | 58 | 526 | 6.18 | 36 | −50 | 62 | 565 |
| MOG | 19 | 5.97 | −28 | −92 | 22 | 5265 | 10.5 | 36 | −86 | 24 | 5265 |
| SOG | 19 | 7.93 | −10 | −84 | 40 | 5265 | 8.78 | 30 | −84 | 26 | 5265 |
| Cuneus | 19,18 | 5.50 | −18 | −68 | 20 | 5265 | 7.51 | 10 | −90 | 24 | 5265 |
| Lingual Gyrus | 17,18 | 6.74 | −20 | −72 | 6 | 303 | 5.29 | 16 | −50 | 2 | 95 |
| Calcarine Gyrus | 17,18 | 6.74 | −20 | −72 | 6 | 303 | 5.90 | 30 | −56 | 4 | 95 |
| MCC | 24 | 5.41 | 2 | 8 | 44 | 971 | 5.41 | 2 | −8 | 44 | 971 |
| ACC | 24,32 | 5.82 | −4 | 20 | 28 | 254 | 4.94 | 8 | 24 | 26 | 254 |
| Insula Lobe | 13 | 5.98 | −30 | 24 | 6 | 321 | 6.45 | 34 | 12 | 6 | 2320 |
| Rolandic Operculum | 6,1 | 5.20 | −46 | −2 | 2 | 23 | 5.64 | 52 | −8 | 10 | 99 |
| Putamen | 49 | 5.19 | −20 | 10 | 12 | 2320 | 6.42 | 24 | 10 | 8 | 2320 |
| Pallidum | 51 | 5.90 | −16 | −4 | −6 | 2320 | 6.38 | 20 | −2 | 2320 |
| Thalamus | 50 | 6.22 | −16 | −12 | 8 | 2320 | 6.63 | 16 | −12 | −8 | 2320 |
| Cerebellum (IV-V) | 5.60 | −8 | −28 | −8 | 10 | 79 | 5.60 | 32 | −38 | −28 | 30 |
| Cerebellum (VI) | 7.47 | −20 | −78 | −20 | 5265 | 5.60 | 32 | −38 | −28 | 30 |
| Cerebellum (VII) | − | − | − | − | − | − | − | − | − | − |
| Cerebellum (Crus 1) | 8.32 | −44 | −66 | −22 | 5265 | 10.05 | 32 | −78 | −18 | 5265 |

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period of rote performance, followed by a 7-min period of improvisation, and ending with a 30s rest period. The instruction for the rote performance period was to repeat the Venezuelan national anthem *Gloria al bravo pueblo* (composed by Vicente Salias and Juan Jose Landaeta) with as little variation between renditions as possible. The instruction for the improvisation period was to freely improvise using imagery of Venezuela as a starting point. The Venezuelan national anthem was selected as the musical subject of the control and improvisation task after discussion with GM herself; GM noted that she had an emotional connection to this piece and it would evoke memories for her given that it was her birth country. In addition to it having personal connection to the participant, this composition was also long enough for the purpose of functional connectivity analysis epochs.

### 2.1. Data analysis

**MIDI Data Analysis:** We applied signal processing methods to analyze the MIDI piano output obtained during fMRI scanning comparing the improvisation condition to both control conditions (Scale and Memory) respectively. The purpose of this analysis was to quantitatively evaluate how the conditions compared on various musical parameters, namely note usage, note variability, note density, duration, and key centers. Values for each of these parameters were calculated using the MIDI Toolbox (Eerola and Toiviainen, 2004) and additional scripts in Matlab (Mathworks). Note usage measured how much of the 35-key keyboard was used for the different conditions, measuring the number of presses per key. Note variability measured variability of note usage across trials for each condition. Note density referred to the number of notes played per second. To make fair comparisons across conditions, notes played in chords were each included independently to compute note density. Duration took into account the length each note was played (independently of whether it started with other notes), then a distribution was constructed to show the proportions of different note lengths used for each condition. The durations of the behavioral data were binned into 12 categories according to a base-2 logarithmic scale. Finally, for key area, the key center for each trial was computed using the Krumhansl-Schmuckler key finding algorithm (Krumhansl, 2001).

