

Musical genre-dependent behavioural and EEG signatures of action planning. A comparison between classical and jazz pianists

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Abstract

It is well established that musical training induces sensorimotor plasticity. However, there are remarkable differences in how musicians train for proficient stage performance. The present EEG study outlines for the first time clear-cut neurobiological differences between classical and jazz musicians at high and low levels of action planning, revealing genre-specific cognitive strategies adopted in production. Pianists imitated chord progressions without sound that were manipulated in terms of harmony and context length to assess high-level planning of sequence-structure, and in terms of the manner of playing to assess low-level parameter specification of single acts. Jazz pianists revised incongruent harmonies faster as revealed by an earlier reprogramming negativity and beta power decrease, hence neutralising response costs, albeit at the expense of a higher number of manner errors. Classical pianists in turn experienced more conflict during incongruent harmony, as shown by theta power increase, but were more ready to implement the required manner of playing, as indicated by higher accuracy and beta power decrease. These findings demonstrate that specific demands and action focus of training lead to differential weighting of hierarchical action planning. This suggests different enduring markers impressed in the brain when a musician practices one or the other style.

Keywords: plasticity, action planning, specialised-musical training, event-related potentials, oscillations

1 INTRODUCTION

2 Human skilled behaviours require optimal adaptation of brain structure and function to proficiently
3 meet environmental demands. Music production is emblematic for how extensive training can foster
4 precision and fluency in performance accompanied by remarkable anatomical and functional changes
5 in sensorimotor brain areas (Herholz and Zatorre, 2012; Münte et al., 2002). Importantly, research in
6 the auditory domain not only points to general effects of musical training but suggests nuanced
7 neurocognitive adaptations depending on specialised training or even stylistic enculturation (Stewart,
8 2008; Tervaniemi, 2009). In fact, not only are low-level auditory perception (Münte et al., 2003;
9 Schneider et al., 2005; Shahin et al., 2008) or basic motor functions (Rüber et al., 2013) differentially
10 shaped by the type of practiced instrument; even higher levels of music anticipation based on
11 structural properties of the music are differentially shaped by practiced genre such as classical, rock or
12 jazz (Eerola et al., 2009; Hansen et al., 2016; Loui et al., 2014; Vuust et al., 2012). However,
13 concerning this last point, virtually all research to date remains confined to the auditory domain,
14 leaving potentially similar impact of genre on production unexplored. Here, we ask whether and how
15 training in different musical styles—classical or jazz—affects musical action planning, with the goal
16 to unveil the neurobiological grounds for specialised cognitive-motor strategies adopted in skilled
17 motor behaviours. We show behavioural and neural differences between musicians from the two
18 genres reflecting differential calibration of hierarchical planning processes depending on classical or
19 jazz training.

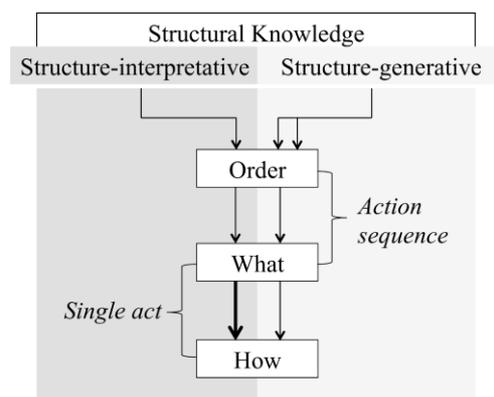
20 It is widely established that skilled behaviours are generated by the interaction of hierarchical
21 representational levels, ranging from movement goals (selection level) down to the specification of the
22 actual muscle commands (execution level) (Diedrichsen and Kornysheva, 2015; Rosenbaum et al.,
23 2007; Verwey et al., 2015). For example, sequential finger movements or simple actions require
24 planning of the whole movement sequence which binds the appropriate single acts ('what' should be
25 done in which order at the *sequence level*), and to specify motor implementation details of each act
26 ('how' to do at the *single act level*) (Grafton and Hamilton, 2007; Koehlin and Summerfield, 2007;
27 Lashley, 1951; Rosenbaum et al., 2007; Schmidt, 1975; Uithol et al., 2012; Verwey et al., 2015;
28 Wohlschläger et al., 2003). Such hierarchical representations of actions are formed through motor
29 training and allow generalization and flexible generation of novel behaviours (Diedrichsen and
30 Kornysheva, 2015; Waters-Metenier et al., 2014). Skilled musicians, for instance pianists, not only
31 accurately specify the fingers used to implement each single act on the keyboard; to enhance fluency,
32 they also plan in advance what to play next based on the preceding musical sequence (Bianco et al.,
33 2016a; Novembre and Keller, 2011; Sammler et al., 2013). However, practice in different genres may
34 predominantly engage one or another hierarchical level of action representation (see below), hence
35 action planning processes may become subject to habits. In this study, we investigate whether
36 experience-dependent biases, as specialized musical training, are manifest at different hierarchical
37 representational levels during music production.

38 Recent event-related potential (ERP) studies identified neural markers of distinct representational
39 levels of musical action planning in piano performance. Specifically, these reports dissociated
40 planning at *sequence* and *single act* level, contrasting high-level music-structural goals, the ‘what’,
41 and low-level setting of appropriate movement parameters, the ‘how’. Classically trained pianists
42 imitated unrehearsed chord sequences in which final chords were violated either in their music-
43 structural fit with the preceding harmonic context, i.e., the sequence-level harmonic goal according to
44 the rules of western tonal music, or in their manner of execution, i.e., the fingering of the single chord.
45 Context-dependent behavioural (response costs) and neural responses (a late “reprogramming”
46 negativity) to the unexpected structure violations indicated that musicians use the context and their
47 knowledge of musical structure to (i) generate motor predictions at the level of the *action sequence*
48 and anticipate the identity of the next chord to play (Novembre and Keller, 2011; Sammler et al.,
49 2013). At the same time, a distinct neural response to violations in the manner of execution (a late
50 positivity) disclosed (ii) the lower-level representation of *single act* movement parameters, that is
51 usually optimally set for achieving the desired action goal (Bianco et al., 2016a). In addition, other
52 research on prediction and motor control in music production documented an increase of frontal theta
53 power during performance errors at sequence-level (i.e., execution of a wrong note) (Ruiz et al.,
54 2011), in line with multiple reports of frontal theta modulations during conflict-detection (Botvinick et
55 al., 2004; Cavanagh and Frank, 2014; Luu et al., 2004; Trujillo and Allen, 2007) and inhibition of
56 anticipated congruent responses (Harmony et al., 2009; Kirmizi-Alsan et al., 2006). Altogether, these
57 studies provide measurable neural evidence that expert musicians plan their actions at different
58 hierarchical representational levels and that they implement motor-predictive/control mechanisms in
59 order to plan performance efficiently and to react to unexpected events/performance errors.

60 However, these neural mechanisms have been investigated only in one type of musician, namely,
61 performers specialising in the classical genre. To the best of our knowledge, no study has tested if
62 these effects depict a rigid, common cognitive organization of motor-predictive strategies developed
63 after extensive general training or whether they can be differentially modulated by specific demands
64 and action focus of the training. For example, improvising jazz or playing a classical concerto requires
65 focus on different levels of performance and may—in the long run—shape action tendencies and
66 cognitive-motor strategies of musicians. Jazz musicians can be said to adopt a *structure-generative*
67 *focus* when playing (more than classical musicians): they focus particularly on building musical
68 *sequences* in real-time and in a way that plays with the audience’s expectations (Beaty, 2015;
69 Pressing, 1984). These skills not only require perfect mastery of musical conventions and (harmonic)
70 rules in order to creatively deviate from them (Johnson-Laird, 2002); they also imply increased
71 familiarity with non-canonical structural alternatives¹ that the musician actively embraces or revokes
72 more or less on the fly (Pressing, 1987). In contrast, classical musicians (more than jazz musicians)

¹ Note that both classical and jazz music traditions are similarly rooted in Western tonal harmony (Goldman, 2012; Johnson-Laird, 2002), which defines the arrangement of chords into well-structured musical sequences (Swain, 1995).

73 adopt a *structure-interpretative focus* when playing: they specifically focus on the range of possible
 74 expressive features to be applied to the musical structure, which is usually fixed by the composer
 75 (Shaffer, 1984). These features include, amongst others (see Keller 2012), the choice of particular
 76 fingerings for each *single act* (e.g., the thumb being stronger and better suited for accentuation;
 77 Parncutt, 2014), which is usually a crucial component in the preparation of classical performance and
 78 requires intensive practice of fingering technique (Gellrich and Parncutt, 1998). This experience not
 79 only entails the ability to select the optimal fingering on the spot, even when the music is unrehearsed
 80 as in sight-reading (Clarke, 2001); it also implies a rapid and straightforward inference of the most
 81 likely forthcoming structural element, to immediately proceed to expressive stages of action planning
 82 (Chaffin et al., 2007; Clarke, 2001). In the present study, we tested the hypothesis that, despite equal
 83 amounts of training, differences in focus of daily practice may induce genre-specific cognitive-motor
 84 strategies, as reflected in neural and behavioural markers of musicians specialising in jazz
 85 improvisation versus classical performance, even when playing the same music. These differences in
 86 strategies may most likely be reflected in different calibration of the hierarchical levels of action
 87 planning (see Figure 1).



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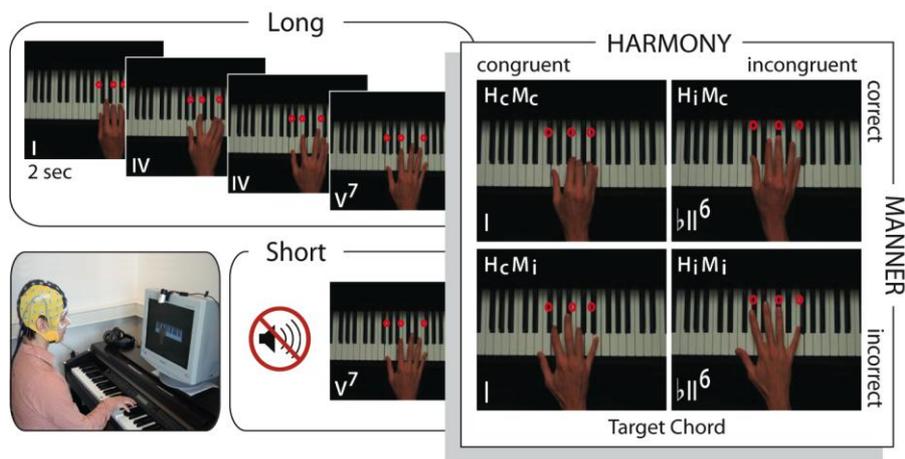
89 **Figure 1. Multiple layers of action planning and hypothesized influence of action focus.** High-level
 90 structure-based plans of action sequences are formed based on structural (e.g., harmonic) knowledge and the
 91 unfolding musical context. These plans determine the appropriate ordering ('Order') and consequently the
 92 identity ('What') of single acts in a sequence. Lower-level parameters (e.g., fingering) are specified at later
 93 stages of action planning. These parameters determine the optimal motoric implementation ('How') of the single
 94 act. This multilayer organization of actions may be tuned by (i) a structure-generative (jazz) or (ii) a structure-
 95 interpretative (classical) action focus: (i) requires active (re)arrangement of structural alternatives at the level of
 96 the action sequence (as indicated by double arrows), while (ii) requires straightforward planning of the most
 97 probable order of the action sequence (single arrow) for rapid assignment of relevant motor parameters of the
 98 single act (bold arrow).

99 To study genre-specific differences at high and low levels of action planning, we adopted the same
 100 real-time music production task as in Bianco et al. (2016) while measuring EEG in jazz and classical
 101 pianists. In complete absence of sound, pianists were required to watch and imitate unrehearsed chord
 102 sequences played by a performing pianist's hand presented in series of photos on a computer screen.

