Brain and Cognition 119 (2017) 45–53

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Jazz musicians reveal role of expectancy in human creativity

Emily Przysinda, Tima Zeng, Kellyn Maves, Cameron Arkin, Psyche Loui*

Wesleyan University, USA

ARTICLE INFO

Keywords:
Expectation
Prediction
Auditory
Electroencephalography
Perception
Cognition

ABSTRACT

Creativity has been defined as the ability to produce work that is novel, high in quality, and appropriate to an audience. While the nature of the creative process is under debate, many believe that creativity relies on real-time combinations of known neural and cognitive processes. One useful model of creativity comes from musical improvisation, such as in jazz, in which musicians spontaneously create novel sound sequences. Here we use jazz musicians to test the hypothesis that individuals with training in musical improvisation, which entails creative generation of musical ideas, might process expectancy differently. We compare jazz improvisers, non-improvising musicians, and non-musicians in the domain-general task of divergent thinking, as well as the musical task of preference ratings for chord progressions that vary in expectation while EEGs were recorded. Behavioral results showed for the first time that jazz musicians preferred unexpected chord progressions. ERP results showed that unexpected stimuli elicited larger early and mid-latency ERP responses (ERAN and P3b), followed by smaller long-latency responses (Late Positivity Potential) in jazz musicians. The amplitudes of these ERP components were significantly correlated with behavioral measures of fluency and originality on the divergent thinking task. Together, results highlight the role of expectancy in creativity.

1. Introduction

One of the most striking features of the human brain is its ability to be creative. Creativity has been defined as the ability to produce work that is novel, high in quality, and appropriate to an audience (Sternberg, Lubart, Kaufman, & Pretz, 2005). While the nature of the creative process is under debate, many believe that creativity relies on real-time combinations of known mental processes (Goldenberg, Mazursky, & Solomon, 1999), with contributions from the society and culture as well as from the person (Csikszentmihalyi, 1996). However, how these neural and cognitive processes are combined is unknown, as they vary across domains and between individuals.

One model of creativity in real time comes from musical improvisation, such as in jazz music, in which individuals spontaneously create novel auditory-motor sequences that are aesthetically and emotionally rewarding (Bengtsson, Csikszentmihalyi, & Ullen, 2007; Berkowitz & Ansari, 2008; Limb & Braun, 2008; Liu et al., 2012). Jazz improvisers show higher divergent thinking ability and openness to experience, even when compared to musicians with other types of training (Benedek, Borovnjak, Neubauer, & Kruse-Weber, 2014). Longitudinal studies have also shown that improvisation training induces improvements in performance on divergent thinking tasks (Karakelle, 2009; Lewis & Lovatt, 2013). Due to its reliance on domain-general as well as domain-specific processes, the study of improvisation is thought to have implications not only for the study of artistic expertise, but also for the neural underpinnings of domain-general processes such as motor control and language production (Beaty, 2015).

While the mechanisms of creativity are unclear, recent work from theoretical and modeling studies suggests that the processing of deviance, or of unexpected events, is key to creativity (Kleinmintz, Goldstein, Mayseless, Abecasis, & Shamay-Tsoory, 2014; Wiggins & Bhattacharya, 2014). If expectation processing is key to creativity, one would expect that individuals with more training in creativity might process expectancy differently. Here we aim specifically to inspect the role of expectation in creativity, using jazz improvisers as a model.

Across multiple modalities, expectation violations from novel stimuli elicit the P3, a positive ERP as measured using event-related potentials as a peak around 300–600 ms after the onset of target events (Arthur & Starr, 1984; Klein, Coles, & Donchin, 1984; Knight, Scabini, Woods, & Clayworth, 1989; Yamaguchi & Knight, 1991). The P3 is elicited across multiple sensory domains and has generally been linked to engagement, arousal, and novelty detection (Friedman, Cycowicz, & Gaeta, 2001; Murphy, Robertson, Balsters, & O'Connell R, 2011). It includes two subcomponents, P3a and P3b (Polich, 2007). P3a (or Novelty P3) is thought to reflect more stimulus-based attention and novelty detection in the frontal lobe, whereas P3b reflects attention- and memory-dependent neuroinhibitory processes especially in the

* Corresponding author at: Department of Psychology, Program in Neuroscience & Behavior, 207 High Street, Middletown, CT 06459, USA.
E-mail address: ploui@wesleyan.edu (P. Loui).

http://dx.doi.org/10.1016/j.bandc.2017.09.008
Received 13 March 2017; Received in revised form 7 August 2017; Accepted 20 September 2017

parietal lobe (P3b) (Murphy, Robertson, Balsters, & O'Connell, 2011; Polich, 2007). The P3 can be followed by an additional parietally-centered late positive potential (LPP), around 400–900 ms, which reflects evaluation and affective appraisal, especially for motivating and task-relevant events (Cacioppo, Crites, Berntson, & Coles, 1993; Schupp et al., 2000).

In addition to the P3 and the late positivity, expectation violations for musical harmony, which has been linked to emotion and meaning in music (Meyer, 1956), additionally elicits an Early Right Anterior Negativity (Koelsch, Gunter, Friederici, & Schroger, 2000; Loui, Wu, Wessel, & Knight, 2009; Steinbeis, Koelsch, & Sloboda, 2006). This Early Right Anterior Negativity (ERAN) bears some similarities to the Mismatch Negativity (Naatanen, Simpson, & Loveless, 1982) in that both are sensitive to unexpected acoustic events and may reflect auditory prediction and comparison; however the ERAN is thought to be more specific to the processing of musical syntax and is sensitive to learning and experience (Koelsch, 2009; Loui et al., 2009).

Our general hypothesis is that creativity depends on sensitivity to unexpected events. Specifically, in the domain of music, we expect that jazz improvisers will process unexpected musical stimuli with increased sensitivity and engagement, as indexed by the ERAN and P3, compared to their musician and non-musician counterparts. Furthermore, we expect that neural indices of unexpectedness will be correlated with measures of divergent thinking.

2. Materials and methods

2.1. Subjects

36 subjects (12 female) participated in the study. Subjects were recruited from Wesleyan University and the Hartt School of Music in exchange for compensation or course credit. Jazz improvising musicians, non-improvising (Classical) musicians, and non-musicians were recruited based on their reported musical experience. All three groups (n = 12 each, sample size determined from previous studies (Loui, Grent-'t-Jong, Torpey, & Woldorff, 2005; Loui et al., 2009)) were matched in age, general intellectual function as assessed using the Shipley Institute of Living Scale (Shipley, 1940), and short term memory (digit span task). Jazz and Classical musician groups were matched in age of onset and number of years of musical training and pitch discrimination thresholds, but the Jazz group had an average of five years of training in musical improvisation, whereas the Classical group had only non-improvisatory musical training. The Jazz group was identified by two criteria: 1) 5+ years training in music that included improvisation. 2) Active participation in improvisatory musical activities 1+ hour per week. Non-improvising ("Classical") musicians were identified using the following criteria: 1) 5+ years of musical training that did not include improvisation. 2) Active participation in non-improvisatory musical activities 1+ hour per week. Participants were included in the non-musician group if they had less than 5 years of previous musical training. Subjects gave informed consent as approved by the Institutional Review Boards of Wesleyan University and Hartford Hospital.