**fMRI Data Analysis:** BOLD images were preprocessed in a standard way using SPM12 (Wellcome Trust Department of Imaging Neuroscience, London, UK), including realignment, coregistration, segmentation, normalization, and smoothing with a 9 mm FHM kernel as well as a high-pass filter = 240s. A first-level general linear model (fixed effects analysis) was estimated using 4 regressors (e.g. one for rest and one for each experimental condition: Scale, Improvise, and Memory). Each regressor was convolved with a standard hemodynamic response function. Design matrices also included covariates of non-interest, which consisted of motion parameters calculated during the realignment stage and mean signal intensity for the run. All contrasts (i.e. Improvise-Rest, Scale-Rest, Memory-Rest, Rest-Improvise, Rest-Scale, Rest-Memory, Improvise-Scale, Scale-Improvise, Improvise-Memory, and Memory-Improvise) were estimated.

In order to get true activations and deactivations, inclusive masking (default $p < 0.05$) was used. To compare the Improvisation to the Scale condition, Improvisation-Scale (FWE correction $p < 0.05$) was masked by Improvise-Rest (true activation), and Scale-Improvise (FWE correction, $p < 0.05$) was masked by Rest-Improvise (true deactivation). Likewise, to compare the Improvisation to the Memory Condition, Improvise-Memory was masked by Improvise-Rest and Memory-Improvise was masked by...
Table 3

| Network              | Estimate [95% CI] | SE   | t    | p    | R2   |
|----------------------|------------------|------|------|------|------|
| Sensory/Hand         | -0.042 [-0.089, 0.005] | 0.023 | -1.806 | 0.076 | 0.037 |
| Sensory/somatomotor  | 0.011 [-0.144, 0.167] | 0.064 | 0.180 | 0.863 | 0.160 |
| Cingulo-opercular    | -0.036 [-0.087, 0.015] | 0.025 | -1.463 | 0.156 | 0.040 |
| Auditory             | 0.013 [-0.052, 0.078] | 0.031 | 0.414 | 0.683 | 0.037 |
| Default mode         | -0.06 [-0.093, -0.026] | 0.017 | -3.569 | 0.00056 | 0.106 |
| Memory retrieval     | -0.061 [-0.201, 0.078] | 0.060 | -1.013 | 0.341 | 0.003 |
| Visual               | 0.1 [0.06, 0.14] | 0.020 | 4.957 | 6.20E-06 | 0.279 |
| Fronto-parietal Task | -0.016 [-0.055, 0.024] | 0.020 | -0.799 | 0.428 | 0.007 |
| Salience             | -0.029 [-0.106, 0.048] | 0.038 | -0.767 | 0.449 | 0.013 |
| Subcortical          | 0.063 [-0.008, 0.133] | 0.034 | 1.835 | 0.079 | 0.087 |
| Ventral attention    | -0.184 [-0.314, -0.053] | 0.062 | -2.989 | 0.009 | 0.318 |
| Dorsal attention     | -0.067 [-0.136, 0.002] | 0.033 | -2.031 | 0.056 | 0.130 |
| Cerebellar           | 0.13 [0.029, 0.289] | 0.065 | 2.002 | 0.092 | 0.300 |

CI: confidence intervals; SE: standard error of the estimate; networks where improvisation significantly alters within-network connectivity after applying the Holm-Bonferroni correction are highlighted in bold typeface.

Table 4

| Network              | Estimate [95% CI] | SE   | t    | p    | R2   |
|----------------------|------------------|------|------|------|------|
| Sensory/Hand         | -0.021 [-0.036, -0.005] | 0.008 | -2.711 | 0.009 | 0.097 |
| Sensory/somatomotor  | -0.015 [-0.025, 0.021] | 0.014 | -1.021 | 0.347 | 0.006 |
| Cingulo-opercular    | -0.022 [-0.043, 0.01] | 0.010 | -2.095 | 0.046 | 0.112 |
| Auditory             | -0.001 [-0.023, 0.002] | 0.006 | -1.685 | 0.106 | 0.074 |
| Default mode         | 0.005 [-0.015, 0.026] | 0.011 | 0.521 | 0.604 | 0.007 |
| Memory retrieval     | 0.002 [-0.064, 0.059] | 0.027 | -0.089 | 0.931 | 0.124 |
| Visual               | -0.039 [-0.054, -0.024] | 0.008 | -5.098 | 3.69E-06 | 0.291 |
| Fronto-parietal Task | 0.001 [-0.022, 0.022] | 0.011 | 0.091 | 0.928 | 0.021 |
| Salience             | -0.013 [-0.025, -0.001] | 0.006 | -2.244 | 0.032 | 0.115 |
| Subcortical          | -0.035 [-0.053, -0.018] | 0.008 | -4.186 | 0.00033 | 0.398 |
| Ventral attention    | -0.02 [-0.048, 0.009] | 0.013 | -1.463 | 0.163 | 0.063 |
| Dorsal attention     | -0.016 [-0.041, 0.008] | 0.010 | -1.390 | 0.180 | 0.042 |
| Cerebellar           | -0.061 [-0.103, -0.02] | 0.017 | -3.606 | 0.011 | 0.632 |