103 Although unusual, absence of sound was essential, as in previous studies, to focus on the cognitive-
104 motor aspects of the task and to eliminate exogenously driven auditory predictive processes. Similarly,
105 the decision to display musical sequences by virtue of a model hand instead of for instance scores
106 aimed to minimise intermediate translation processes of abstract symbolic stimuli into action, and to
107 level out potential inter-individual or between-group differences in score-reading abilities.

108 To address (i) planning at high *action sequence* level, we manipulated the predictability and harmonic
109 fit of the final chord by placing it at the end of 5- or 2-chord sequences (long/short Context) and by
110 rendering it harmonically (in)congruent with the preceding musical context (congruent/incongruent
111 Harmony). Given that long compared to short sequences provide more information for harmonic
112 structure building, context-*dependent* behavioural costs and a late negativity (Sammler et al., 2013;
113 Bianco et al., 2016a) associated with the harmonic violation were taken as relevant indices of high-
114 level structure-plan building/reassessment. To address (ii) the lower level of *single act*
115 *implementation*, the final chord was manipulated not only in terms of Harmony (i.e. ‘what’ to play)
116 but also in terms of fingering used for execution (conventional/unconventional Manner; i.e. ‘how’ to
117 play). Because movement parameters are related to single acts and are specified at late stages of action
118 planning, context-*independent* response time costs and a late positivity (Bianco et al., 2016a)
119 associated with the manner violation were taken as indices of low-level movement parameter setting
120 of single acts. Beyond these behavioural and ERP signatures, we further explored neural oscillatory
121 activity in the theta band as an established marker of action monitoring in specialized musicians (Ruiz
122 et al., 2011) and the beta band as a correlate of general motor processes (Kilner et al., 1999) and error
123 detection during action observation, planning and execution (Koelewijn et al., 2008; Ruiz et al., 2011;
124 Tzagarakis et al., 2010).

125 We hypothesised different weightings and dynamics within different hierarchical levels of action
126 planning depending on classical and jazz training: (i) If a *structure-generative focus* fosters active
127 (re)arrangement of structural alternatives at the level of the *action sequence*, then jazz compared to
128 classical pianists should show behavioural and neural signals of less conflict and greater flexibility in
129 the processing and revision of their motor plans when responding to harmonically unexpected final
130 chords, particularly in the long context; (ii) if a *structure-interpretative focus* leads pianists to rely on
131 the most likely structure-plan to rapidly proceed to setting the manner of execution at the level of the
132 *single act*, then classical compared to jazz pianists should show behavioural and neural signals of
133 greater conflict in response to harmonic novelties, yet greater accuracy in setting appropriate fingering
134 parameters.



135

136 **Figure 2. Experimental design.** In absence of sound, pianists executed unrehearsed chord progressions by
 137 imitating a performing hand presented in series of photos. The sequences were manipulated in their last chord in
 138 terms of Harmony (congruent/incongruent) and Manner (correct/incorrect). Furthermore, the length of the
 139 Context (long/short) manipulated the overall structure-based predictability of the last chord.

140

141 **MATERIAL AND METHODS**

142 **Participants**

143 Fifteen classical pianists (classical group, CG, 11 females) and 15 jazz pianists (jazz group, JG, 1
 144 female)² gave informed consent to participate in the study. All pianists had received formal training at
 145 music academies with focus on the classical or jazz genre, e.g., the Hochschule für Musik und Theater
 146 “Felix Mendelssohn-Bartholdy” in Leipzig. **Classical pianists were a subset of the original dataset of**
 147 **26 individuals** (from Bianco et al., 2016) chosen to match the jazz pianists in the following criteria:
 148 The two groups were comparable in age (mean age \pm SEM of CG: 25.5 ± 1 years; JG: 25.7 ± 1.3 years;
 149 $t(28) = 0.123, p > .903$), total accumulated hours of piano training across their life (CG: 11886 ± 1621
 150 hours; JG: 11485 ± 1387 hours; $t(28) = -0.188, p > .852$), and onset of piano playing (age of onset,
 151 CG: 6.7 ± 0.7 years; JG: 9.0 ± 1.0 years; $t(28) = 1.88, p > .071$). All pianists had at least 6 years of
 152 musical training. At the time of testing, all participants were similarly musically active in terms of
 153 current piano practice, as revealed by the comparison of average practice hours per week over the past
 154 year (CG: 8.9 hours; JG: 13.3 hours; $t(28) = 1.19, p > .245$). The criteria to qualify as a classical
 155 pianist was to have no jazz or improvisation experience, while a minimum of 2 years of jazz piano
 156 training was required to be assigned to the jazz group. The JG had in fact more accumulated training

² Studies on sex-difference in fine-motor skills have so far shown no effects of sex at expert stages of motor performance (Dorfberger et al., 2009), and no relationship between sex and jazz improvisation ability, skills or knowledge (Madura, 1996). However, it is possible that the gender imbalance we encountered in recruiting the jazz group may have social-psychological grounds, e.g., confidence and attitude, that influence female participation in instrumental jazz improvisation (Wehr-Flowers, 2006).

157 hours in jazz than in classical piano (in JG: 7202 ± 954 jazz training hours and 4684 ± 621 classical
158 training hours; $t(28) = 2.78, p < .014$). On a scale from 1 to 9, the JG reported to practice music more
159 often without reading from scores than the CG (CG: 4.8 ± 0.6 ; JG: 6.5 ± 0.5 ; $t(28) = 2.22, p < .035$),
160 although both groups reported comparable abilities to read scores (CG: 5.73 ± 0.7 ; JG: 4.26 ± 0.6 ;
161 $t(28) = -1.72, p > .100$). All participants were naïve with regard to the purpose of the study and
162 received monetary compensation for participation. The local ethics committee of the University of
163 Leipzig approved the study (016-15-260-12015).

164 **Stimuli**

165 Stimuli were the same as those used in Bianco et al. (2016a), i.e., photos showing a male pianist's
166 right hand playing sequences of chords on the piano (Yamaha Clavinova CLP150). All participants
167 were presented with 72 sequences that were composed according to the rules of classical harmony in
168 four tonalities with either two or four sharps or flats, i.e., D, E, Bb, and Ab major. Sequences consisted
169 of chords of three keystrokes each and differed in melodic contour. The last chord of each sequence
170 was manipulated according to a 2 x 2 factorial design, in terms of Harmony (H) to target structure-
171 based planning (congruent Tonic chord vs. an incongruent Neapolitan chord) and/or in terms of
172 Manner (M) to target parameter specification (conventional fingering – i.e., 124, 125, 135, vs.
173 unconventional fingering – i.e., 123, 235, 245, where 1 represents the thumb, 2 the index and 3, 4 and
174 5 the middle, the ring and the little finger, respectively; for a more detailed description of the stimuli,
175 see Bianco et al., 2016a and Figure 2). Thirty-six sequences were conventional in terms of both
176 Harmony and Manner (H congruent/M correct: H_cM_c), 12 contained violations in terms of Harmony
177 but not Manner (H incongruent/M correct: H_iM_c), 12 in terms of Manner but not Harmony (H
178 congruent/M incorrect: H_cM_i), and 12 were violated in terms of both factors (H incongruent/M
179 incorrect: H_iM_i). The harmonic predictability of the last chord was manipulated by placing it either at
180 the end of five-chord sequences (long context for high predictability), or two-chord sequences (short
181 context for low predictability). The two-chord sequences were identical with the last two chords of the
182 five-chord sequences. Hence, comparing the 4 conditions across the two contexts allowed us both to
183 measure context-dependent structure-based planning of the last chord while controlling for motoric
184 differences, i.e., longer movement trajectories from penultimate to incongruent / unconventional
185 chords than in the congruent / conventional conditions. The total duration of the long and short
186 sequences was 12 and 6 sec, respectively, including a 2 sec preparatory photo showing a hand about to
187 press the first chord, followed by photos of the 5- or 2-chord sequences presented at a rate of 2 sec per
188 photo. Each trial started with a visual fixation cross of 0.5 sec and ended with a black screen of 1.5 sec
189 after the final photo of the stimulus sequence. To facilitate recognition of the relevant keys and
190 fingers, red circles were superimposed on top of each pressed key for the whole duration of the photo.

191 **Procedure**

192 We adopted the same experimental procedure as Bianco et al. (2016a). Pianists were asked to watch
193 the photo series of the model hand on a computer monitor (100 Hz refresh rate) and simultaneously to
194 execute the chords with their right hand on a MIDI (musical instrument digital interface) piano
195 (Yamaha Clavinova CLP150, Yamaha Music Europe GmbH, Rellingen, Germany) (see Figure 2).
196 Note that the piano was muted and no sound was presented with the photos. Pianists were instructed to
197 execute the chords one by one, as quickly and accurately as possible, both in terms of the keys pressed
198 (Harmony) and in terms of fingering (Manner). The experiment consisted of 6 experimental blocks.
199 Each block contained 24 non-violated trials (H_cM_c) intermixed with 24 trials of one of the violation
200 conditions (H_iM_c , H_cM_i , or H_iM_i), separately for long and short sequences. Block order was
201 counterbalanced across participants and alternated between blocks with long and short sequences. To
202 increase the number of trials, each pianist participated in two sessions on separate days with the same
203 stimuli and the same block order. In order to acquaint participants with the task, the first session
204 started with 6 short blocks of 24 practice trials each (12 H_cM_c and 12 H_iM_c , H_cM_i , or H_iM_i in long or
205 short context) in tonalities that were not used in the main experiment (G, F, Db, and B major).
206 Stimulus presentation and response registration were controlled by Presentation software (Version
207 14.9, Neurobehavioural System, Inc.). MIDI piano key values were converted into a serial signal
208 compatible with Presentation software through a custom-built MIDI interface. Participants' right
209 hands were filmed with a video camera placed above the keyboard for (off-line) analysis of their
210 fingering accuracy.

211 **EEG data acquisition**

212 EEG recordings were acquired from 61 Ag/AgCl electrodes (Fpz, Fp1, Fp2, AFz, AF3, AF4, AF7,
213 AF8, Fz, F3, F4, F5, F6, F7, F8, F1, FC2, FCz, FC3, FC4, FC5, FC6, FT7, FT8, FC1, F2, Cz, C1, C2,
214 C3, C4, C5, C6, T7, T8, CPz, CP3, CP4, CP5, CP6, TP7, TP8, P1, P2, Pz, P3, P4, P5, P6, P7, P8,
215 CP1, CP2, POz, PO3, PO4, PO7, PO8, O1, O2, Oz) placed according to the international 10-20 system
216 (Sharbrough et al., 1991). The left mastoid (M1) served as reference. Three additional electrodes were
217 placed on the sternum as common ground, on the right mastoid bone (M2), and on the tip of the nose
218 for off-line re-referencing. Vertical and horizontal EOG was recorded from two bipolar montages, one
219 with electrodes located above and below the left eye, the other with two electrodes placed on the outer
220 canthus of each eye. Signals were amplified using a 24-bit Brainvision QuickAmp 72 amplifier (Brain
221 Products GmbH, Gilching, Germany) with input impedances below 5 k Ω and digitised at a 500 Hz
222 sampling rate.

223 **Behavioural data analysis**

224 Response times (RTs) and execution errors of the last chord of valid trials were analysed as in
225 previous studies (Novembre and Keller, 2011; Sammler et al., 2013; Bianco et al., 2016). Trials were
226 considered valid when (1) no key and fingering mistakes occurred in the last and the second last
227 chords, (2) the keystrokes within a chord were synchronous (i.e., no more than 150 msec elapsed

228 between the first and the last of the 3 keystrokes) and (3) RTs were below 3000 msec (Drost et al.,
229 2005). RTs were averaged across the three keystrokes and were time-locked to the onset of the photo
230 showing the last chord. Fingering of the participants was analysed through off-line inspection of the
231 video recordings of their hands. Statistical evaluation of the RT data was done using four-way
232 analyses of variance (ANOVAs) with the repeated-measures factors Harmony
233 (congruent/incongruent), Context (long/short), Manner (correct/incorrect), and the between-subjects
234 factor Group (classical/jazz). Errors were analysed with two analogous ANOVAs, separately for key
235 and fingering errors.