2.2. Procedures

After subjects gave consent to participate in the study, control tests were done including a psychophysical pitch discrimination threshold-finding test (Loui, Guenther, Mathys, & Schlaug, 2008) to rule out differences due to pitch discrimination, the Shipley test of general intelligence (Shipley, 1940), and a digit span short term memory task (Baddeley, 2003). These showed no significant differences among the three groups as shown in Table 1. Subjects also completed a survey on their musical background, indicating their age of onset and duration of general musical training, the duration of jazz and improvisation training, amount of time spent on musical activities, and their self-rated ability to improvise. The control tests were followed by an EEG experiment (Harmonic Expectation Task) and a behavioral experiment (Torrance Test of Creative Thinking).

2.2.1. EEG: harmonic expectation task

Event-Related Potentials were used to examine musical expectancy in the three groups, borrowing from an established paradigm in music cognition to test for musical expectation (Koelsch et al., 2000; Loui & Wessel, 2007). Stimuli consisted of chord progressions generated from sine wave complexes with fundamental frequencies ranging from 174.61 Hz to 1318.51 Hz. Each sine wave complex was presented with a fixed amplitude envelope with a rise time of 5 ms and a fall time of 105 ms. Sine wave complexes were presented in groups of five, with an inter-onset time of 1000 ms between successive complexes within a group. The fundamental frequencies of the tone complexes formed musical chord progressions that were either of high, medium, or low expectation as predicted by music theory, similar to stimuli used in a previous study (Loui & Wessel, 2007). The high expectancy chord progressions were in accordance with Western music tradition (I-I-IV-V-I). The medium expectancy chord progression replaced the third chord with a slightly unexpected Neapolitan chord, but this chord still functioned correctly according to Western tonal standards (I-I-N-V-I). The low expectancy chord progression replaced the last chord with a Neapolitan chord (I-I-IV-V- N), which is unacceptable in that context within Western tonal standards. High, medium, and low expectation chord progressions were presented with equal probability and played in all 12 keys. Each trial consisted of one such chord progression, followed by a preference rating where subjects were instructed to rate their preference for the chord progression on a scale from 1 (dislike) to 4 (like). Entering a preference rating triggered the next trial, with a new five-chord chord progression. The trials were presented in blocks of 60, and each subject completed at least 3 blocks (maximum 6 blocks) and the keys of all the chord progressions were randomized for each block. In contrast to previous experiments (Loui, Grent-'t-Jong, Torpey, & Woldorff, 2005) which included a different type of deviant to which subjects responded, the present study required subjects to attend to the feature of musical harmony, as these were hypothesized to elicit the ERAN and P3 complex, which were our main ERPs of interest. EEG was recorded using PyCorder software from a 64-channel BrainVision actiCHamp setup with electrodes corresponding to the international 10–20 EEG system. Impedance was kept below 10 kOhms. The recording was continuous with a raw sampling rate of 1000 Hz. EEG recording took place in a sound attenuated, electrically shielded chamber.

2.2.2. Divergent thinking task

A domain-general creativity task was assessed to test whether the Jazz group might be more creative even in non-musical contexts. Subjects completed a short version of the Torrance Test of Creative Thinking (Torrance, 1968), in which they were given six open-ended verbal prompts (e.g. "List all the uses you can think of for a paper clip.") and had three minutes to respond to each prompt. Subjects were told that the task was a measure of general creativity and that they should try to give as many answers as they could.

2.3. Data analysis

2.3.1. EEG: harmonic expectation task

Behavioral ratings were exported from Max/MSP (Zicarelli, 1998) to SPSS for analysis. EEG data were analyzed in BrainVision Analyzer. Preprocessing included applying infinite impulse response filters with a low-pass cutoff of 30 Hz and a high-pass cutoff of 0.5 Hz. Raw data inspection was used to exclude data points with a higher gradient (> 50 uV/msec), high mins and max (> 200 uV), and extreme amplitudes (−200 to 200 uV), resulting in exclusion of 11.8% percent of the segments, with this percentage being similar across groups and across conditions (all $p > 0.10$). Ocular correction ICA was applied to remove eye artifacts for each subject. The data were then segmented into chords

Table 1
Means and standard deviations for age, musical experience, and baseline test performance comparing Non-musicians, Classical musicians, and Jazz musician subjects.

	Non-musicians (n = 12)	Classical musicians (n = 12)	Jazz musicians (n = 12)	Non-musicians vs. classical musicians	Non-musicians vs. Jazz musicians	**Classical vs Jazz musicians**
Pitch discrimination (Hz)	10.6 (8.8)	5.6 (3.3)	4.6 (3.5)	ns	ns	ns
Digit Span (digits)	7.5 (1.3)	7.2 (1.9)	8.1 (1.5)	ns	ns	ns
Shipley (raw score)	17.8 (1.3)	17.1 (1.6)	17.0 (1.9)	ns	ns	ns
Age (years)	19.3 (1.3)	21.1 (4.4)	20.3 (1.4)	ns	ns	ns
Age of onset (years)	9.7 (2.4)	7.2 (1.9)	8.2 (3.2)	ns	ns	ns
Duration of training (years)	1.6 (1.4)	10.3 (1.9)	9.3 (3.7)	$t(22) = 12.4$ $p < 0.001$	$t(22) = 6.7$ $p < 0.001$	ns
Duration of improvisation training (years)	0.0	1.1 (1.7)	5.8 (3.5)	$t(22) = 2.3$ $p = 0.03$	$t(22) = 7.7$ $p < 0.001$	$t(22) = 5.2$ $p < 0.001$

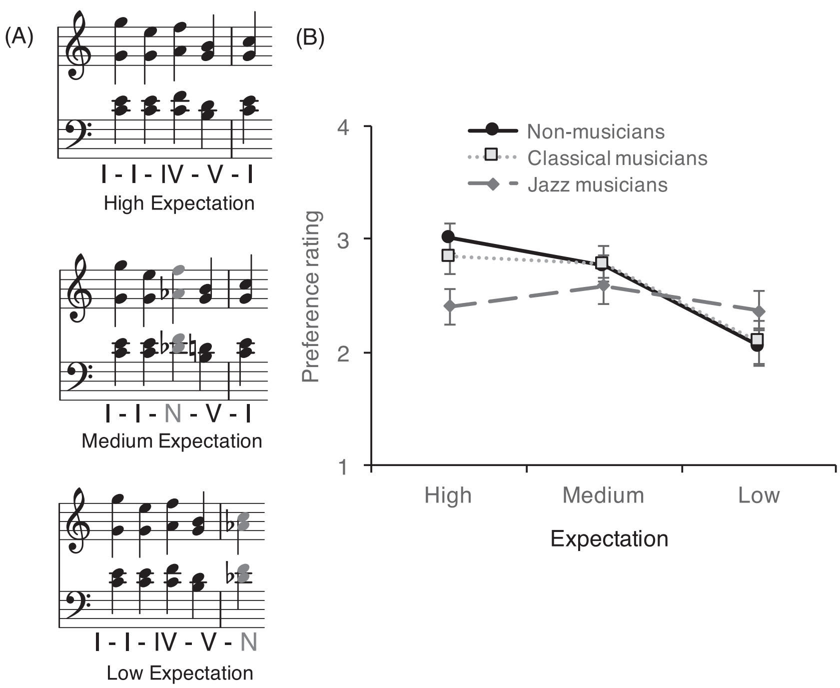

Fig. 1. (A) Examples of musical stimuli from high, medium, and low expectation conditions. (B) Preference ratings of Jazz musician, Classical musician, and Non-musician groups for high, medium, and low expectation conditions, showing a significant interaction between group and condition.