CI: confidence intervals; SE: standard error of the estimate; networks where improvisation significantly alters participation coefficient after applying the Holm-Bonferroni correction are highlighted in bold typeface.

Rest-Improvise. The minimum cluster size was 10 voxels. SPM Anatomy Toolbox (Forschungszentrum Jülich GmbH) (Eickhoff et al., 2005) was used to create minima and maxima tables for anatomical location of voxel clusters. Anatomical results of these minima were then confirmed using the Automated Anatomical Labeling Toolbox (Tzourio-Mazoyer et al., 2002) and the WFU PickAtlas Toolbox (Maldjian et al., 2003).

2.2. Functional connectivity analysis

Preprocessing: Data were preprocessed and analyzed in subject space, using regions of interest (ROI) defined in the Power atlas (Power et al., 2011) that were transformed into subject space. Preprocessing of the resting-state scan consisted of slice time correction, realignment (motion correction), coregistration of the MPRAGE to the resting-state scan, segmentation of the MPRAGE, and normalization of the coregistered MPRAGE to the MNI template using unified segmentation (Ashburner and Friston, 2005). Backward deformation fields were calculated during the normalization step and applied to ROI masks consisting of a 10 mm sphere around each coordinate for each of 264 regions of interest in the Power atlas (Power et al., 2011), to transform the Power atlas ROIs back into subject space. Resting-state data were further preprocessed by simultaneous regression (Hillquist et al., 2013; Lindquist et al., 2019) consisting of nuisance variables, detrending, despiking (Patel et al., 2014), and bandpass filtering (0.008-0.09 Hz) using the Canlab toolbox (http://github.com/canlab). Nuisance regressors included six motion regressors from realignment, a scrubbing vector generated using outlier detection and intermediate settings (global-signal z-value threshold = 5, subject-motion mm threshold = 0.9) in the ART toolbox (Whitfield-Gabrieli and Nieto-Castanon, 2012), and the first 5 principal components of twice eroded cerebro-spinal fluid and four-eroded white matter masks.

Global signal was not removed, as doing so can introduce structured statistical artifacts into resting-state functional connectivity data (Murphy and Fox, 2017). Twice-eroded CSF and four-eroded white matter masks were used as the signal in these regions controls for non-neural physiological variance (Behzadi et al., 2007; Muschelli et al., 2014) and masks at these erosion levels do not contain global signal (Power et al., 2017). We then extracted time courses from these preprocessed, unsmoothed, whole-brain BOLD data using the 264 subject-space Power Atlas ROIs.

Analysis: We then tested the association of task condition (rote performance vs improvisation) on measures of network modularity and network integrity for network of ROIs as defined in the Power atlas. Network integrity for a given network was defined as the within-network pair-wise Fisher-transformed correlations for each ROI within that network. A decrease in within-network pair-wise Fisher-transformed correlation was interpreted as a decrease in network integrity. Network modularity was assessed using the network theory measure called participation coefficient (Rubinov and Sporns, 2010). Participation coefficient, when applied to a continuous connectivity measure such as a Fisher-transformed correlation, is a measure of the strength of connections of nodes in one network to nodes in other networks. Participation coefficient is calculated separately for negative and positive correlations. Decreases (movement towards zero) in either negative or positive participation coefficient across nodes of a network represent increased modularity of that network (lower inter-network connectivity of network nodes), whereas increases (movement away from zero) in either negative or positive participation coefficient represent decreased network modularity (greater inter-network connectivity of nodes in that network).

