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Nijhuis, Patti; Keller, Peter E.; Nozaradan, Sylvie; Varlet, Manuel

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# Null effects of musical groove on cortico-muscular coherence during isometric contraction

Patti Nijhuis [a,*], Peter E. Keller [a,d], Sylvie Nozaradan [b], Manuel Varlet [a,c]

[a] The MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Sydney, Australia
[b] Institute of Neuroscience (Ions), Université catholique de Louvain (UCL), Belgium
[c] School of Psychology, Western Sydney University, Sydney, Australia
[d] Center for Music in the Brain, Department of Clinical Medicine, Aarhus University, Denmark

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ABSTRACT

Humans have a natural tendency to move to music, which has been linked to the tight coupling between the auditory and motor system and the active role of the motor system in the perception of musical rhythms. High-groove music is particularly successful at inducing spontaneous movement, due to the engagement of (motor) prediction processes. However, how music listening transfers to the muscles even when no movement is intended is less known. Here we used cortico-muscular coherence (CMC) to investigate changes along the cortico-muscular pathway in response to different levels of groove in music listening without intention to move. Electroencephalography (EEG), Electromyography (EMG) from the finger and foot flexors, and continuous force signals were recorded in 18 participants while listening to either high-groove music, low-groove music or silence. Participants were required to hold a steady isometric contraction during all listening conditions. Subjective ratings confirmed that different levels of groove were successfully induced. However, no evidence was found for an effect of music, even high-groove music, on participants' CMC and ability to maintain a steady force for both upper and lower limbs irrespective of musical expertise. These results thus do not support a top-down influence of groove on cortico-muscular coupling. Nevertheless, it remains possible that such influence might occur in the form of dynamic modulations and/or with more active listening. Therefore, these results encourage further research to better understand the effects of groove on the motor system.

## 1. Introduction

People have a natural tendency to move to music (Janata et al., 2012; Zentner and Eerola, 2010). Children already show movement to music from a very young age (Fujii et al., 2014; Honing et al., 2009; Huron, 2006; Witek et al., 2014; Zentner and Eerola, 2010). When listening to rhythmic music, it is often difficult to suppress the natural urge to tap the feet or fingers along with the beat. This urge to move to music is often ascribed to the tight coupling between the auditory and motor system and the active role of the motor system in the perception of musical rhythms (Zatorre et al., 2007). While a growing number of studies corroborate the evidence for an engagement of the motor system in the brain when listening to music (e.g., Särkämö et al., 2016), how this effect transfers through the body to the muscles even when no movement is intended remains unknown. Here we combine Electroencephalography (EEG) and Electromyography (EMG) techniques to investigate changes along the cortico-muscular pathway induced by music listening while maintaining an isometric contraction, especially high-groove music characterised by stronger induction of spontaneous movement.

The active role of the motor system in music and rhythm perception has been shown in numerous studies that revealed that even without actual movement the perception of auditory rhythms activates motor regions in the brain, including premotor cortices, supplementary motor areas (SMA), and the basal ganglia (Bengtsson et al., 2009; Chen et al., 2006, 2008a; Grahn and Brett, 2007; Kornysheva et al., 2010; Schubotz et al., 2000), with stronger activity for musicians compared to non-musicians (Cameron and Grahn, 2014; Chen et al., 2008b). Studies have also shown music-induced modulations in the amplitude of neural oscillations in the beta band (≈20 Hz), which are critical for movement production and control (Engel and Fries, 2010; Khanna and Carmena, 2015; Pfurtscheller, 1981). Such motor activity suggests that temporal

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[*] Corresponding author. MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Locked Bag 1797, Penrith, NSW, 2751, Australia.
*E-mail address:* p.nijhuis@westernsydney.edu.au (P. Nijhuis).

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features of music, such as the ongoing rhythm, directly engage auditory-motor links that facilitate moving in time with the music. Furthermore, auditory-motor interactions and movement facilitation have been shown to be stronger with extensive musical training (Chen et al., 2008b, Rosenkranz et al., 2007, see Zatorre et al., 2007 for a review).