and the trials were averaged and baseline corrected. We compared ERP traces for high and low expectation chords (the last chord in each progression), and for high and medium expectation chords (the third chord in each progression). We also plotted difference waves for medium minus high expectation conditions, and for low minus high expectation conditions. Mean amplitudes for time windows of interest (230–280 ms, 410–480 ms, 800–850 ms) for each subject were then exported from BrainVision Analyzer and analyzed in SPSS. For the medium vs. high expectation contrast, the FCz electrode was chosen to test for the ERAN (Loui, Wu, Wessel, & Knight, 2009; Koelsch et al., 2000). For the low vs. high expectation contrast, since a frontal positivity (P3a) was observed in midline electrodes whereas a frontal negativity (ERAN) was observed in the lateral frontal electrodes, the FCz electrode was chosen to test for the P3a, while electrode F8 was chosen for the ERAN (Polich, 2007; Koelsch, Schroger, & Gunter 2002). The P2 electrode was chosen to represent the P3b component and the late positive potential (Polich, 2007). For each of these time windows and electrodes, we performed a mixed factors ANOVA with a within-subjects factor of expectancy (low vs. high or medium vs. high) and a between-subjects factor of group (jazz, classical, nonmusician). Since these were time windows and electrodes representing specific ERP components that we hypothesized might be different between groups, we also performed planned paired-samples *t*-tests comparing the two expectancy conditions for each group, while applying Bonferroni correction to control the type I error rate across the three planned *t*-tests. Tests of the three a priori hypotheses were conducted using Bonferroni-adjusted alpha levels of 0.01667 per test (0.05/3).

2.3.2. *Divergent thinking task*

Subjects' responses were coded for fluency and originality. Fluency was calculated as the number of unique responses. Responses from 16 independent control subjects (recruited online from Mechanical Turk) were used to create a baseline for originality. The subjects were then scored for originality with unique responses receiving 3 points, responses that occurred once in the baseline receiving 2 points, and responses that occurred twice in the baseline receiving 1 point. Scoring of subjects' responses were done by raters who were blinded to the group status of each subject. Outlier trials were excluded using the Tukey method with a conservative multiplier of 2.2 (Tukey, 1977). This resulted in the removal of 2 single question scores in different participants, one from the Classical musician group and one from the Jazz group. Z-scores were calculated for each of the questions.

3. Results

3.1. *Decreased preference for expected stimuli in Jazz musicians*

Behavioral results from preference ratings for high expectation, medium expectation, and low expectation chord progressions showed a main effect of expectation ($F(2,66) = 17$, $p < 0.001$, $\eta^2 = 0.301$), and an interaction between group and expectation ($F(4,66) = 3.2$, $p = 0.018$, $\eta^2 = 0.113$) (Fig. 1B). The non-musicians strongly preferred the high expectation condition followed by the medium ($t(23) = 2.3$, $p = 0.03$, $d = 0.618$) and low expectation conditions (high vs. low: $t(23) = 3.5$, $p = 0.0019$, $d = 1.841$; medium vs. low: $t(23) = 3.4$, $p = 0.0023$, $d = 1.535$). The musicians showed a strong preference for both the high and medium expectation conditions compared to the low expectation condition (high vs. low: $t(23) = 2.7$, $p = 0.01$, $d = 1.262$; medium vs. low: $t(23) = 4.1$, $p < 0.001$, $d = 1.457$). In contrast, Jazz musicians showed slightly higher ratings for the medium expectation condition, and were undifferentiated between the high and low expectation conditions. Furthermore, ratings for the high expectation condition were negatively correlated with duration of Jazz training: $r(34) = -0.36$, $p = 0.029$, with duration of improvisation training: $r(34) = -0.49$, $p = 0.003$, and with the number of Jazz hours played per week: $r(34) = -0.58$, $p < 0.001$), thus supporting an inverse relationship between training in Jazz improvisation and preference for the expected.

3.2. ERPs show neural sensitivity for medium vs. high expectancy events

A repeated measures ANOVA on the dependent variable of mean amplitude with a within-subjects factor of expectancy (medium versus high expectancy conditions) and a between-subjects factor of group (Jazz, Classical, Nonmusician) shows a main effect of expectation in the frontal channel FCz at time 230–280 ms ($F(1,33) = 14.12$, $p = 0.001$, $\eta^2 = 0.276$) but no interaction or main effect of group, confirming that the ERAN is elicited in the medium expectation condition (Fig. 2). The ERAN in the medium expectation condition is visually larger in the Jazz and Musician groups compared to the non-musician group, but this interaction did not reach significance. However, planned comparisons (paired-sample *t*-tests) between medium and high expectancy conditions in each subject group showed a highly significant difference in the Jazz group ($t(11) = 4.3$, $p = 0.001$, $d = 1.02$) that survived Bonferroni correction for three groups, a marginal difference in the Classical group ($t(11) = 2.03$, $p = 0.067$, $d = 0.99$), and no significant difference in the non-musician group. The difference wave (medium minus high expectancy) topography (Fig. 2a) showed left lateralization of the ERAN, which was confirmed by a mixed ANOVA with mean amplitude of the difference wave (medium vs. high) as the dependent variable, and the between-subjects factor of group and the within-subjects factor of electrode (FC3, FC1, FC2, FC4). There was a main effect of electrode ($F(3, 99) = 15.1$, $p < 0.0001$, $\eta^2 = 0.675$) but no main effect of group or interaction. Follow-up paired-samples *t*-tests compared respective electrodes on each side and confirmed that the ERAN was left lateralized (FC1 vs. FC2

$t(35) = 5.15$, $p < 0.001$, $d = 0.45$, FC3 vs. FC4: $t(35) = 3.2$, $p = 0.001$, $d = 0.55$) and survived Bonferroni correction at the $p = 0.025$ level for two electrode comparisons. The two later time windows of interest (410–480 ms, 800–850 ms) showed no significant main effects of expectation or group, and no significant interaction.