To assess differences between rote and improvisation periods on network modularity and integrity, we first fit the following general linear model:

\[ \text{Integrity} = \beta_0 + \beta_1 \text{Task} + \beta_2 \text{Network} + \beta_3 \text{Task} \times \text{Network} + \epsilon \]

where Integrity is the network integrity, Task is the task condition (rote performance vs improvisation), Network is the network of ROIs, and \( \beta_0, \beta_1, \beta_2, \beta_3 \) are the model parameters. The interaction term Task \times Network captures the effect of task condition on network integrity while controlling for the main effects of task and network. The model was fit separately for each network, and the resulting parameter estimates were used to generate a t-statistic for each network:

\[ t = \frac{\beta_3}{SE(\beta_3)} \]

where SE(\( \beta_3 \)) is the standard error of the estimated interaction coefficient. The t-statistic was then thresholded at a false discovery rate (FDR) corrected p-value of 0.05 to identify networks where the interaction term was significant.
model to data from all networks:

\[ DV = 1 + \beta_{\text{improvisation}} + \beta_{\text{network}} + \beta_{\text{improvisation} \times \text{network}} \]

Separate models were fit with DV defined as either the average of all pair-wise within-network Fisher-transformed correlations for each ROI (network integrity), or positive or negative node-wise participation coefficient each ROI (network modularity), for a total of three models that were fit. Main effects and interactions of task condition (rote vs improvisation) and network label were assessed for each model. Separate general linear models were then fit for each network as a test of planned comparisons between task condition for each network, using the following general linear model:

\[ DV = 1 + \beta_{\text{improvisation}} \]

Separate models were fit with DV defined as either the average of all pair-wise within-network Fisher-transformed correlations for nodes (ROIs) of a given network (network integrity), or positive or negative node-wise participation coefficient for ROIs of a given network (network modularity), for a total of three models that were fit for each network. Mixed-effects models were fit in MATLAB. Statistical significance levels were corrected for family-wise error rate using the Holm-Bonferroni method (Holm, 1979).

3. Results

**Behavioral Data:** We performed a quantitative analysis of the MIDI data gathered for the neuroimaging paradigm as well as a motivic musical analysis of the improvisation trials. Analysis of the MIDI output data suggested that the improvisation condition was generally more complex than both Control conditions (see details below), which is not surprising given that GM was allowed free artistic reign to improvise for the experimental condition while the control conditions were more constrained.

**MIDI Data:** We compared the note usage for each condition. As expected, GM used every note for the scale trials and exactly 16/35 notes for each memorized trial. However, although improvised trials were based on the memorized piece, GM used 31.8 notes (range 29.35) for the improvised trials indicating that she greatly expanded her repertoire.
of notes and key areas during improvisation. To compare note variability across conditions, we computed the fano factor of note presses per key across trials for each condition (ignoring keys that were never used in a condition). GM had a fano factor of 8.7 presses/key in improvised trials, but only 0.08 presses/key in memorized trials and 0.14 presses/key in scale trials. A one-way ANOVA with Tukey’s comparisons indicated that the note variability of improvised trials was significantly different than both scale and memorized trials (F(2,83) = 39.18, p < 0.0000001). These results indicate that GM performed music with higher complexity and variability on improvised trials.

When comparing the Scale condition to the Improvise condition on note density, no significant effect was found. However, note density significantly increased for the Improvise condition (mean = 8.55 notes/sec) compared to the Memory condition (mean = 6.74 notes/sec), t(14) = 2.92, p < 0.05, two-sample t-test suggesting that more notes were played per unit time in the Improvisation condition. While small inconsistencies in tempo during the control condition resulted in a small standard deviation of 0.079 notes/second, the improvised conditions had a much larger standard deviation of 5.67 notes/second, suggesting that the Memory condition maintained a relatively steady tempo while there was variability in temps for the Improvisation trials. This increase in note density for the Improvisation condition may be purely related to an increase in tempo.

An analysis of the distribution of duration of notes showed that GM used more variety in note lengths for the Improvise condition vs. the Memory condition (chromatic scale) in the Scale paradigm (p < 0.001, Kolmogorov-Smirnov test) which is not surprising given that improvisations were likely not as homogeneous in rhythms as a repeated chromatic scale. When comparing the Improvise condition to the Memory condition, a Kolmogorov-Smirnov test likewise revealed a significant difference (p < 0.001) for the note distributions. Additional analysis also showed that the slope of the Improvised condition’s distribution chart is flatter than the Memory condition, suggesting a greater variety of note lengths used. While nearly one third of the notes used in the Memory condition were from bin 3, the highest proportion of any note length from the Improvised condition was 0.18 (bin 2). This is both a function of variety across trials, as these results come from an aggregated set of the Improvised condition, and also from greater variety within trials, for example if a chord is held by the left hand for 2–4 s while the right hand arpeggiates 1/8th-second notes on top of it. Again, this result is not surprising considering that the Memory condition involved a written composition while the Improvised condition allowed for more rhythmic flexibility and artistic freedom.