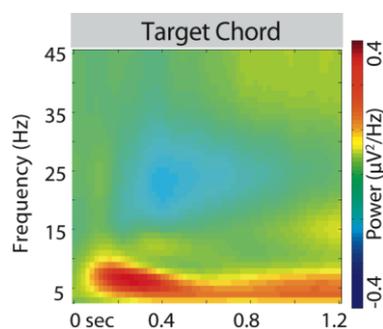
236 **EEG data analysis**

237 **Pre-processing.** EEG data were pre-processed using EEGLAB 9 (Delorme and Makeig, 2004)
238 implemented in MATLAB 7.4. Data were first re-referenced to the algebraic mean of the mastoids and
239 filtered with a 0.3-Hz high-pass filter (FIR 5854 points, Blackman window). Then, electrode drifts,
240 strong muscle and technical artefacts were manually rejected and data were entered into an
241 Independent Component Analysis (ICA) to parcel out the contribution of artefacts such as eye
242 movements, continuous tension of muscles, slow drifts and technical noise. After 45-Hz low pass
243 filtering (fir, 810 points, Blackman window), epochs were extracted from behaviourally correct trials
244 between -900 and 2200 msec relative to the onset of the last (target) chord. Only trials with signal
245 voltages within $\pm 80 \mu\text{V}$ at all electrodes were included in further analyses and averaged separately for
246 each condition. 21% and 38% of the total number of trials were discarded in the classical (CG) and
247 jazz group (JG), respectively. To ensure that group differences cannot be attributed to trial count or
248 signal-to-noise ratio, we randomly eliminated further trials in CG to equate them with the trial
249 numbers of the JG in each condition.

250 **Event-related potentials.** For each participant and each condition, event-related potentials (ERPs)
251 were computed from -200 to 1200 ms relative to the onset of the target photo and baseline correction
252 was performed (baseline: -200 to 0 ms). For statistical analysis, mean amplitudes were extracted
253 separately for each condition from 9 regions of interest (ROIs) in specific time-windows (see below).
254 The ROIs comprised: (i) left anterior (F3, F5, F7, FC3, FC5, FT7, AF3), (ii) left central (C3, C5, T7,
255 CP3, CP5, TP7), (iii) left posterior (P3, P5, P7, PO3, PO7), (iv) middle anterior (F1, FZ, F2, FC1,
256 FCZ, FC2, AFZ), (v) middle central (C1, CZ, C2, CP1, CPZ, CP2), (vi) middle posterior (P1, PZ, P2,
257 POZ), (vii) right anterior (F4, F6, F8, FC4, FC6, FT8, AF4), (viii) right central (C4, C6, T8, CP4,
258 CP6, TP8), (ix) right posterior (P4, P6, P8, PO4, PO8). Time windows were defined for analyses of
259 the Harmony and the Manner effects according to the relative effects found in previous research
260 (Bianco et al., 2016a; Sammler et al., 2013) and adjusted to the new data-set according with objective
261 criteria as following: assuming that different map topographies and polarities directly indicate
262 different underlying generators (Michel et al., 2004), borders of the time windows were placed at the
263 average time point (across electrodes) at which changes in polarity and/or topography were found in
264 one or the other group. This procedure yielded time windows (i) from 370 to 550 ms and (ii) from 550

265 to 1200 ms for Harmony effects; (i) from 180 to 420 ms and (ii) from 420 to 800 ms for Manner
266 effects. Non-parametric cluster-based permutation tests applied to the data with standard parameters in
267 FieldTrip (<http://www.fieldtriptoolbox.org>) led to qualitatively similar results as those obtained with
268 the above defined time windows, hence validating the choice of the borders. Statistical analyses of
269 mean amplitude values were carried out by means of six-way ANOVAs with the repeated measures
270 factors Harmony (congruent/incongruent) x Context (long/short) x Manner (correct/incorrect) x
271 Laterality (left/middle/right) x AntPost (anterior/central/posterior) and the between-subjects factor
272 Group (classical/jazz), separately for each time window **and in line with our previous work (Bianco et**
273 **al., 2016a; Sammler et al., 2013)**. Greenhouse-Geisser correction for non-sphericity was applied where
274 appropriate (Keselman and Rogan, 1980).

275 **Time-frequency analysis.** Time-frequency (TF) analysis was carried out in FieldTrip
276 (<http://www.fieldtriptoolbox.org>, downloaded on 2012-12-05) (Oostenveld et al., 2011). To define
277 frequency bands and time windows that were generally associated with visual-motor processing of
278 chords regardless of experimental manipulation, we first analysed TF responses consistently evoked
279 by all (not only the final) chords. Therefore, the preprocessed EEG data were cut into epochs
280 from -900 to 2200 ms for each chord of long and short sequences. Epochs with voltages exceeding a \pm
281 80 μ V rejection criterion at one or more electrodes were rejected. Then, TF information was extracted
282 from each clean trial in 1-Hz bins within a 1-45 Hz frequency range using a Hanning-tapered window
283 with 5 cycles and steps of 20 ms (using the ‘ft_freqanalysis’ function with ‘mtmconvol’ method as
284 implemented in FieldTrip) and collapsed across all conditions and groups. Trials were baseline-
285 corrected (-400 to ms with respect to the onset of the target photo) and further divided by the baseline
286 band power to centre values on zero (Figure 3). **To reduce the set of statistical inferences, we adopted**
287 **a rigorous data-driven approach:** time-points and frequency bins in which average power (across all
288 electrodes) differed significantly from zero (Bonferroni-corrected) were used to define time-frequency
289 borders/regions for statistics. These were: 4-6 Hz (theta band) (i) from 220 to 480 ms and (ii) from
290 1080 to 1200 ms, and 22-26 Hz (beta band) (i) from 360 to 520 ms.



291
292 **Figure 3.** Raw spectral power change averaged across all electrodes during imitation of all chords across all
293 conditions and groups. Time zero corresponds to chord onset on screen.
294

295 For statistical comparison of the TF data of the final chords, mean power values were then extracted in
296 the three time-frequency regions identified above, in the same 9 ROIs as used for the ERP analysis.
297 Six-way ANOVAs with the repeated measures factors Harmony (congruent/incongruent) x Context
298 (long/short) x Manner (correct/incorrect) x Laterality (left/middle/right) x AntPost
299 (anterior/central/posterior) and the between-subjects factor Group (classical/jazz) were calculated
300 separately for theta and beta frequency band. Greenhouse-Geisser correction for non-sphericity was
301 applied where appropriate. Non-parametric cluster-based permutation tests (cf. Maris and Oostenveld
302 2007) with specific contrasts of interest (effects of Harmony and Manner for each context and each
303 group) corroborated the main effects yielded by the ANOVAs.

304 **RESULTS**

305 The present study compared musical action planning between classical (CG) and jazz pianists (JG) at
306 (i) action sequence and (ii) single act levels. Behavioural and electrophysiological signatures (ERPs
307 and spectral power) of (i) sequence-level structure-based planning should be *context-dependent*, i.e.
308 statistically stronger in long than short sequences, reflected in interactions of Harmony x Context,
309 while markers of (ii) single-act parameter specification should be *context-independent*, i.e. reflected in
310 main effects of Manner (without Manner x Context interaction). Genre-specific differences in these
311 planning processes should surface as Group x Harmony x Context and Group x Manner interactions,
312 respectively.

313 **Behavioural data**

314 **Response times.** Statistical values of the four-way mixed-measures ANOVA with factors Harmony
315 (congruent/incongruent), Context (long/short), Manner (correct/incorrect), and Group (classical/jazz)
316 are reported in Table 1 and Figure 4A-B. Overall, both groups performed similarly fast (no main effect
317 of Group; $p > .594$), and imitated harmonically congruent chords faster than incongruent chords (main
318 effect of Harmony; $p < .001$; no interaction of Group x Harmony; $p > .660$). However, differences
319 were revealed in the way classical and jazz pianists reacted to harmonic manipulations in the two
320 contexts: A significant interaction of Group x Harmony x Context ($p < .046$) indicated a stronger
321 effect of context on the execution of harmonically congruent vs. incongruent chords in the classical
322 (CG) compared to the jazz group (JG). Follow-up ANOVAs with factors Harmony and Context testing
323 CG and JG separately confirmed an interaction of Harmony x Context only in the CG [$F(1,14) =$
324 $17.51, p < .001, \eta_p^2 = .56$], not in the JG [$F(1,14) = 1.37, p > .261, \eta_p^2 = .09$]. This suggests differences
325 in structure-based planning between the two groups, with CG being potentially inclined to build
326 narrower plans than JG to rapidly proceed to planning expressive features, and/or JG being potentially
327 better able than CG to flexibly adapt their plans to unexpected external musical events, as practiced
328 during structure-generative training.

329 Both groups were overall faster in executing conventional compared to unconventional fingerings, as
330 expected (main effect of Manner; $p < .001$; no interaction of Group x Manner; $p > .146$). Neither CG

331 nor JG showed significant Manner x Context interactions (no Manner x Context interaction; $p > .149$;
332 no Group x Manner x Context interaction; $p > .745$) indicating that movement parameters are
333 specified at the level of single acts (not of the action sequence) regardless of training specialization.

334

335 **Error analysis.** Key and fingering errors were analysed separately (for statistical details, see Table 1)
336 because they are assumed to be associated with structure-based planning (i.e., Harmony) or parameter
337 specification, respectively (i.e., Manner; see Bianco et al., 2016a; Novembre & Keller, 2011). Overall,
338 pianists committed very few errors (mean \pm SEM of key errors: $2.0 \pm 0.2\%$; fingering errors: $9.0 \pm$
339 0.8%). With regard to key errors, classical and jazz pianists performed similarly well (CG: $3.0 \pm 1.0\%$;
340 JG: $2.0 \pm 1.0\%$; no main effect of Group; $p > .166$) and produced less key errors during execution of
341 harmonically congruent than incongruent chords (main effect of Harmony; $p < .001$; no interaction of
342 Group x Harmony; $p > .116$), especially in the long context (interaction of Harmony x Context; $p <$
343 $.017$; no interaction of Group x Harmony x Context; $p > .980$).

344 Importantly, classical pianists were overall more accurate than jazz pianists in imitating the fingering
345 (error rate in CG: $4.0 \pm 1.0\%$; JG: $14.0 \pm 4.0\%$; main effect of Group; $p < .001$), most likely due to
346 stronger focus on hand posture in classical than jazz education (see also below). Accordingly, both
347 groups committed more errors when imitating unconventional compared to conventional fingerings
348 (main effect of Manner; $p < .001$), however, particularly the JG (interaction of Group x Manner, $p <$
349 $.011$) (see Figure 4C). Moreover, more fingering mistakes in the harmonically incongruent than
350 congruent chords (main effect of Harmony; $p < .049$) in jazz compared to classical pianists (a trend in
351 the interaction of Group x Harmony; $p > .079$) suggest that the JG allocated more resources to the keys
352 to be pressed when harmonic violations occurred, to the detriment of the manner of execution. Finally,
353 an interaction of Group x Manner x Context x Harmony ($F(1, 28) = 7.056$, $p < .012$, $\eta^2 = 0.201$)
354 indicated that only the CG (Manner x Context x Harmony in CG: $F(1, 28) = 7.94$, $p < .014$, $\eta_p^2 = .36$;
355 in JG: $F(1, 28) = 2.35$, $p > .148$, $\eta_p^2 = .14$) committed more fingering errors when the manner was
356 violated on top of harmonically congruent chords in the long context (Manner x Context interaction in
357 harmonically congruent chords: $F(1,14) = 10.34$, $p < .006$, $\eta_p^2 = .42$; in harmonically incongruent
358 chords $F(1,14) = 0.50$, $p > .490$, $\eta_p^2 = .03$). This indicates that the CG, more than the JG, tended to
359 associate conventional fingering with congruent harmony, suggesting that structure-interpretative
360 focus strengthens the link between structure-based plan and optimal parameter specification.