3.3. ERPs show increased sensitivity and engagement to high vs. low expectancy events in Jazz musicians

In general, ERP responses to high vs. low expectancy conditions showed that the Jazz group had a larger early right anterior negativity (ERAN: 230–280 ms), followed by a larger P3b (410–480 ms) compared to both other groups. Additionally, all subjects showed a large P3a (410–480 ms), and Classical musicians showed a larger late positive potential (800–850 ms) compared to both other groups. Fig. 3 shows findings for each group at each time window, and we present results

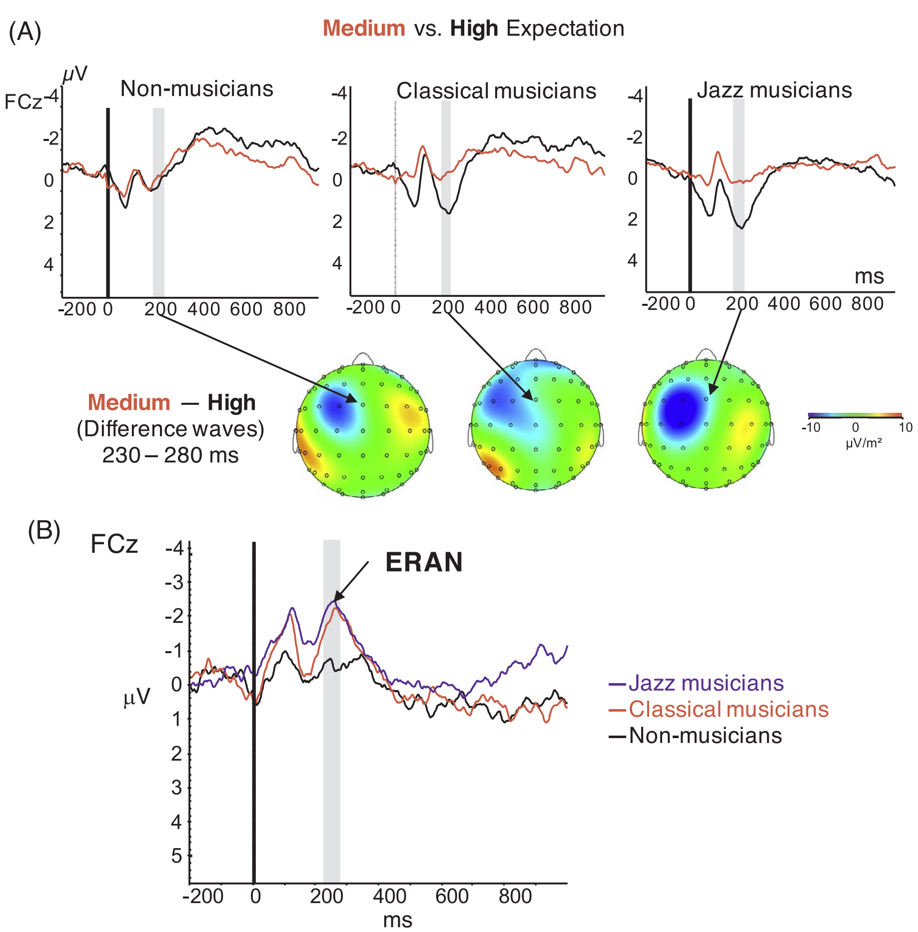

Fig. 2. (A) ERP responses to high and medium expectancy chords for Non-musician, Classical musician, and Jazz musician groups over site FCz. Grey bars indicate significant differences in the time window indicated (230–280 ms). Topos plots of the difference waves are shown for each group at the same time window. (B) Difference waves of unexpected minus expected ERPs comparing Non-musician, Musician, and Jazz musician groups over site FCz. Grey bars indicate significant differences within the indicated time window (230–280 ms).

from each time window below.

3.3.1. 230–280 ms

A repeated measures ANOVA on the dependent variable of mean amplitude during the ERAN time window (230–280 ms) showed an interaction between group and expectancy ($F(2,33) = 4.2$, $p = 0.02$, $\eta^2 = 0.184$), indicating that the ERAN effect differed between groups. Only the Jazz group showed an ERAN, as indicated by a difference in planned comparisons between low and high expectancy conditions ($t(11) = 2.8$, $p = 0.01$, $d = 0.873$) that survived Bonferroni correction for three groups, whereas the Classical musicians and non-musicians did not differ between the high and low expectancy conditions.

3.3.2. 410–480 ms

The frontal electrode FCz was chosen to test for the frontal P3a effect. A repeated measures ANOVA showed a highly significant main effect of expectancy ($F(1,33) = 82.65$, $p < 0.001$, $\eta^2 = 0.860$) and a marginally significant interaction between group and expectancy ($F(2,33) = 2.99$, $p = 0.064$, $\eta^2 = 0.0492$). Planned paired-samples *t*-tests for each group confirmed that the P3a component was significant in Jazz ($t(11) = 5.51$, $p < 0.001$, $d = 1.371$), Classical ($t(11) = 7.10$, $p < 0.001$, $d = 1.427$), and non-musician groups ($t(11) = 3.28$, $p = 0.007$, $d = 0.814$), which all survived Bonferroni correction for three groups.

The parietal electrode P2 was chosen to test for the parietal P3b effect. A repeated measures ANOVA on the dependent variable of mean amplitude during the time window of the P3b component (410–480 ms) showed a significant main effect of expectancy ($F(2,33) = 30$, $p < 0.001$, $\eta^2 = 0.410$) and a significant interaction between group and expectancy ($F(2,33) = 5.0$, $p = 0.01$, $\eta^2 = 0.139$). Planned paired-samples *t*-tests show a large P3b component in the Jazz (high vs. low $t(11) = 4.9$, $p < 0.001$, $d = 1.189$) and the Classical musician groups (high vs. low: $t(11) = 3.3$, $p = 0.007$, $d = 0.725$), both surviving Bonferroni correction for three groups, whereas the non-musician group showed no P3b (no significant difference between high and low expectancy conditions).

3.3.3. 800–850 ms

A main effect of expectancy ($F(2,33) = 12$, $p = 0.002$, $\eta^2 = 0.230$) is observed at the time window of the late positive potential (800–850 ms). Planned comparisons showed that only the Classical musician group had a significant difference between the high and low expectancy conditions ($t(11) = 2.7$, $p = 0.02$, 1.107), but this did not survive Bonferroni correction for 3 groups. The Jazz and Non-musician groups showed no difference between the two conditions, indicating that the late positivity is only seen in the Classical musician group.

3.4. ERP-behavioral correlations

ERP components were correlated with different measures of musical experience. The ERAN component for the low minus high expectation condition (mean amplitude of the difference wave at the 230–280 ms time window) was correlated with the duration of general musical training ($r(34) = -0.35$, $p = 0.034$), duration of private lessons ($r(34) = -0.46$, $p = 0.005$), the duration of Jazz training ($r(34) = -0.51$, $p = 0.002$), the duration of improvisation training ($r(34) = -0.34$, $p = 0.041$), and self-ratings of improvisation abilities ($r(34) = -0.53$, $p = 0.001$) among the jazz musicians. The P3b component (mean amplitude from parietal site P2 at the 410–480 ms time window) was correlated with duration of general musical training ($r(34) = 0.44$, $p = 0.007$) but not with the jazz experience measures, suggesting that the P3b is enhanced by general musical training, rather than jazz improvisation training specifically.