The key center for each trial was also computed for Memory vs. Improvise. The composition used for the control was centered on G Major. Although the improvised trials were typically centered in G Major and the closely related D Major, GM explored a range of 10 different keys throughout the improvisations.

Musical Structure: Music motivic analysis was performed on the improvisation trials to examine whether any structure or method was used to create improvisations. GM reported anecdotally that she has no memory of what happens during her improvisation. Our analysis of her improvised music, however, suggests that she has an extraordinary ability to extemporaneously create coherent music. For example, she often creates and implements themes rigorously into a logical musical structure; one of her improvisation trials followed an AA BA CAC form, reminiscent of the structure of a Classical music rondo (which follows the form ABAAB). When not playing a melody, GM’s developmental sections used segments of the primary motives as a way of recalling main ideas (see Fig. 2). Thus, her improvisations sound like structured, Classical-style compositions in that she creates clear musical ideas and weaves them into coherent forms. GM’s musical stream of consciousness is remarkably organized. See Fig. 2 for motivic analysis of GM’s improvisations.

Neuroimaging (fMRI) Data: Contrast analyses were performed comparing the experimental improvisation condition to both the low-
improvisation is generally associated with activation rather than deactivation of brain structures and these structures belong to various domains (i.e. auditory processing, limbic system, visual network etc) suggesting that improvisation is a multimodal process for GM. Moreover, the brain areas involved such as the supplementary motor area, angular gyrus, cingulate cortex, and inferior frontal gyrus are areas reputed to be involved in improvisation as supported by data from group experiments of improvisation as well (Bashwiner, 2018; McPherson and Limb, 2018; Pinho et al., 2016). Interestingly, the neural activity associated with improvisation is generally found bilaterally. This experiment is a departure from many previous experiments on the neuroscience of creativity because GM was allowed to use both hands, which may explain the bilateral neural activity. However, it is currently difficult to disentangle whether the lateralization here is due simply to the use of both hands or because it is unique to GM’s brain and creative abilities. To probe the issue of lateralization more fully, future experiments would have to perform group experiments where participants are allowed to use both hands to improvise in order to probe this question with more statistical rigor. As of now, because GM is only a single subject, we cannot interpret this data more broadly or definitively (see Discussion) but we believe lateralization may be an important factor to examine in future work.

Functional Connectivity Results: We observed main effects of task condition ($F(1) = 4.096, p = 0.0436$) and network ($F(12) = 36.987, p < 0.00001$), as well as an interaction between condition and network on within-network connectivity ($F(12) = 5.742, p < 0.00001$). We also observed main effects of task condition ($F(1) = 19.106, p < 0.00005$) and network ($F(12) = 12.421, p < 0.00001$) for positive participation coefficient ($F(12) = 2.026, p < 0.05$), and for task condition ($F(1) = 43.013, p < 0.00001$), network ($F(12) = 4.665, p < 0.00001$), and an interaction between task condition and network ($F(12) = 4.762, p < 0.00001$) for negative participation coefficient. These findings demonstrate that both network integrity and network modularity changes with improvisation, and networks differ in the degree of these changes.

Improvisation: Network integrity (within-network connectivity) was decreased in the default mode network and increased in the visual network during improvisation compared to rote performance (Table 3). Participation coefficient (e.g. a measure of the strength of connections of nodes in one network to nodes in other networks) for positive correlations was decreased during improvisation in visual and subcortical networks (Table 4 and Fig. 5) while participation coefficient for negative correlations was increased during improvisation for sensory/somatomotor, subcortical, and dorsal attention networks (Table 5 and Fig. 5). Taken together, these changes in participation coefficient during improvisation (decreased positive connectivity and increased negative connectivity to other networks) demonstrate increased modularity of these networks during improvisation.