361 **ERP data**

362 **Harmony ERPs.** In both groups, harmonically incongruent (compared to congruent) chords evoked a
363 late posterior negativity between 550 and 1200 ms, which was stronger in the long than the short
364 context (see also Table 2 for statistical details). This indicates that both CG and JG adopted predictive
365 strategies at the sequence-level based on the context and had to reprogram their pre-planned action in
366 response to the harmonic violations. Most importantly, this negativity started significantly earlier in
367 jazz pianists, already between 370 to 550 ms, than in classical pianists (only after 550 ms) (Figure

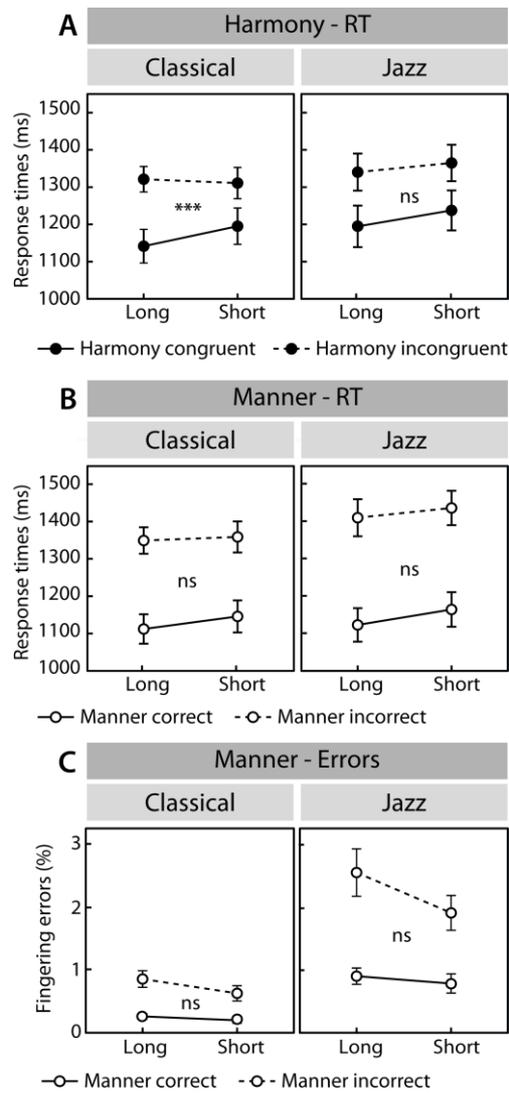
368 5A). This earlier onset might reflect prompt revision of the pre-planned motor act in JG, enabling
369 them to compensate potential behavioural costs during execution. Effects are displayed in Figure 5A
370 and will be statistically assessed below.

371 In the *1st time window* (370 to 550 ms), only the JG showed an early posterior negativity that was
372 stronger in the long than in the short context (interaction of Harmony x AntPost: $p < .017$, interaction
373 of Group x Harmony x Context x AntPost x Laterality: $p < .029$).

374 In the *2nd time window* (550 to 1200 ms), both groups displayed a similar late negativity that was
375 stronger in the long than in the short context (interactions of Harmony x Context x Laterality: $p <$
376 $.023$; Harmony x Context x AntPost: $p < .048$; no interactions involving Group x Harmony x Context:
377 $ps > .143$).

378 **Manner ERPs.** In both CG and JG, manner incorrect compared to correct chords evoked similar
379 neural signatures comprising an early left anterior positivity (180 to 420 ms), followed by a late
380 posterior positivity (420 to 800 ms). None of these potentials was stronger in the long than the short
381 context, similarly in both groups, indicating that both CG and JG planned low-level movement
382 parameters (i.e., fingering) at the level of the single act (not the musical sequence). Effects are
383 displayed in Figure 5B and will be statistically assessed below (see also Table 3 for statistical details).

384 In the *1st time window* (180 to 420 ms), a left-anterior positivity was elicited by manner incorrect
385 compared to manner correct chords in both groups (interaction of Manner x AntPost x Laterality: $p <$
386 $.004$), with CG showing a more broadly distributed positivity than JG (interaction of Group x Manner
387 x AntPost x Laterality; $p < .008$). In the *2nd time window* (420 to 800 ms), the positivity attained a
388 predominantly central-posterior distribution in both groups as confirmed by a Manner x AntPost x
389 Laterality interaction ($p < .026$), and no interaction involving the factor Group ($ps > .054$).



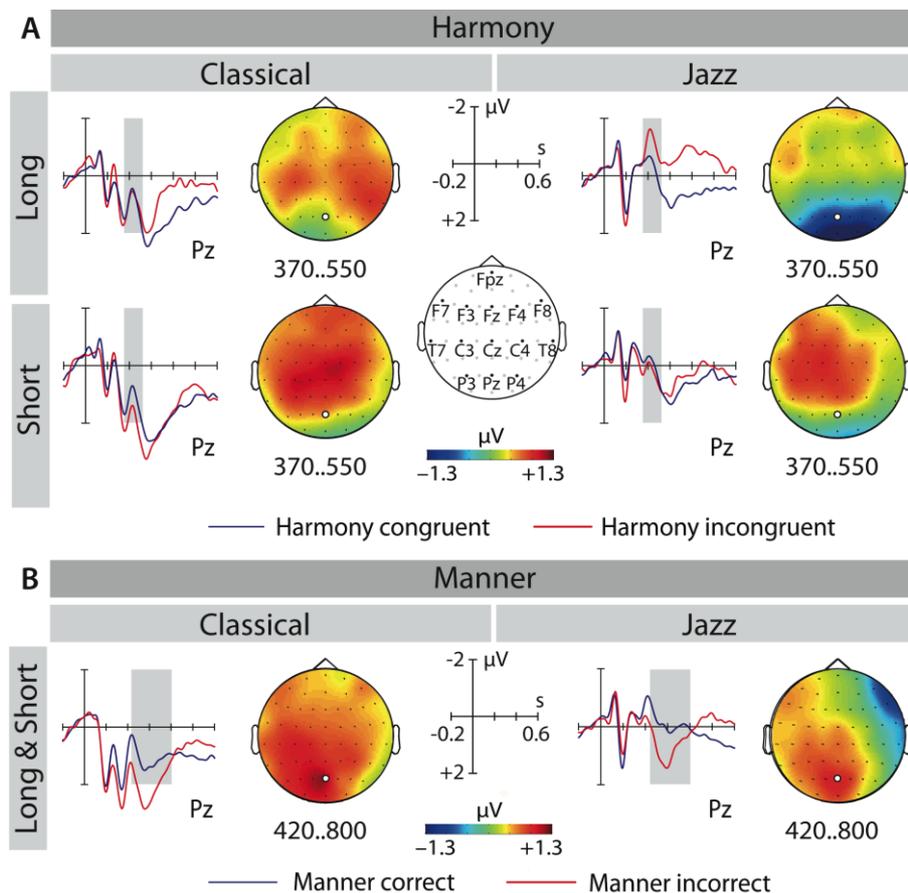
390

391 **Figure 4.** Mean RTs and Manner errors for classical (left panels) and jazz pianists (right panels). (A) RTs
 392 during imitation of harmonically incongruent (dashed line) and congruent chords (solid line), (B) RTs during
 393 imitation of manner incorrect (dashed line) and correct chords (solid line), and (C) fingering errors during
 394 imitation of manner incorrect (dashed line) and correct chords (solid line) in the long and short context. Error
 395 bars indicate ± 1 SEM. Asterisks indicate significance of the Harmony x Context and Manner x Context
 396 interactions: *** $p < .001$, ns: $p > .05$.

Table 1. Results of the ANOVAs with factors Group x Harmony x Manner x Context on the behavioural data.

Effect	$F(1,28)$	p -value	η_p^2
<i>Response times</i>			
G	< 1	.594	< .01
H	124.85	< .001	.82
M	190.65	< .001	.87
H x C	14.13	< .001	.34
M x C	2.20	.149	.07
G x H	0.20	.660	.01
G x M	2.24	.146	.07
G x H x C	4.34	.046	.13
G x M x C	< 1	.745	< .01
<i>Key errors</i>			
G	2.02	.166	.07
H	33.59	< .001	.55
M	2.66	.114	.09
H x C	6.40	.017	.19
M x C	< 1	.799	< .01
G x H	2.64	.116	.09
G x M	< 1	.964	< .01
G x H x C	< 1	.980	< .01
G x M x C	1.10	.302	.04
<i>Fingering errors</i>			
G	17.36	< .001	.38
H	4.23	.049	.13
M	34.70	< .001	.55
H x C	< 1	.790	< .01
M x C	6.51	.016	.19
G x H	3.33	.079	.11
G x M	7.36	.011	.21
G x H x C	2.40	.133	.08
G x M x C	1.75	.197	.06

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, $\eta_p^2 > 0.1$ = small effect size (Bortz and Döring, 2003). G = Group, H = Harmony, M = Manner, C = Context.



398

399 **Figure 5. ERP effects of Harmony and Manner.** (A) ERPs evoked by harmonically incongruent (red line)
 400 compared to congruent chords (blue line) in the long (top) and short context (bottom) in CG (left panel) and JG
 401 (right panel). (B) ERPs evoked by manner incorrect (red line) compared to correct chords (blue line) averaged
 402 across long and short contexts in CG (left panel) and JG (right panel). Time windows are shaded in grey.
 403 Topography maps for each statistical time window depict the difference potentials of harmonically incongruent /
 404 manner incorrect minus congruent / correct chords. Positions of the respective electrodes are indicated as “o” in
 405 the head-plots.

Table 2. Harmony ERPs – Results of the ANOVAs on ERP amplitude values with factors Group x Harmony x Context x AntPost x Laterality in two time windows.

Effect	df	1st tw: 370...550 ms			2nd tw: 550...1200 ms		
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
G	1,28	3.92	.058	0.12	3.00	.094	0.10
H	1,28	4.97	.034	0.15	8.32	.007	0.23
H x AP	2,56	9.09	.004	0.25	1.93	.173	0.06
H x L	2,56	1.51	.230	0.05	5.56	.013	0.17
H x AP x L	4,112	1.00	.398	0.03	2.83	.043	0.09
H x C	1,28	8.34	.007	0.23	3.88	.059	0.12
H x C x AP	2,56	2.05	.160	0.07	4.00	.048	0.13
H x C x L	2,56	3.98	.024	0.12	4.46	.023	0.14
H x C x AP x L	4,111	1.03	.377	0.04	1.43	.241	0.05
G x H	1,28	3.77	.062	0.12	0.28	.601	0.01
G x H x AP	2,56	1.79	.191	0.06	3.92	.051	0.12
G x H x L	2,56	0.30	.742	0.01	0.07	.878	0.01
G x H x AP x L	4,112	0.37	.778	0.01	1.17	.326	0.04
G x H x C	1,28	0.00	.984	0.01	0.34	.562	0.01
G x H x C x AP	2,56	1.54	.227	0.05	0.09	.808	0.01
G x H x C x L	2,56	0.57	.567	0.02	0.44	.607	0.02
G x H x C x AP x L	4,112	3.38	.029	0.11	1.77	.163	0.06

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, > 0.1 = small effect size (Bortz & Döring, 2003). G = Group, H = Harmony, C = Context, AP = AntPost, L = Laterality. Degrees of freedom were corrected after Huynh-Feldt if necessary.

Table 3. Manner ERPs – Results of the ANOVAs on ERP amplitude values with factors Group x Manner x Context x AntPost x Laterality in two time windows.