3.5. Superior divergent thinking skills in musicians

As a domain-general creativity task, subjects completed questions in a divergent thinking task from the Torrance Test of Creative Thinking (Torrance, 1968). Subjects' responses were scored for Fluency and Originality, as described in the Data analysis section. Fig. 4 shows results from the divergent thinking task across three groups. One-way ANOVAs looking at differences between the groups showed only a marginal effect of group on Fluency ($F(2,33) = 3.0$, $p = 0.063$, $\eta^2 = 0.154$), but a statistically significant main effect of group on Originality ($F(2,33) = 3.6$, $p = 0.038$, $\eta^2 = 0.179$), with both groups

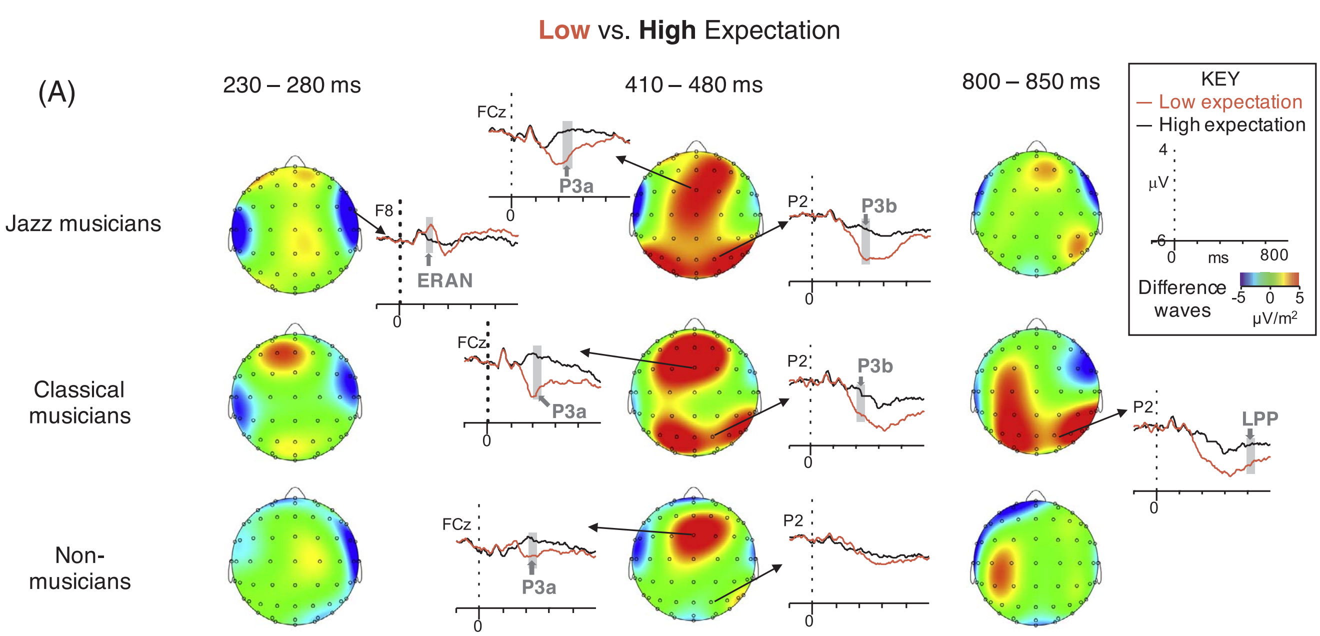

Fig. 3. (A) Topography of difference waves (Low minus High expectation) at each time window (230–280 ms, 410–480 ms, 800–850 ms) for each group. Traces show significant differences at the tested electrodes. Grey bars over the ERPs indicate significant differences between ERPs for high and low expectation at the indicated time window. (B) Difference waves for low minus high expectancy chords from specific sites in Fig. 3, overlaying the three groups, showing ERAN at site F8, P3a at site FCz, and P3b and LPP at site P2.

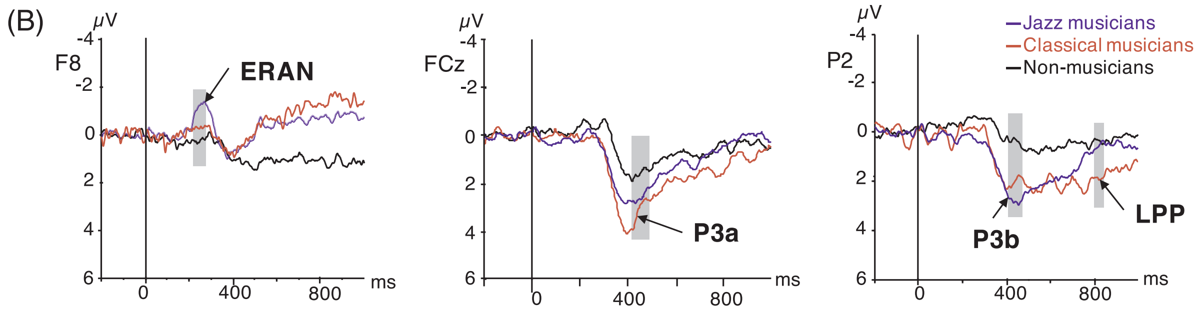

Fig. 3. (*continued*)

of musicians scoring higher on originality than the non-musicians (Fig. 4). Fluency scores were higher in Classical musicians compared to non-musicians ($t(22) = 2.5$, $p = 0.02$, $d = 1.031$), whereas Originality scores were higher in Jazz musicians compared to non-musicians ($t(22) = 2.3$, $p = 0.030$, $d = 1.017$) and also higher in Classical musicians compared to non-musicians ($t(22) = 2.8$, $p = 0.010$, $d = 1.157$). These results are further supported by correlations between measures of Originality and Fluency scores with measures of general musical training: duration of general training (Originality: $r(34) = 0.44$, $p = 0.007$, Fluency: $r(34) = 0.45$, $p = 0.006$) and duration of private lessons (Originality: $r(34) = 0.60$, $p < 0.001$ Fluency: $r(34) = 0.59$, $p < 0.001$).

3.6. ERP associations with divergent thinking

We further assessed relationships between domain-general tests of creativity and our ERP measures for expectancy. We tested for correlations between amplitude of the ERAN and P3b from the low minus high expectation conditions, as these were the components that showed significant group by condition interactions, and Fluency and Originality from the divergent thinking test (Fig. 4). The amplitude of the ERAN was significantly correlated with Originality ($r(34) = -0.40$, $p = 0.017$) and Fluency ($r(34) = -0.36$, $p = 0.030$). The amplitude of the P3b component was also significantly correlated with Originality ($r(34) = 0.40$, $p = 0.016$) and Fluency ($r(34) = 0.35$, $p = 0.038$).