4. Discussion

In this case study investigation of Classical performer and improviser Gabriela Montero (GM), we used functional magnetic resonance imaging and functional connectivity data analysis to identify the neural correlates of improvisation in comparison to ‘rote’ musical activity. The data presented here represents activity in a single, unique brain of a well-known creative artist. Overall, functional neural imaging results show that improvisation, in comparison to the control conditions, resulted in significant large clusters of activation as well as several focal clusters of deactivation in various brain structures. These results here suggest that, for GM, improvisation is a distinctive musical and neural process from the act of performing pre-learned music or automatic musical tasks like repeatedly playing a chromatic scale. GM’s pattern of brain activity during improvisation was similar when compared to both control conditions, Scale and Memory. The differences in neural activity during improvisation represent GM’s process of extemporaneously creating complex musical content, rather than differences related to the musical complexity of the control conditions. Improvisation in comparison to the control conditions resulted in activation of brain areas from various systems including frontal cognitive areas, auditory areas, motor areas, limbic areas, and visual areas. For GM, improvisation is a highly multimodal process. Moreover, even though GM reports that she is not conscious of what she is doing when improvising, musical motivic analysis of her improvisation trials suggests that GM often returns to musical material she had played earlier in the improvisation. Her improvisations are structured and cohesive, suggesting that her musical stream of consciousness is remarkably organized.

Given our current knowledge of the neuroscience of improvisation based on group experiments of professional musicians, it is not surprising that improvisation in GM engaged auditory areas, default network areas, limbic areas and motor areas. However, activation of the visual cortex (i.e. occipital areas like occipital gyrus, lingual gyrus and calcarine gyrus) is striking and perhaps a little unusual. This engagement of the visual system suggests that GM engages in some level of visual imagery when she improvises. GM has reported that she is constantly hearing and composing music “in her head,” even when speaking to others. She is constantly creating music without trying. Musical imagery, or voluntarily hearing music in one’s head, has been found to primarily engage auditory areas (Herholz et al., 2012; Zatorre and Halpern, 2005 and Zatorre et al., 2010). More complex manipulation of imagined musical melodies, however, has been associated with cortical parietal activity, an area implicated in visual mental rotation tasks (Lu et al., 2017; Zatorre, Halpern and Bouffard, 2010). It is possible that if GM is constantly hearing and composing music in her head, she may be manipulating musical melodies (e.g., transposition, reversal, other manipulations). Alternatively, associated visual images may emerge during improvisation as well—for example free-floating images that inspire her or visualizations of music. Finally, music theorists have proposed the idea that conceptual musical spaces exist within the mind, modeling how listeners may conceive and cognitively understand musical relationships (Lerdahl, 2001). While speculative, these may all serve as possible explanations for the visual network engagement found during improvisation for GM. Our functional connectivity data suggested increased modularity of the visual network (i.e. the decreased positive and increased negative participation) during improvisation which might reflect less integration of visual input to behavioral output. In other words, visual input is not strictly necessary for GM’s motor output. Thus, she may not necessarily be looking at a score or visualizing the notes on the keyboard as she is actually playing the piano, but is likely still engaging in some sort of visual imagery, as supported by the neural imaging data. Future experiments and interviews with GM are necessary to further explore this.

The co-activation of motor and auditory areas along with the visual network engagement in GM is interesting. Previous studies on musical creativity have found involvement of not only auditory areas but motor areas as well (see discussion in Bashwiner and Bacon, 2019). Although we do not know exactly how GM’s improvisation process works, it is possible that her improvisations are evolving out of her motor behavior rather than strictly as an auditory process, coming from the fingers in addition to the ear as a form of embodied creativity. GM often reports that improvising for her is similar to “turning on a faucet” and that she can do this at any time without prior preparation. Given her years of experience playing piano, it is possible that she is using learned patterns to create new patterns when improvising which may also explain the cohesive structure underlying her improvisations. Indeed, many experienced jazz musicians learn patterns and schemas that can then be called upon rapidly and structured in new creative ways when improvising (Pressing, 2001).