Effect	df	<i>1st tw: 180...420 ms</i>			<i>2nd tw: 420...800 ms</i>		
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
G	1,28	2.92	.099	0.09	3.51	.071	0.11
M	1,28	0.35	.557	0.01	10.12	.004	0.27
M x AP	2,56	4.99	.028	0.15	4.81	.030	0.15
M x L	2,56	9.78	.001	0.26	8.35	.001	0.23
M x AP x L	4,112	4.95	.004	0.15	3.47	.026	0.11
C x M	1,28	0.22	.640	0.01	0.31	.579	0.01
C x M x AP	2,56	2.65	.112	0.09	2.16	.148	0.07
C x M x L	2,56	1.48	.239	0.05	1.31	.277	0.04
C x M x AP x L	4,111	2.49	.047	0.08	2.03	.117	0.07
G x M	1,28	1.06	.311	0.04	1.72	.200	0.06
G x M x AP	2,56	0.07	.827	0.01	0.04	.875	0.01
G x M x L	2,56	0.09	.913	0.01	0.63	.538	0.02
G x M x AP x L	4,112	4.42	.008	0.14	2.79	.054	0.09
G x C x M	1,28	0.00	.981	0.01	0.01	.940	0.01
G x C x M x AP	2,56	0.87	.366	0.03	0.03	.899	0.01
G x C x M x L	2,56	0.30	.699	0.01	2.77	.071	0.09
G x C x M x AP x L	4,112	1.10	.358	0.04	1.98	.123	0.07

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, > 0.1 = small effect size (Bortz & Döring, 2003). G = Group, H = Harmony, C = Context, AP = AntPost, L = Laterality. Degrees of freedom were corrected after Huynh-Feldt if necessary.

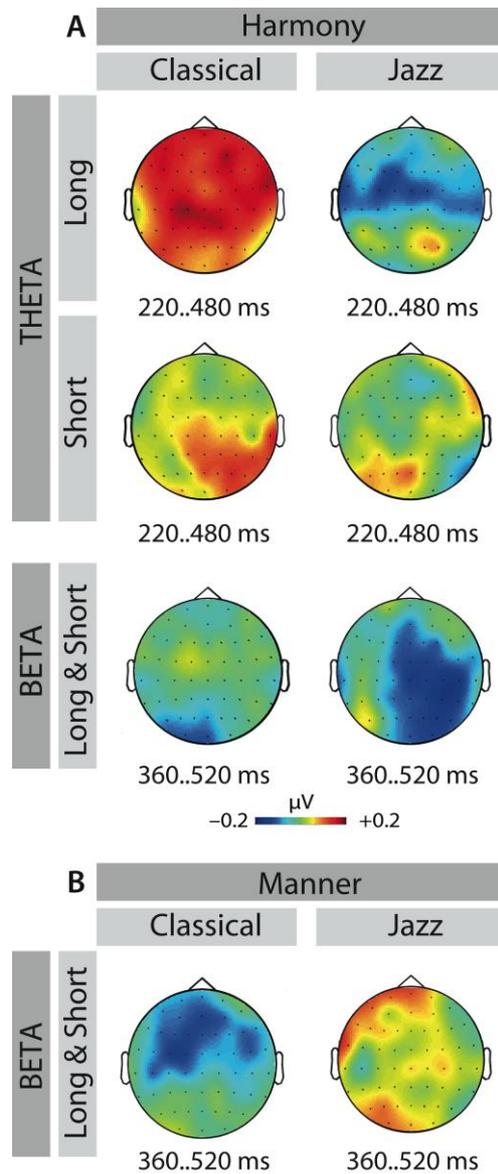
408 **Time frequency data**

409 **Harmony theta.** Only CG, not JG, showed a strong increase of early theta power during harmonically
410 incongruent compared to congruent chords, particularly in the long sequences, disclosing that this
411 effect was associated with sequence-level structure-based planning (see Table 4 and Figure 6A). In
412 fact, in the *1st time window* (220 to 480 ms), a Group x Harmony x Context x AntPost x Laterality
413 interaction ($p < .042$) indicated a broad increase in theta power after the violation only in CG and only
414 in long sequences (interaction of Harmony x Context in CG: $p < .013$; but not in JG: $p > .633$). No
415 relevant effects were found in the *2nd time window* (1080 to 1200 ms).

416 **Harmony beta.** An interaction of Group x Harmony x Laterality and of Group x Harmony x AntPost
417 ($ps < .035$, see Table 4) indicated that beta power associated with the violation decreased more
418 strongly in JG than in CG, but similarly in both contexts (interaction of Group x Harmony x Context:
419 $ps > .071$).

420 **Manner theta.** No significant group differences were found; therefore manner-related effects in theta
421 will not be discussed.

422 **Manner beta.** Beta power decreased in manner-incorrect compared to correct conditions in both
423 contexts (interaction of Manner x Antpost: $p < .039$, interaction of Manner x Context: $ps > .220$) (see
424 Table 4). However, this effect appeared to be mainly driven by a stronger decrease of beta power in
425 CG than in JG, as can be seen in Figure 6B. Although a Group x Manner x AntPost interaction fell
426 short of statistical significance ($p > .082$), exploratory ANOVAs for each group separately lent some
427 support for a CG-driven beta de-synchronisation (interaction of Manner x AntPost in the CG: $p < .015$;
428 JG: $p > .230$).



429

430 **Figure 6. Spectral power effects of Harmony and Manner.** (A) Topography of normalised power change in
 431 the harmonically incongruent minus congruent chords for CG (left panel) and JG (right panel) in the theta band
 432 (*1st time window*) separately for the long and the short context, and in the beta band averaged across long and
 433 short contexts. (B) Topography of normalised power change in the manner incorrect minus correct condition for
 434 CG (left panel) and JG (right panel) in the beta band averaged across long and short contexts.

435

Table 4. Time frequency analysis – Results of the ANOVAs on spectral power values with factors Group x Violation x Context x AntPost x Laterality.

Effect	df	Harmony theta <i>tw: 220...480 ms</i>			Harmony beta <i>tw: 360...520 ms</i>			Manner beta <i>tw: 360...520 ms</i>		
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
G	1,28	8.72	.006	0.24	2.99	.095	0.1	2.99	.095	0.10
V	1,28	1.79	.192	0.06	5.56	.026	0.17	0.16	.692	0.01
V x AP	1,28	0.42	.571	0.01	2.47	.115	0.08	4.18	.039	0.13
V x L	1,28	1.96	.150	0.07	3.40	.041	0.11	0.02	.985	0.01
V x AP x L	2,56	1.14	.334	0.04	0.18	.893	0.01	0.18	.883	0.01
V x C	2,56	1.70	.202	0.06	1.44	.241	0.05	0.00	.969	0.01
V x C x AP	1,28	0.27	.719	0.01	0.10	.817	0.01	0.44	.602	0.02
V x C x L	2,56	4.08	.032	0.13	0.28	.701	0.01	1.25	.295	0.04
V x C x AP x L	2,56	0.35	.759	0.01	0.39	.818	0.01	1.49	.220	0.05
G x V	2,56	0.70	.409	0.02	0.10	.757	0.01	0.70	.410	0.02
G x V x AP	2,56	1.15	.305	0.04	4.24	.035	0.13	3.01	.082	0.10
G x V x L	4,112	1.46	.241	0.05	6.58	.003	0.19	0.09	.842	0.01
G x V x AP x L	2,56	0.35	.759	0.01	2.51	.071	0.08	0.49	.661	0.02
G x V x C	2,56	0.33	.568	0.01	0.19	.669	0.01	0.24	.630	0.01
G x V x C x AP	4,112	0.97	.373	0.03	2.61	.106	0.09	0.16	.805	0.01
G x V x C x L	4,112	0.02	.952	0.01	3.02	.071	0.1	0.94	.395	0.03
G x V x C x AP x L	4,112	3.02	.042	0.10	0.73	.571	0.03	1.11	.352	0.04

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, > 0.1 = small effect size (Bortz & Döring, 2003). G = Group, V = Violation (i.e., Harmony or Manner), C = Context, AP = AntPost, L = Laterality. Degrees of freedom were corrected after Huynh-Feldt if necessary. No effects involving H were found for Manner theta.

436

437 **Post-experiment ratings.** In the debriefing questionnaires after the experiment, both groups reported
438 similar active prediction of the next chord during execution of the chord progressions (mean \pm SEM on
439 a scale from 1 to 9; CG: 5.64 ± 0.37 ; JG: 4.26 ± 0.67 ; $t(28) = -1.79$, $p > .080$), indicating that both
440 groups were adopting predictive strategies about the what to play. Moreover, none of the pianist
441 groups reported explicit reliance on auditory imagery to predict the next chord (CG: 4.68 ± 0.68 ; JG:
442 4.06 ± 0.52 ; $t(28) = -0.21$, $p > .83$). However, prediction strategies differed significantly between
443 groups, with JG preferring to internally name the harmonic chord functions (CG: 3.78 ± 0.62 ; JG: 6.40
444 ± 0.43 ; $t(28) = 3.46$, $p < .002$), and CG paying more attention to the hand as a whole (CG: 5.57 ± 0.32 ;
445 JG: 3.67 ± 0.57 ; $t(28) = -2.92$, $p < .007$). These preferences are compatible with the key and fingering
446 error results described above and may reflect more explicit harmony and manner processing in jazz
447 and classical pianists, respectively.

448

449 DISCUSSION

450 The present data show clear-cut neural differences between jazz and classical pianists resulting in
451 different behavioural outcome under same task-demands. Within an overall similar hierarchical core
452 structure of action control, pianists differently weigh high-level structure-based planning of the action
453 sequence and low-level parameter specification of single acts during execution of unrehearsed musical

454 sequences without sound. Classical pianists rapidly narrow down sequence-level structural
455 interpretations to optimally set movement parameters at single-act level, while jazz pianists remain
456 aware of structural alternatives for longer, allowing them to flexibly revise structure-based action
457 plans when faced with harmonic incongruities. These results argue for training-style influence on core
458 high- and low-level processes of action planning, upgrading the notion of sensorimotor plasticity
459 (Herholz and Zatorre, 2012; Münte et al., 2002) to high-level motor cognition.

460 **Hierarchical action planning regardless of genre-specific training**

461 Before turning to genre-specific group differences, it is worth pointing out that jazz pianists showed a
462 similar multi-level core structure of action planning as previously identified in classical pianists
463 (Bianco et al., 2016a), and in line with hierarchical action theories (Rosenbaum et al., 2007; Vallacher
464 and Wegner, 1987; Wohlschläger et al., 2003; see Figure 1). At *sequence-level*, both groups,
465 regardless of training specialization, used long-term knowledge of structure and accumulating
466 harmonic contextual evidence to narrow down the possibilities of likely forthcoming chords ('what' to
467 play). This was indicated by faster and more accurate imitation of harmonically congruent compared
468 to incongruent chords, particularly in the long context, and by the context-dependent negativity
469 (Figure 6A) associated with the reprogramming of a prepotent motor response when expectancies are
470 violated (Leuthold and Jentzsch, 2002; Sammler et al., 2013). Similarly, at the *single-act level*, the
471 manner of execution was specified at late stages of action planning³ regardless of training
472 specialization. This was indicated by slower imitation of unconventional manner along with more
473 fingering errors, irrespective of context length, and a context-independent positivity (Figure 6B)
474 associated with visual-spatial detection of fingering mistakes in action observation (Panasiti et al.,
475 2016). Altogether, combined data from differently specialised musicians indicate that previously
476 identified multilayer planning processes (i.e., concerning the sequence and the single acts levels)
477 constitute core levels of the hierarchical representation of skilled behaviours. Future studies should
478 test to what extent this core structure is generalizable to action planning in other instrument players or
479 in non-musical production contexts.