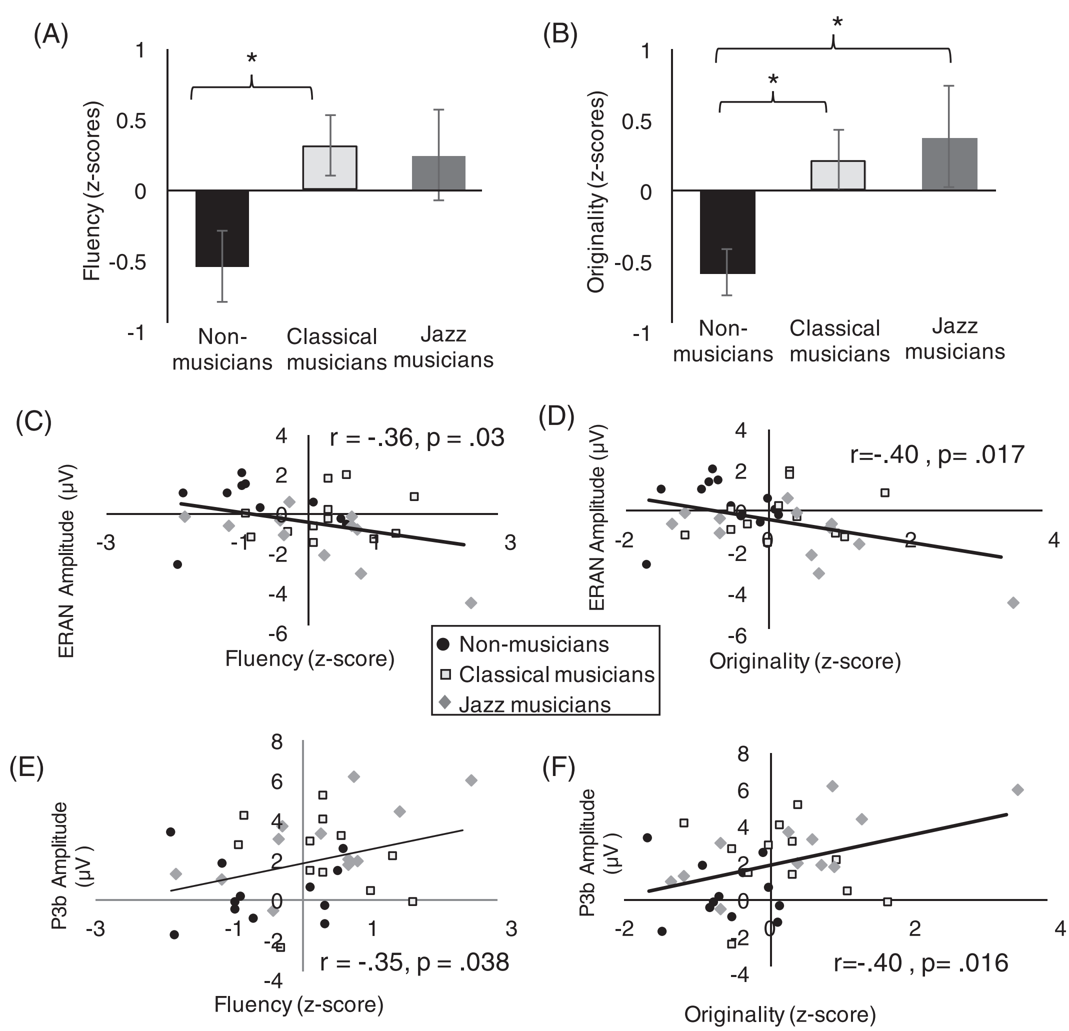

Fig. 4. (A-B) Divergent thinking test performance (z-scores) for the three groups in fluency (A) and originality (B). (C-F) Correlations between fluency and originality z-scores and amplitudes of the ERAN (C-D) and P3 (E-F).

Separately correlating these measures for each group showed that while non-musicians and Classical musicians had no significant relationship between behavioral and ERP measures, Jazz musicians had large correlations (ERAN vs. Fluency: $r(11) = -0.69$, $p = 0.012$; ERAN vs. Originality: $r(11) = -0.72$, $p = 0.008$; P3b vs. Fluency: $r(11) = 0.66$, $p = 0.021$; P3b vs. Originality: $r(11) = 0.73$, $p = 0.008$).

4. Discussion

Using Jazz improvisation training as a model, we show for the first time that jazz improvising musicians have higher preference and markedly different neural sensitivity to unexpected musical stimuli. These neural measures of expectations in a musical context are correlated with measures of domain-general creativity. Based on these results, we posit that creative perception and cognition depends on sensitivity and engagement to unexpected events within the relevant domain.

Expectations are manipulated using an established set of stimuli that follow musical-syntactic rules to elicit high, medium, and low expectation conditions. These stimuli are known to elicit the ERAN, a component that reflects perceptual sensitivity and is thought to be specific to musical syntax, as well as the P3 when the unexpected events are task relevant (Koelsch et al., 2002; Loui et al., 2005). Here we see the ERAN for the medium and low expectation conditions, as well as the P3a, P3b, and LPP for the low expectation condition only. All subjects were sensitive to the manipulation of expectancy, as indicated by a highly significant frontal P3a for low expectation events in all groups. Additionally, Jazz musicians had a significantly larger ERAN and P3b, followed by an earlier return to baseline (smaller late positive potential) in response to unexpected events. These findings suggest that people with training in creativity, when confronted with unexpected events, have increased perceptual sensitivity (as indexed by the ERAN), followed by higher engagement (as indexed by the P3b), followed by a faster return to baseline after the occurrence of unexpected events. In contrast, Classical musicians had a large frontal P3a and parietal P3b followed by a significant late positive potential, suggesting novelty detection and engagement, as well as subsequent further cognitive or motivated analysis of unexpected events. Compared to both musician groups, non-musicians only showed a frontal P3a, suggesting only frontal attention-dependent mechanisms in detecting unexpected musical events. These ERP effects are not explained by differences in familiarity, as the low expectation condition is equally unfamiliar in Classical and Jazz music. The effects are also not explained by differences in short term memory, IQ, or low-level perceptual differences such as pitch discrimination ability, as these are matched among the three groups. Since our two musician groups were reasonably well-matched but only the jazz group had significant improvisation training, we believe that these situations most likely result as part of their improvisation training (however we acknowledge there may have been pre-existing differences not captured by our screening, as would be true of any between-subjects study).

The ERAN for the low expectation condition showed significant correlations with improvisation training, whereas the P3b correlated with general musical training. Although these correlations only reflect associations and cannot be interpreted as causal, the pattern of results suggests that general musical training may increase task-relevant cognitive processing in the relevant domain of music, whereas jazz improvisation training may also enhance perceptual sensitivity to unexpected stimuli.

Although we label our early component as an ERAN (early right anterior negativity), the effect is surprisingly left-lateralized. We keep the label ERAN consistent with previous literature (Koelsch, 2009) stating that although the neural correlates of the ERAN, ELAN, mismatch-negativity and right anterior temporal negativity share similar neural correlates, the ERP generated by the unexpected Neapolitan chord is labeled as the ERAN in keeping with its functional significance of reflecting music-syntactic processing, rather than a rightward laterality per se. This nomenclature parallels the ELAN (early left anterior negativity) component, which is related to linguistic local phrase structure (Friederici, 1996). While the left lateralization in the medium vs low expectancy component is surprising, it may reflect that the medium expectancy chord is embedded in the middle of the phrase and thus recruits similar neural resources that process local phrase structure in language, as opposed to the final resolution in the low expectancy chord. Taking all of this evidence together, the early frontal negative component likely reflects sensitivity to unexpected musical events, regardless of the lateralization.

In contrast with previous studies (Koelsch et al., 2000; Loui et al., 2005) in which the ERAN was observed even in non-musicians, here we see the P3a in non-musicians for low expectation stimuli. This could be a result of the use of a different task in this experiment. Instead of passive listening or detection of a second deviant, which have been shown to elicit an ERAN and late negativity (N5) in musicians and non-musicians (Koelsch et al., 2000), in this experiment we ask subjects to make preference ratings, which forces the subjects to attend to the different expectation conditions within the stimuli. This elicits the frontal P3a and parietal P3b, together known as the P3 complex, which is elicited by task-relevant target detection (Arthur & Starr, 1984; Polich, 2007). While the P3a is observed in all subjects, the P3b is shown here to be sensitive to differences between groups. As the P3a is thought to index frontal attention and novelty-detection mechanisms (Polich, 2007; Friedman et al., 2001) and the P3b is effective as a predictor of engagement and arousal (Murphy, Robertson, Balsters, & O'Connell, 2011), we interpret the findings as showing that all subjects detect the unexpected chord as being novel (i.e. less expected). However, the Jazz musicians are more engaged by this unexpectedness, which would facilitate a quicker reaction in real time improvisation, whereas this may not be as necessary when performing pre-determined harmonies in classical music.