Functional connectivity data analysis allowed us to look at both network integrity and network modularity in GM’s brain when improvising. Results for network integrity, a measure of within-network connectivity, suggests that improvisation is associated with a decrease in connectivity within the default mode network and an increase in connectivity within the visual network. Improvisation has been associated with decreased self-awareness and feelings of control, consistent with
flow state (Csikszentmihalyi, 2008). Flow state has been previously associated with decreased activity within regions of the default-mode network (Ulrich et al., 2016; Ulrich et al., 2014). Given the association between default-mode network activity with introspection, theory of mind, memory, and self-referential processing, and flow-state, the decreases in network integrity (within-network connectivity) observed within GM may be associated with GM entering a flow state — the heightened optimal experience of deep focus, creativity, and enjoyment that often accompanies creative tasks — during improvisation (Limb and Braun, 2008; Csikszentmihalyi, 2008). Despite the implication that flow states represent a decrease of sense of self, artists like GM also call on their emotions and personal identity when performing. Therefore, the pattern of activity reported here may be reflective of the fact that musical improvisation is an expression of emotion and identity, even if they are not specifically the primary subject of conscious thought.

Investigating between-network connections indicate that the visual, subcortical, somatosensory, and dorsal attention networks have an increase in network modularity. In short, the activity of these particular networks become more distinct from the activity of other networks, suggesting that these networks act more independently of one another while GM is improvising. Regarding the increased modularity of the subcortical network (including the thalamus and basal ganglia), a similar interpretation might apply as what we mentioned about the visual network above, specifically that the subcortical network is not coupled with the behavioral output. While it is not necessarily expected that less integration of these primary subcortical regions critical to rhythm and movement would be associated with improvisation, it is possible that this is precisely this lower level of integration with higher cognitive networks that allows GM to enter the flow state. Considering the fact that GM likens improvisation to a game and that she is largely unconscious of what happens during her improvisations, the neural results describe here may lend evidence to GM’s entrance into a flow state while improvising.

This case study investigation allowed us to tailor experimental tasks to a world-class improviser, selecting musical tasks that spoke to her unique abilities as a Classical music improviser with remarkable technical facility on the keyboard. Naturally, a case study investigation does not have the statistical rigor associated with group experiments featuring larger sample sizes, but the case study approach used here allowed us to capture some of the individual variability that might underlie musical creativity. To date, our models of the neuroscience of creativity have been built on group experiments where the brains of musicians are averaged together in aggregate. We hope, however, that with the inclusion of more case studies in creativity research such as this investigation of GM’s improvisational process, we may be able to contribute to the evolving model of the neuroscience of creativity (Barrett and Limb, 2019). For example, from this investigation, we have gleaned that for GM, improvisation is a multimodal process engaging brain areas from various networks and that the visual network is important to her improvisation process. Moreover, improvisation for her manifests primarily as activation in various brain structures rather than the distinctive pattern of widespread prefrontal deactivation seen in professional jazz musicians (Limb and Braun, 2008), with deactivation observed in non-prefrontal regions (cerebellum, left middle temporal gyrus, angular gyrus and inferior parietal lobule) for GM during improvisation. Thus, it is possible that eminent classical improvisers may conceive of improvisations in a different manner from jazz musicians, which will likewise manifest in different patterns of brain activity from what has been seen through group experiments on jazz musicians. Alternatively, it is possible that the pattern of brain activity we see here is idiomatic and specific to GM.

In the future, combining neural imaging experiments along with in-depth interviews with artists who are each treated as a unique data point may shed light on the biological means that allow extreme creativity to flourish. Additionally, studying an individual artist in depth (i.e. over several fMRI scanning sessions) may create the confound of producing a learning effect and habitation to the fMRI scanner, but may also provide a richer, deeper understanding of how that artist’s brain gives rise to musical improvisation. By studying eminent musicians who are creativity outliers even among elite professional musicians, we may be able to see whether genius artists show biological activity that is an extension of our current model of the neural activity underlying musical creativity, or whether they show unique patterns of brain activity. These signature differences in neural activity between different artists may be critically important components to the generation of the wide diversity of behaviors, outcomes, and expressive voices found in art.

Acknowledgments

The authors would like to thank Gabriela Montero for participating in this experiment. The authors would also like to thank Vani Dewan for biographical research on the artist. The UCSF Sound and Music Perception Lab is supported in part by an award from the National Endowment for the Arts (Award Number: 1844330-38-C-18). C.J.L. has received research support from Advanced Bionics (medical advisory board, consultant), Med-El (advisory board), Oticon (consultant), and Spiral Therapeutics (chief medical officer) for unrelated work. All other authors declare no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.116496.

Data and code availability statement

The data and code used in this study are available upon direct request for use and modification. Where existing toolboxes were used for data analysis, citations have been provided.

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