480 **Greater structural flexibility in jazz pianists**

481 Within this hierarchical core structure of action planning, the present data highlight a variable tuning
482 of the action control hierarchy depending on action tendencies developed through classical or jazz
483 training as will be discussed in the following. At the *sequence level*, classical pianists showed the
484 tendency to build narrower structural plans than jazz pianists, while jazz pianists showed greater
485 readiness and flexibility to revise their structure plans in case of harmonically unexpected chords.
486 Classical pianists displayed a context-dependent slowing of response times, an increase of early

³ Note that particularly in classical performance, fingering is usually worked out by pianists during training and can thus be planned ahead in *rehearsed* pieces. The present task comprised *unrehearsed* music material only, hence, reducing anticipatory planning of fingering.

487 conflict-related theta when asked to imitate harmonic violations (Harmony x Context interaction),
488 while jazz pianists showed none of these effects (Harmony x Context x Group interaction; Figures 4A
489 and 6A). Instead, they reacted to harmonic violations with an earlier onset of the context-dependent
490 “reprogramming” negativity (Figure 5A, 1st *time window*: 370 to 550 ms), a stronger de-
491 synchronisation of beta power (between 360 and 520 ms), and lower fingering accuracy.

492 Improvisation in jazz practice focuses on the active and flexible re-arrangement of structure-based
493 plans often in non-canonical ways (Clarke, 2001; Pressing, 1987). The present neurobehavioural data
494 reflect this structure-*generative* focus and readiness for novelties and argue for an easier access to
495 several simultaneously pre-activated harmonic options, the most likely of which has right of way but
496 can be rapidly reprogrammed into one of the other alternatives (Cisek, 2006). Although it remains to
497 be clarified whether the earlier onset of the negativity in the jazz group reflects an earlier action
498 “reprogramming”, or faster visual detection of the harmonically unexpected chord in the displayed
499 hand actions (Panasiti et al., 2016; Stefanics et al., 2011), it speaks for quicker reassessment of
500 structure-based action plans after jazz training, which may in fact prevent response time costs (no
501 context-dependent slowing). This jazz-specific optimization of structure-based planning indicates a
502 stronger propensity for *online* extraction of harmonic relationships that may even be proceduralized
503 (Hansen et al., 2016), lending greater flexibility in handling harmonic violations. This account was
504 further supported by high self-reported attention to harmony, the absence of early conflict-related
505 effects in the theta band, observed instead in classical pianists (see below), and a stronger decrease in
506 beta power after harmonic violations than in classical pianists. Beta de-synchronization typically
507 accompanies movement preparation (Pfurtscheller and Lopes, 1999) and is enhanced during
508 observation of incorrect actions (Koelewijn et al., 2008). This fits with the latency of the present beta
509 effect between target onset and action execution, and may suggest that jazz pianists were motorically
510 more prepared to encode harmonic content of the displayed action, allowing faster error detection and
511 more flexible execution. On the other hand, greater focus on harmony in jazz pianists, which binds
512 more resources to high-level sequence planning, might have come at the expense of low-level action
513 plans, especially under time pressure. Indeed, jazz compared to classical pianists had higher rates of
514 fingering errors suggesting a speed-accuracy trade-off (Berlyne, 1957) observed across two levels of
515 action planning.

516 Classical pianists, in turn, experienced more cognitive conflict and effort than jazz pianists when a
517 structural revision was required in the long context, as shown by the early context-sensitive increase of
518 theta power after the harmonic violation (220 to 480 ms). Increased theta power constitutes a conflict
519 signal of frontal control functions (Botvinick et al., 2004; Cavanagh et al., 2009; Miller and Cohen,
520 2001) and is enhanced during inhibition of prepotent actions and initiation of goal-relevant responses
521 (Aron et al., 2014; Harmony et al., 2009; Kirmizi-Aslan et al., 2006; Munakata et al., 2011; Ruiz et al.,
522 2011). Note that classical pianists still showed increased theta power (220 to 480 ms) when jazz
523 pianists already displayed the “reprogramming” negativity (onset at 370 ms). This suggests that

524 classical pianists experienced higher cognitive effort to resolve conflict in response to the unexpected
525 chord, which may have delayed reprogramming and induced context-sensitive response time costs. In
526 other words, classical pianists' structure-*interpretative* focus, which aims for fast narrowing of
527 harmonic possibilities to rapidly proceed to expressive stages of action planning (the 'how', see
528 below) (Clarke, 2001; Shaffer, 1984), may have necessitated greater cognitive effort to initiate other
529 alternatives in case of structural-harmonic deception. On the other hand, pre-activation of only the
530 most likely harmonic option may serve to optimize lower-level single act planning to meet the high
531 expressive demands in classical training as will be discussed below.

532 Finally, it should be stressed that classical and jazz pianists did not differ in their reported auditory
533 imagery scores during mute production in our task. Hence, between-group differences in structure-
534 based planning more likely derive from motor-specific than auditory tendencies developed through
535 long-term practice of the one or the other style. This interpretation also finds support in recent
536 neuroimaging evidence that silent imitation of harmonic violations did not elicit auditory brain
537 activation in expert pianists (Bianco et al., 2016b). Future studies should test how between-group
538 differences in auditory perception influence action planning.

539

540 **Greater focus on movement parameters in classical pianists**

541 At *single act level*, classical compared to jazz pianists revealed a higher propensity to encode and
542 accurately set movement parameters (as reflected by Group x Manner interactions): Classical pianists
543 were overall more accurate in the imitation of the fingering (Figure 4C) that was partly determined by
544 pianists' higher-level structural-harmonic predictions (Manner x Harmony x Context interaction in
545 CG, not JG). Moreover, they showed a broader early positivity (180 to 420 ms; Figure 5B) and a
546 stronger decrease of beta power (360 to 520 ms) upon detection of the fingering violation (Figure 6B).

547 These manner-related data indicate that classical compared with jazz pianists were more focused on
548 the way musical acts are motorically rendered. Structure-interpretative abilities imply that pianists
549 rapidly plan expressive features on top of the musical structure by relying on strong associations
550 between fingering and frequent musical patterns (Gellrich and Parncutt, 1998). Greater fingering
551 accuracy, stronger self-reported focus on hand posture, a more broadly distributed early positivity
552 (Bianco et al., 2016a; Polich, 2007) and a stronger decrease in beta power in CG than JG reflect
553 classical pianists' enhanced focus on the fingering. In line with our account that classical pianists
554 rapidly project over-trained movement parameters to the structure-based plan as soon as it has
555 emerged from the context, classical pianists' imitation of unconventional fingering was in fact least
556 accurate on top of structurally *congruent* chords (Manner x Harmony x Context interaction only in
557 CG). This suggests that they anticipated fingerings that matched with their structure-based plans.
558 Crucially, the stronger decrease in beta power indicates that classical pianists were overall motorically
559 more prepared to encode the fingering of the displayed action (Candidi et al., 2014; Fagioli et al.,

2007; Hommel, 2010), potentially facilitating error detection in the photos (Koelewijn et al., 2008) and supporting own execution (Ruiz et al., 2011; Tzagarakis et al., 2010). Interestingly, the similar beta power decrease found in jazz pianists, but for harmonic violations (as discussed above), may express the differential habitual action focus after specialized training. These findings suggest that beta oscillations are not only modulated when the observed action is erroneous (Caetano et al., 2007; Koelewijn et al., 2008; van Schie et al., 2004), but that the modulation increases for specific types of action errors ('what' and 'how') that are in the focus of the performer.

Altogether, these findings show that classical and jazz pianists give different weights to the hierarchical levels of action planning, intuitively and despite identical instruction and material: On the one hand, habitual action focus on structure generation and revision in jazz may inadvertently bind resources to high levels of planning, even in a task that did not require creative improvisation. On the other hand, the building of solid associations between finger configurations and frequent structural figures (e.g., scales, intervals, cadences) in classical training (Clarke et al., 1997; Gellrich and Parncutt, 1998; Parncutt, 2014) may shift focus from high to low levels to ease the structure-based selection of fine-grained expressive features that colour interpretative performance (Clarke, 2001). Therefore, these findings demonstrate that generative jazz training coincides with a higher flexibility to deal with harmonic possibilities, whereas interpretative classical training enhances the preparedness to accurately set fine movement parameters. Whether the different prevalence of maladaptive plastic changes such as focal dystonia in classical and jazz pianists (Altenmüller and Jabusch, 2009; Elbert et al., 1998) is tied to differential action focus is an interesting topic for future research. In sum, this genre-specific weighting of the motor control hierarchy suggests that, beyond general musical long-term knowledge and contextual evidence, habitual focus plays an important role in the optimization of not only auditory (Eerola et al., 2009; Hansen et al., 2016; Vuust et al., 2012) but also motor predictive processes.

CONCLUSION

The findings of the current study demonstrate that complex actions are not rigid entities but can reflect specialised cognitive-motor strategies depending on previous experience and habitual action focus. We show that (i) structure-based planning at the level of the action sequence and (ii) movement parameter specification at the level of single acts are plastic processes in action control: they are calibrated differently – despite equal instruction and task – depending on the stylistic specialization of musicians. Remarkably, long-term adaptive plasticity in the action control hierarchy was behaviourally reflected in structure flexibility in jazz pianists and fine movement accuracy in classical pianists during the execution of the same task. Hence, the specific demands and focus of previous experience may result in dramatic and enduring changes in performers' motor control system, providing neurobiological accounts for the great divide between musicians of the "swing" and the "legit" style.

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795

Table 1. Results of the ANOVAs with factors Group x Harmony x Manner x Context on the behavioural data.

Effect	$F(1,28)$	p -value	η_p^2
<i>Response times</i>			
G	< 1	.594	< .01
H	124.85	< .001	.82
M	190.65	< .001	.87
H x C	14.13	< .001	.34
M x C	2.20	.149	.07
G x H	0.20	.660	.01
G x M	2.24	.146	.07
G x H x C	4.34	.046	.13
G x M x C	< 1	.745	< .01
<i>Key errors</i>			
G	2.02	.166	.07
H	33.59	< .001	.55
M	2.66	.114	.09
H x C	6.40	.017	.19
M x C	< 1	.799	< .01
G x H	2.64	.116	.09
G x M	< 1	.964	< .01
G x H x C	< 1	.980	< .01
G x M x C	1.10	.302	.04
<i>Fingering errors</i>			
G	17.36	< .001	.38
H	4.23	.049	.13
M	34.70	< .001	.55
H x C	< 1	.790	< .01
M x C	6.51	.016	.19
G x H	3.33	.079	.11
G x M	7.36	.011	.21
G x H x C	2.40	.133	.08
G x M x C	1.75	.197	.06

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, $\eta_p^2 > 0.1$ = small effect size (Bortz and Döring, 2003). G = Group, H = Harmony, M = Manner, C = Context.

Table 2. Harmony ERPs – Results of the ANOVAs on ERP amplitude values with factors Group x Harmony x Context x AntPost x Laterality in two time windows.

Effect	df	1st tw: 370...550 ms			2nd tw: 550...1200 ms		
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
G	1,28	3.92	.058	0.12	3.00	.094	0.10
H	1,28	4.97	.034	0.15	8.32	.007	0.23
H x AP	2,56	9.09	.004	0.25	1.93	.173	0.06
H x L	2,56	1.51	.230	0.05	5.56	.013	0.17
H x AP x L	4,112	1.00	.398	0.03	2.83	.043	0.09
H x C	1,28	8.34	.007	0.23	3.88	.059	0.12
H x C x AP	2,56	2.05	.160	0.07	4.00	.048	0.13
H x C x L	2,56	3.98	.024	0.12	4.46	.023	0.14
H x C x AP x L	4,111	1.03	.377	0.04	1.43	.241	0.05
G x H	1,28	3.77	.062	0.12	0.28	.601	0.01
G x H x AP	2,56	1.79	.191	0.06	3.92	.051	0.12
G x H x L	2,56	0.30	.742	0.01	0.07	.878	0.01
G x H x AP x L	4,112	0.37	.778	0.01	1.17	.326	0.04
G x H x C	1,28	0.00	.984	0.01	0.34	.562	0.01
G x H x C x AP	2,56	1.54	.227	0.05	0.09	.808	0.01
G x H x C x L	2,56	0.57	.567	0.02	0.44	.607	0.02
G x H x C x AP x L	4,112	3.38	.029	0.11	1.77	.163	0.06

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, > 0.1 = small effect size (Bortz & Döring, 2003). G = Group, H = Harmony, C = Context, AP = AntPost, L = Laterality. Degrees of freedom were corrected after Huynh-Feldt if necessary.