Behavioral differences in preference ratings show that Jazz musicians prefer the unexpected chord progressions, relative to Classical musicians and non-musicians who prefer the expected. The negative correlation between ratings on the high expectancy chord and jazz training might mean that jazz training discourages sounds that are too expected or ordinary, and encourages a higher tolerance, or relative preference, for more unexpected or complex stimuli. This could be because Jazz musicians acquire a larger musical-harmonic vocabulary as a result of improvisation training. This is in accordance with Berlyne's (1971) theory on the relationship between preference and increasing complexity, where the optimal complexity shifts towards more complex for individuals with more domain-specific knowledge in the field (Berlyne, 1971). The different preferences between the Classical and Jazz musician groups, despite both having knowledge of music, suggests that there are key differences between jazz and classical music training. One of these could be the experimental nature of jazz training that calls for jazz musicians to use their knowledge of the domain to create novel music in real time. Through training in improvisation, jazz musicians may be more exposed to novel, unexpected, or complex harmonies that might result in an increased preference or tolerance for unexpected musical harmonies (Biasutti, 2015). Alternatively, jazz musicians could have chosen to participate in jazz improvisation training because of their higher preference for novelty and unexpectedness in the first place. As the current results are cross-sectional only, they cannot tease apart the direction of causality between jazz improvisation and preference for the unexpected. Nevertheless, the current results provide empirical evidence for an interaction between expectation and training, where people with jazz improvisation training, people with non-improvisatory musical training, and people without formal musical training were perceiving and engaging with the unexpected chords differently as seen in behavioral and neural measures. These differences may stem from the different body of musical expertise that jazz musicians have acquired compared to classical musicians.

Furthermore, the persistence of the late positivity in the non-improvising musicians shows that jazz musicians recover more quickly from unexpected musical events than non-improvising musicians. This difference may arise because jazz and classical musical training require different types of listening skills, causing jazz musicians to be more inclined to switch to a different cognitive strategy immediately after the unexpected chord. As jazz improvisation occurs in real time, it is not practical to dwell on an event that seems out of place, but the non-improvising musicians may see the out-of-place event as an error that requires further cognitive analysis. In addition, the improvisatory and experimental nature of jazz training can encourage musicians to take notes and chords that are out of place and use them as a pivot to transition to new tonal or musical ideas. This could lead to the increased cognitive flexibility in jazz musicians that allows them to recover from unexpected events more quickly. Learning to identify chord progressions by ear is an important element of jazz training because it is necessary to understand the harmonic structure in order to generate chords in real-time in response both to the underlying chord progressions and to other members of the group. However for classical musicians, responses to harmonic structure and to other players in a performance are manifested in other components of musical performance, such as dynamics, phrasing, and intonation, rather than by the generation of new chord progressions as these are predetermined in composed (non-improvisatory) music (Biasutti, 2015). Therefore, jazz musicians might be more inclined to attend to unexpected harmonies and then rapidly reorient back to the task at hand. Conversely, the non-improvising musicians hear the unexpected harmony as being incongruous with the context, and continue to devote cognitive resources to resolve this incongruity, giving rise to the persistence of the late positivity in non-improvising musicians. This further cognitive processing may reflect a judgment of the unexpected chord as a mistake, which could be beneficial for classical musicians, as they often need to recognize errors so they can avoid the same mistake in subsequent performances. Thus, our results suggest that differences in musical training result in different neural responses to unexpected events that may differentially benefit the task demands imposed by the two different types of musical performance.

Questions from the Torrance Test of Creative Thinking are used here as a domain-general measure of creativity. In contrast to most cognitive tests, which have a one-to-one mapping between question and target response, the TTCT requires divergent thinking, or the generation of multiple responses from a single prompt. Although this assessment tool is relatively domain-general (i.e. it does not require specialized knowledge or experience, unlike in musical performance), we see some evidence of more creative performance in people with musical training, with classical musicians outperforming non-musicians in fluency, and classical and jazz musicians both outperforming non-musicians in originality. Consistent with previous results (Benedek et al., 2014; Kleinmintz et al., 2014), our results provide evidence for higher domain-general creative abilities in musically trained subjects. Furthermore, here we observe correlations between TTCT scores and ERP components elicited by violations of musical expectancy. The P3b component, which is correlated with general musical training, is also correlated with the divergent thinking test measures, suggesting that musical training may be associated with creative tasks as moderated by the neural processing of target events. The finding that the ERAN component, which is associated with jazz improvisation training in this study, is also correlated with TTCT scores suggests that improvisation training does influence domain-general creative thinking abilities. As seen in Fig. 4 and indicated by the correlations for single groups, the jazz group seems to drive these associations between the TTCT and ERP components. This suggests that for the non-musician and classical musician groups, these two tasks are inherently dissimilar, but jazz training may bridge the gap by forming an association between these seemingly unrelated domains. This connection between domains may arise from jazz training methods that are more likely to incorporate non-musical aspects when developing improvisational skills, e.g. jazz improvisation training may involve experimenting with sounds to match different extra-musical ideas, such as verbal prompts, visual imagery, and/or emotions to be communicated (Biasutti, 2015). Therefore, the connection between domain-general creativity tasks and music-specific perceptual processes may be clearer in jazz musicians than in non-jazz musicians and non-musicians.

The effects of domain-general creativity and musical-specific creativity that arise from jazz improvisation are difficult to tease apart. This is because through their training jazz musicians are exposed to unexpected events that are musical, and thus the processing of unexpected events is highly embedded in the musically specific training. The TTCT could be considered a domain-general measure of ability to respond to unexpected events, as it asks participants to respond to questions that they wouldn't think of answering every day. With this interpretation, responding to unexpected events would be considered a component of domain-general creativity. The correlations that we found between the ERAN and P3b ERP components and TTCT suggest that the neural underpinnings of both music-specific and domain-general expectations are related to domain-general creativity. Taken together we believe our results indicate the dual role of domain general and specific creativity in improvisation. Future longitudinal studies, as well as studies on other groups such as actors receiving non-musical improvisational training, could help to tease apart the specific contributions of these domains to the processing of musical expectancy.

Together, results from behavioral and EEG data show higher performance in creativity in musicians. The underlying cognitive mechanism likely entails increased sensitivity to expectations, and increased engagement to unexpected events. This sensitivity to expectation is indexed by higher preference ratings for unexpected chord progressions in jazz musicians, coupled with increased amplitude in the ERAN and P3b, two ERP waveforms that index perceptual sensitivity and cognitive engagement respectively. Results suggest that creativity entails being sensitive and engaged with unexpected events within a well-learned context, and that training sharpens our expectations and can have general implications for how humans learn to be creative.

Acknowledgements

Supported by grant funding from the Imagination Institute and the Grammy Foundation to PL. We thank Pheeroan Aklaff for helpful conversations, Sarah Knight and Tedra James for scoring responses to the TTCT, and all our participants.

References

Arthur, D. L., & Starr, A. (1984). Task-relevant late positive component of the auditory event-related potential in monkeys resembles P300 in humans. *Science, 223*(4632), 186.

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829–839.

Beaty, R. E. (2015). The neuroscience of musical improvisation. *Neuroscience & Biobehavioral Reviews, 51*, 108–117.

Benedek, M., Borovnjak, B., Neubauer, A. C., & Kruse-Weber, S. (2014). Creativity and personality in classical, jazz and folk musicians. *Personality and Individual Differences, 63*(100), 117–121.

Bengtsson, S. L., Csikszentmihalyi, M., & Ullen, F. (2007). Cortical regions involved in the generation of musical structures during improvisation in pianists. *Journal of Cognitive Neuroscience, 19*(5), 830–842.

Berkowitz, A. L., & Ansari, D. (2008). Generation of novel motor sequences: The neural correlates of musical improvisation. *Neuroimage, 41*(2), 535–543.

Berlyne, D. E. (1971). *Aesthetics and psychobiology.* New York: Appleton-Century-Crofts.

Biasutti, M. (2015). Pedagogical applications of the cognitive research on music improvisation. *Frontiers in Psychology, 6*.

Cacioppo, J. T., Crites, S. L., Berntson, G. G., & Coles, M. G. H. (1993). If attitudes affect how stimuli are processed, should they not affect the event-related brain potential? *Psychological Science, 4*(2), 108–112.

Csikszentmihalyi, M. (1996). *Creativity: Flow and the psychology of discovery and invention.* New York: Harper Collins Publishers.

Friederici, A. D. (1996). The time course of syntactic activation during language processing: A model based on neuropsychological and neurophysiological data. *Brain and Language, 50*(3), 258–291.
Friedman, D., Cycowicz, Y. M., & Gaeta, H. (2001). The novelty P3: An event-related brain potential (ERP) sign of the brain's evaluation of novelty. *Neuroscience & Biobehavioral Reviews, 25*(4), 355–373.
Goldenberg, J., Mazursky, D., & Solomon, S. (1999). Creative sparks. *Science, 285*(5433), 1495–1496.
Karakelle, S. (2009). Enhancing fluent and flexible thinking through the creative drama process. *Thinking Skills and Creativity, 4*(2), 124–129.
Klein, M., Coles, M. G., & Donchin, E. (1984). People with absolute pitch process tones without producing a P300. *Science, 223*(4642), 1306–1309.
Kleinmintz, O. M., Goldstein, P., Mayseless, N., Abecasis, D., & Shamay-Tsoory, S. G. (2014). Expertise in musical improvisation and creativity: The mediation of idea evaluation. *PLoS One, 9*(7), e101568.
Knight, R. T., Scabini, D., Woods, D. L., & Clayworth, C. C. (1989). Contributions of temporal-parietal junction to the human auditory P3. *Brain Research, 502*(1), 109–116.
Koelsch, S. (2009). Music-syntactic processing and auditory memory: Similarities and differences between ERAN and MMN. *Psychophysiology, 46*(1), 179–190.
Koelsch, S., Gunter, T., Friederici, A. D., & Schroger, E. (2000). Brain indices of music processing: "Nonmusicians" are musical. *Journal Cognitive Neuroscience, 12*(3), 520–541.
Koelsch, S., Schroger, E., & Gunter, T. C. (2002). Music matters: Preattentive musicality of the human brain. *Psychophysiology, 39*(1), 38–48.
Lewis, C., & Lovatt, P. J. (2013). Breaking away from set patterns of thinking: Improvisation and divergent thinking. *Thinking Skills and Creativity, 9*, 46–58.
Limb, C. J., & Braun, A. R. (2008). Neural substrates of spontaneous musical performance: An fMRI study of jazz improvisation. *PLoS One, 3*(2), e1679.
Liu, S., Chow, H. M., Xu, Y., Erkkinen, M. G., Swett, K. E., Eagle, M. W., & Braun, A. R. (2012). Neural correlates of lyrical improvisation: An FMRI study of freestyle rap. *Science Reports, 2*, 834.
Loui, P., Grent-'t-Jong, T., Torpey, D., & Woldorff, M. (2005). Effects of attention on the neural processing of harmonic syntax in Western music. *Brain Research Cognitive Brain Research, 25*(3), 678–687.
Loui, P., Guenther, F. H., Mathys, C., & Schlaug, G. (2008). Action-perception mismatch in tone-deafness. *Current Biology, 18*(8), R331–332.
Loui, P., & Wessel, D. (2007). Harmonic expectation and affect in Western music: Effects of attention and training. *Perception & Psychophysics, 69*(7), 1084–1092.
Loui, P., Wu, E. H., Wessel, D. L., & Knight, R. T. (2009). A generalized mechanism for perception of pitch patterns. *Journal of Neuroscience, 29*(2), 454–459.
Meyer, L. (1956). *Emotion and meaning in music.* Chicago: University of Chicago Press.
Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'Connell, R. G. (2011). Pupillometry and P3 index the locus coeruleus-noradrenergic arousal function in humans. *Psychophysiology, 48*(11), 1532–1543.
Naatanen, R., Simpson, M., & Loveless, N. E. (1982). Stimulus deviance and evoked potentials. *Biological Psychology, 14*(1–2), 53–98.
Polich, J. (2007). Updating P300: An integrative theory of P3a and P3 b. *Clinical Neurophysiology, 118*(10), 2128–2148.
Schupp, H. T., Cuthbert, B. N., Bradley, M. M., Cacioppo, J. T., Ito, T., & Lang, P. J. (2000). Affective picture processing: The late positive potential is modulated by motivational relevance. *Psychophysiology, 37*(2), 257–261.
Shipley, W. C. (1940). A self-administering scale for measuring intellectual impairment and deterioration. *Journal of Psychology, 9*, 371–377.
Steinbeis, N., Koelsch, S., & Sloboda, J. A. (2006). The role of harmonic expectancy violations in musical emotions: Evidence from subjective, physiological, and neural responses. *Journal Cognitive Neuroscience, 18*(8), 1380–1393.
Sternberg, R. J., Lubart, T. I., Kaufman, J. C., & Pretz, J. E. (2005). Creativity. In K. J. Holyoak, & R. G. Morrison (Vol. Eds.), *The Cambridge handbook of thinking and reasoning: Vol. 137*, (pp. 351–369). Cambridge University Press Cambridge.
Torrance, E. P. (1968). Examples and rationales of test tasks for assessing creative abilities. *Journal of Creative Behavior, 2*(3), 165–178.
Tukey, J. W. (1977). *Exploratory data analysis.* Addison-Wesley Publishing Company.
Wiggins, G., & Bhattacharya, J. (2014). Mind the gap: An attempt to bridge computational and neuroscientific approaches to study creativity. *Frontiers in Human Neuroscience, 8*.
Yamaguchi, S., & Knight, R. T. (1991). P300 generation by novel somatosensory stimuli. *Electroencephalography and Clinical Neurophysiology, 78*(1), 50–55.
Zicarelli, D. (1998). An extensible real-time signal processing environment for Max. *Paper presented at the proceedings of the international computer music conference*. Ann Arbor, USA: University of Michigan.