Table 3. Manner ERPs – Results of the ANOVAs on ERP amplitude values with factors Group x Manner x Context x AntPost x Laterality in two time windows.

Effect	df	<i>1st tw: 180...420 ms</i>			<i>2nd tw: 420...800 ms</i>		
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
G	1,28	2.92	.099	0.09	3.51	.071	0.11
M	1,28	0.35	.557	0.01	10.12	.004	0.27
M x AP	2,56	4.99	.028	0.15	4.81	.030	0.15
M x L	2,56	9.78	.001	0.26	8.35	.001	0.23
M x AP x L	4,112	4.95	.004	0.15	3.47	.026	0.11
C x M	1,28	0.22	.640	0.01	0.31	.579	0.01
C x M x AP	2,56	2.65	.112	0.09	2.16	.148	0.07
C x M x L	2,56	1.48	.239	0.05	1.31	.277	0.04
C x M x AP x L	4,111	2.49	.047	0.08	2.03	.117	0.07
G x M	1,28	1.06	.311	0.04	1.72	.200	0.06
G x M x AP	2,56	0.07	.827	0.01	0.04	.875	0.01
G x M x L	2,56	0.09	.913	0.01	0.63	.538	0.02
G x M x AP x L	4,112	4.42	.008	0.14	2.79	.054	0.09
G x C x M	1,28	0.00	.981	0.01	0.01	.940	0.01
G x C x M x AP	2,56	0.87	.366	0.03	0.03	.899	0.01
G x C x M x L	2,56	0.30	.699	0.01	2.77	.071	0.09
G x C x M x AP x L	4,112	1.10	.358	0.04	1.98	.123	0.07

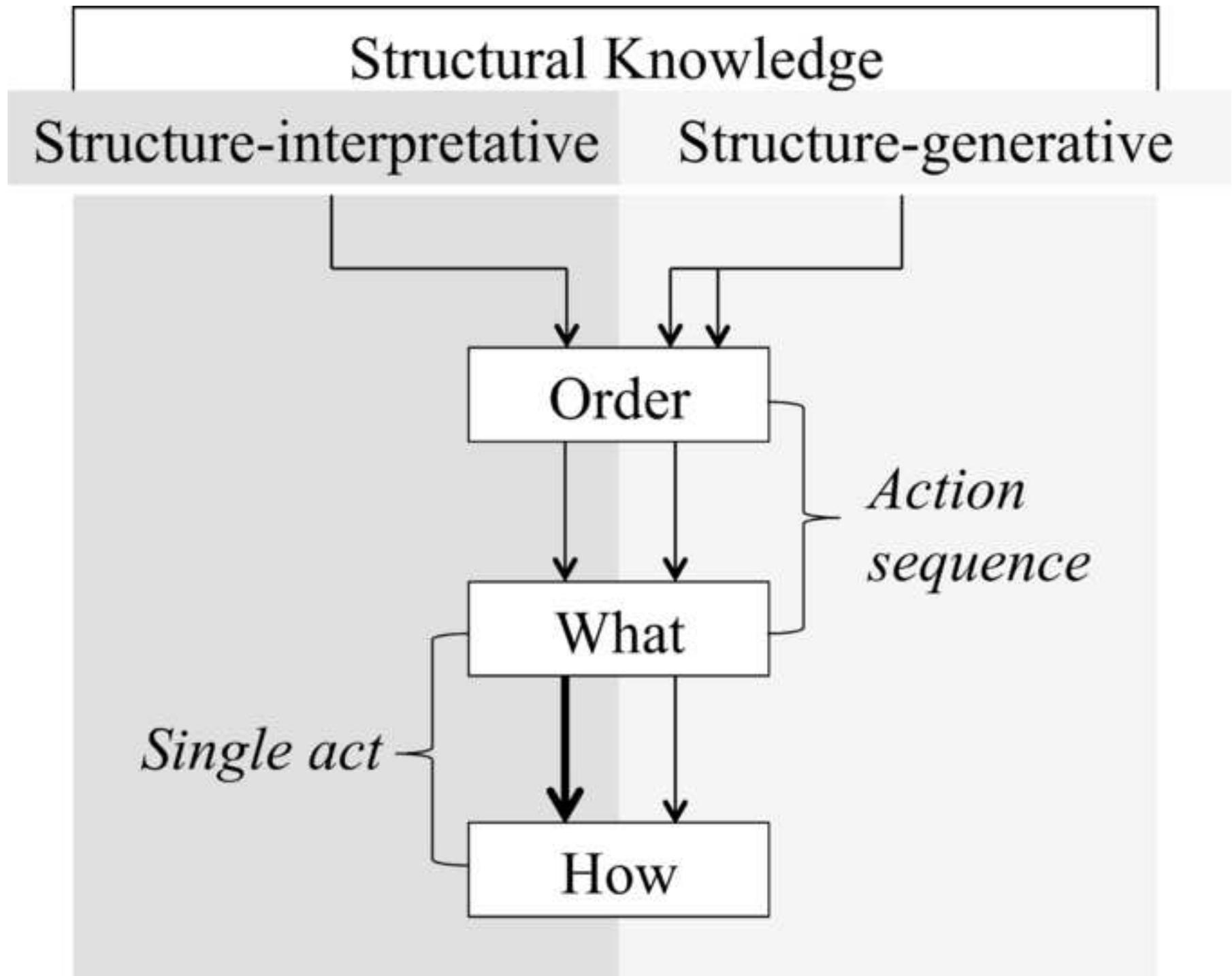
Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, > 0.1 = small effect size (Bortz & Döring, 2003). G = Group, H = Harmony, C = Context, AP = AntPost, L = Laterality. Degrees of freedom were corrected after Huynh-Feldt if necessary.

Table 4. Time frequency analysis – Results of the ANOVAs on spectral power values with factors Group x Violation x Context x AntPost x Laterality.

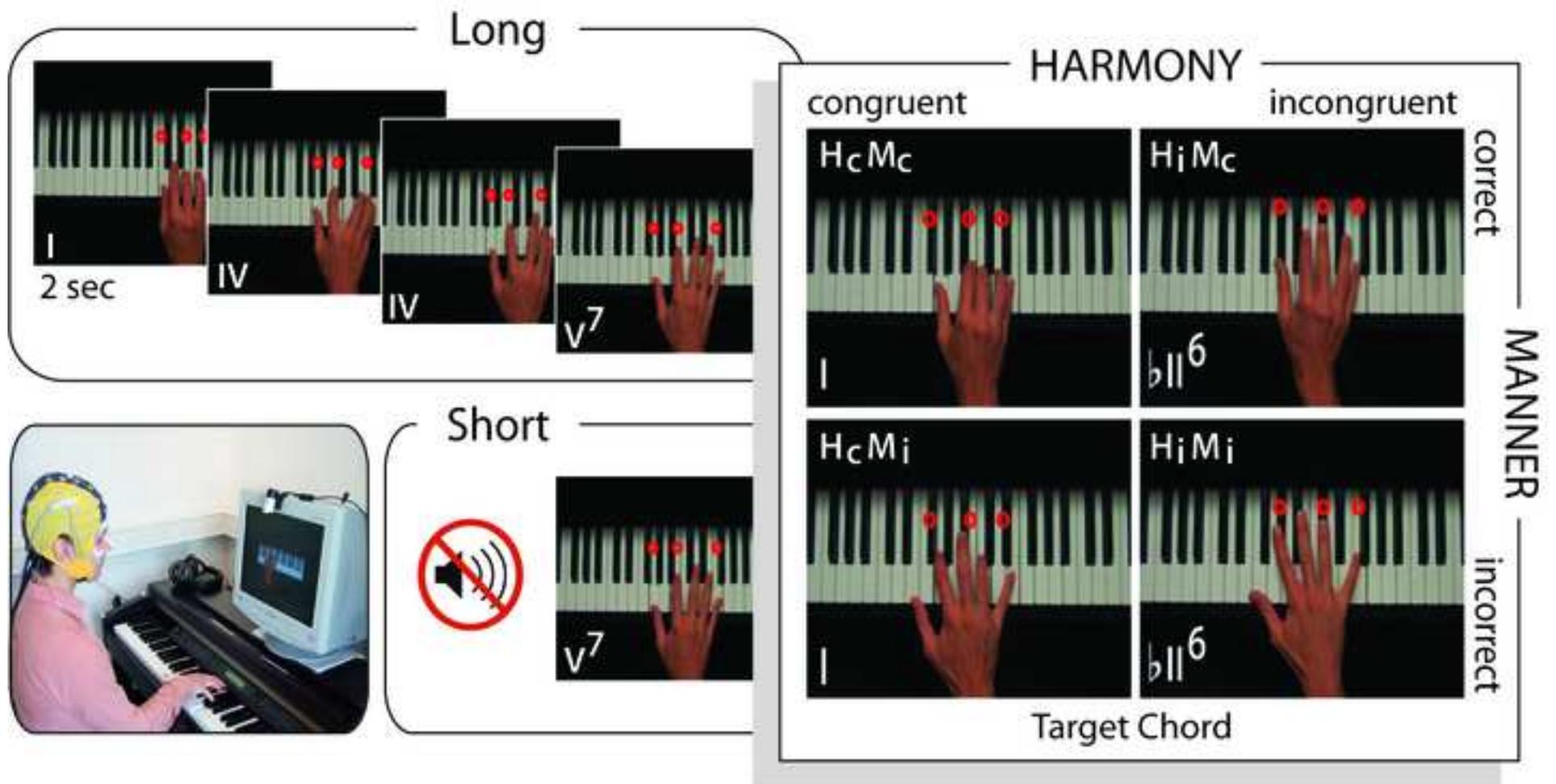
Effect	df	Harmony theta <i>tw: 220...480 ms</i>			Harmony beta <i>tw: 360..520 ms</i>			Manner beta <i>tw: 360..520 ms</i>		
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
G	1,28	8.72	.006	0.24	2.99	.095	0.1	2.99	.095	0.10
V	1,28	1.79	.192	0.06	5.56	.026	0.17	0.16	.692	0.01
V x AP	1,28	0.42	.571	0.01	2.47	.115	0.08	4.18	.039	0.13
V x L	1,28	1.96	.150	0.07	3.40	.041	0.11	0.02	.985	0.01
V x AP x L	2,56	1.14	.334	0.04	0.18	.893	0.01	0.18	.883	0.01
V x C	2,56	1.70	.202	0.06	1.44	.241	0.05	0.00	.969	0.01
V x C x AP	1,28	0.27	.719	0.01	0.10	.817	0.01	0.44	.602	0.02
V x C x L	2,56	4.08	.032	0.13	0.28	.701	0.01	1.25	.295	0.04
V x C x AP x L	2,56	0.35	.759	0.01	0.39	.818	0.01	1.49	.220	0.05
G x V	2,56	0.70	.409	0.02	0.10	.757	0.01	0.70	.410	0.02
G x V x AP	2,56	1.15	.305	0.04	4.24	.035	0.13	3.01	.082	0.10
G x V x L	4,112	1.46	.241	0.05	6.58	.003	0.19	0.09	.842	0.01
G x V x AP x L	2,56	0.35	.759	0.01	2.51	.071	0.08	0.49	.661	0.02
G x V x C	2,56	0.33	.568	0.01	0.19	.669	0.01	0.24	.630	0.01
G x V x C x AP	4,112	0.97	.373	0.03	2.61	.106	0.09	0.16	.805	0.01
G x V x C x L	4,112	0.02	.952	0.01	3.02	.071	0.1	0.94	.395	0.03
G x V x C x AP x L	4,112	3.02	.042	0.10	0.73	.571	0.03	1.11	.352	0.04

Bold values indicate significant results ($p < .05$). Partial eta squared $\eta_p^2 > 0.5$ = large effect size, $\eta_p^2 > 0.3$ = medium effect size, > 0.1 = small effect size (Bortz & Döring, 2003). G = Group, V = Violation (i.e., Harmony or Manner), C = Context, AP = AntPost, L = Laterality. Degrees of freedom were corrected after Huynh-Feldt if necessary. No effects involving H were found for Manner theta.

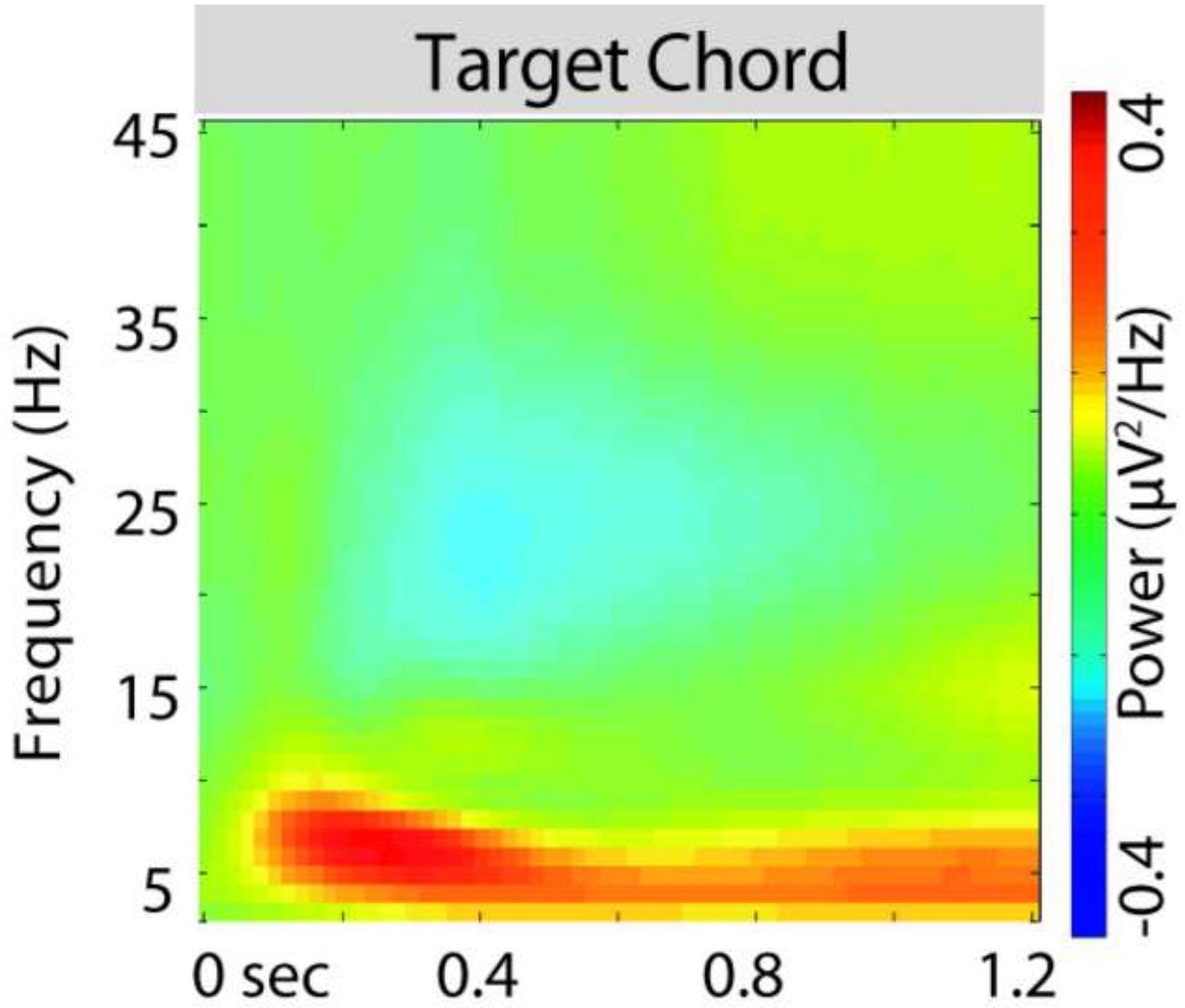
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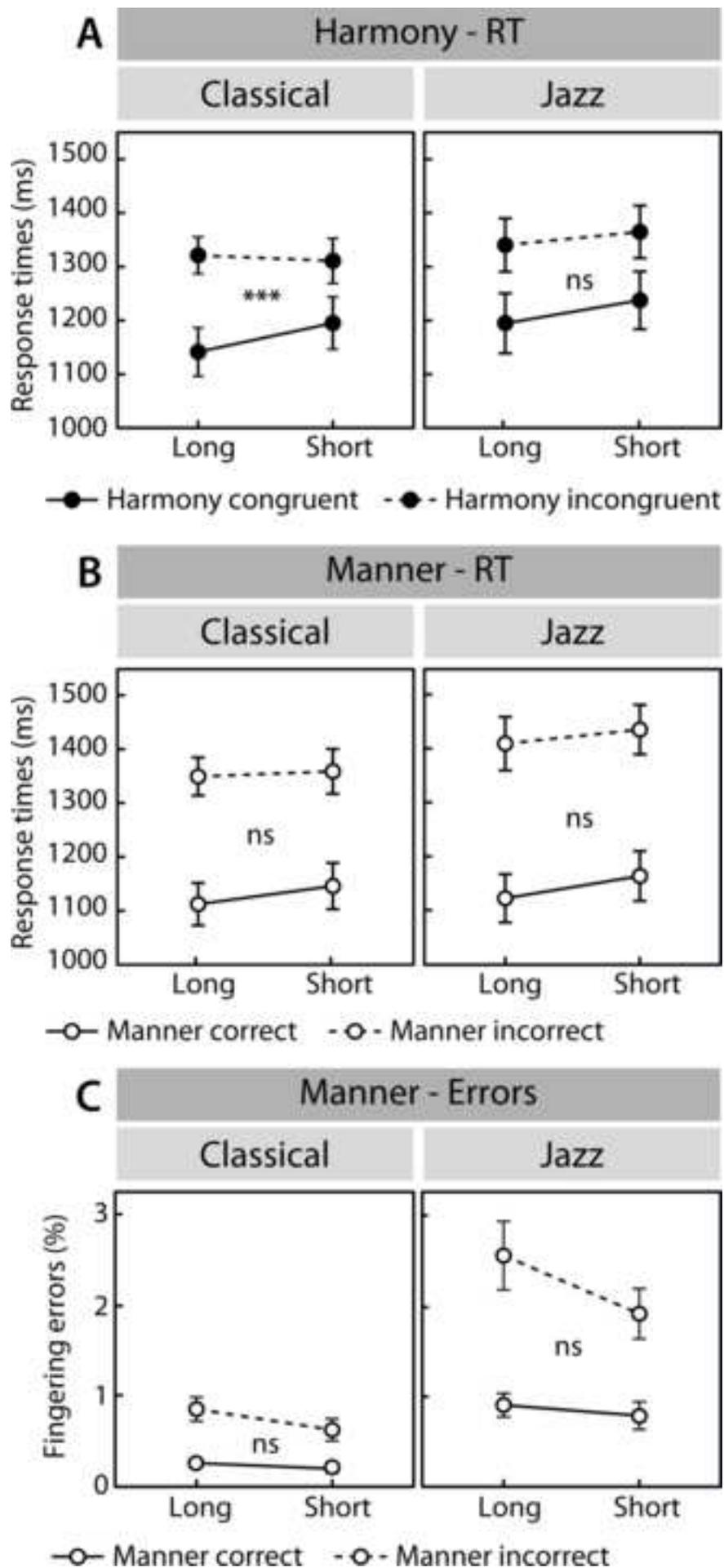


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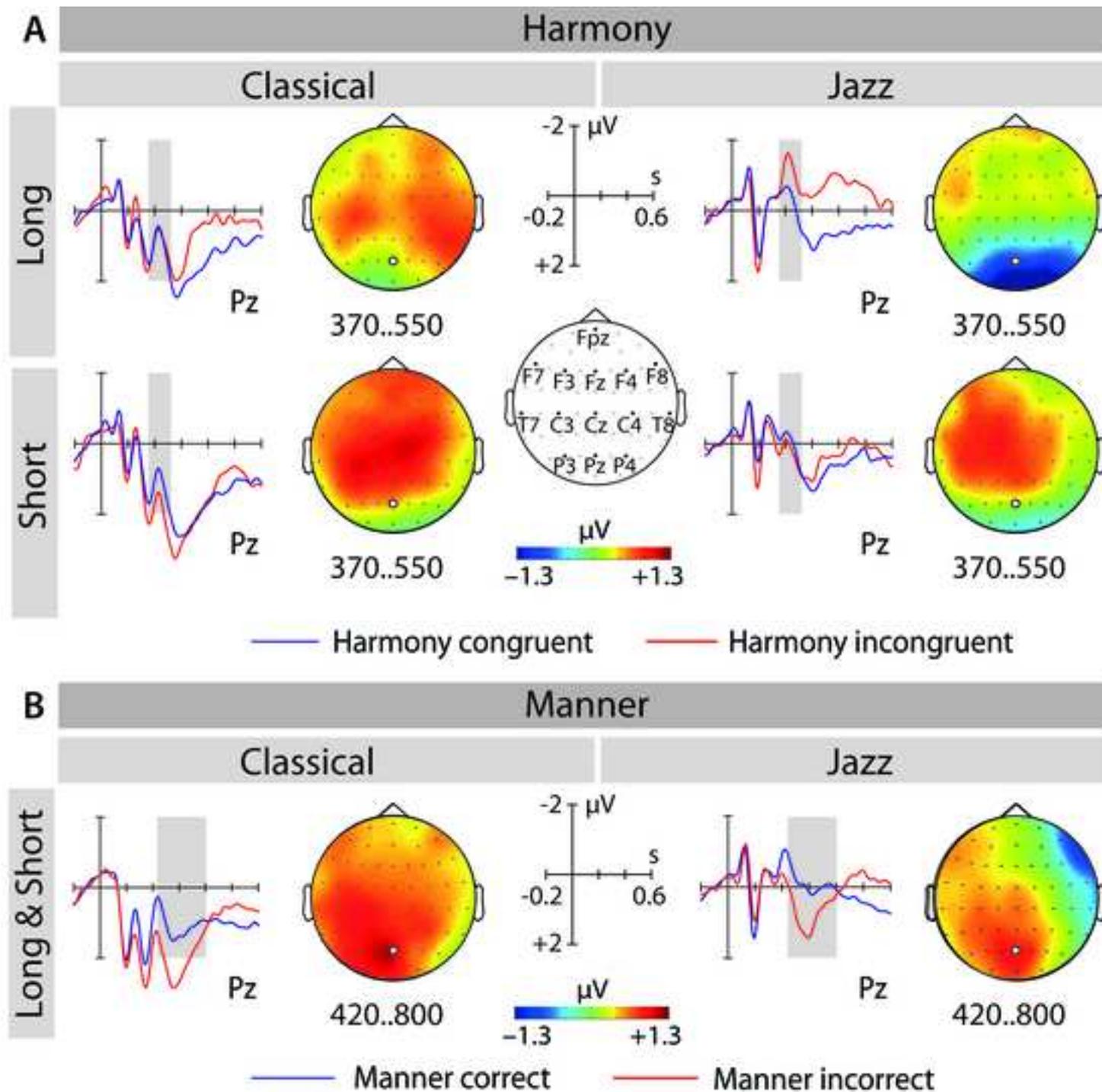


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