Motor regions have been suggested to play a critical role in extracting the beat from the music and forming an internal temporal representation (Araneda et al., 2017; Bengtsson et al., 2009; Grahn, 2009, 2012; Grahn and Rowe, 2009; Chapin et al., 2010; Wiener et al., 2010; Teki et al., 2011, 2012; McAuley et al., 2012). The motor system has been argued to be involved in generating temporal predictions via covert and unconscious action simulation to predict when future (auditory) events will occur (Arnal, 2012; Cannon and Patel, 2020; Patel and Iversen, 2014; Keller et al., 2007; Pecenka et al., 2013; Ross et al., 2016; Schubotz, 2007). This is supported by work showing that temporal predictions in the context of regular auditory stimuli are driven by motor signals to the auditory cortex (Morillon and Baillet, 2017). In the context of beat perception, the efferent signals of these covert actions may act as an internal representation of the beat, or 'pacing signal', informing beat-based expectations and in turn facilitating movement to a beat (Kotz et al., 2016).

Interestingly, certain types of music are particularly enticing to move to, and more potent at inducing synchronised movement than other music (Janata et al., 2012). Such music is considered high in groove, and yields a pleasurable experience (Janata et al., 2012). Properties of the musical structure and acoustic properties, such as rhythmic and harmonic complexity (Matthews et al., 2019), syncopation (Sioros et al., 2014; Witek et al., 2014, 2017) and spectral flux (Burger et al., 2013; Stupacher et al., 2016) seem to play a crucial role in the experience of groove and the induction of movement. In particular, a moderate degree of rhythmic (and harmonic) complexity, including syncopation, is thought to induce groove (Huron and Ommen, 2006; Keller and Schubert, 2011; Matthews et al., 2020; Witek et al., 2014). It has been suggested that deviations from a predictable rhythm cause the listener to make a greater effort, i.e. increasing their predictive engagement, to follow the rhythm than with a simple and fully predictable isochronous metronome (Levitin et al., 2017). According to Iyer (2002), this "active" listening experience through increased predictive engagement would be essential to the experience of groove, and a medium rhythmic complexity strikes a balance between satisfying and violating rhythmic expectations. This theory of medium (rhythmic) complexity as the crucial characteristic of groove to optimally engage prediction processes is supported by a study by Matthews et al. (2020) that found medium complexity rhythms scored high on groove ratings and led to increased activity in areas that are critical for generating an internal representation of the beat, including the putamen, caudate, SMA and dorsal premotor areas (see Araneda et al., 2017; Grahn and Rowe, 2009; Merchant et al., 2015). In addition to an increase in activity, higher complexity rhythms that were correlated with higher groove ratings have also been linked to stronger neural entrainment, i.e., entrainment of ongoing neural oscillations to regularities in stimulus rhythms (Cameron et al., 2019).

Therefore, it is well established that the motor system is actively involved in music listening, and inducing groove in particular (generating the pleasurable urge to move along), through its involvement in time-keeping and temporal prediction. However, the involvement of the motor system during music listening beyond cortical and subcortical regions remains unknown. It is unclear how music, especially high-groove music characterised by high movement induction, spontaneously modulates activity along the cortico-muscular pathway, and thus, intrinsic behavioural motor functioning.

Of particular interest in the present study is cortico-muscular coherence (CMC), a measure that quantifies the degree of synchronisation between cortical and muscular activities, which has been shown to play a critical role in movement production and control (Halliday et al., 1995). CMC is used to assess the communication between cortical regions and muscles, and can be obtained by combining EEG or MEG with EMG (Fries, 2005). CMC, which is usually measured best during low-intensity isometric contraction, has been found to peak over primary motor regions contralateral to the active limb, and in the beta frequency range around 20 Hz (Conway et al., 1995; Feige et al., 2000; Halliday et al., 1998; Hari and Salenius, 1999; Salenius et al., 1997; Witham et al., 2011; for reviews see Bourguignon et al., 2019; Mima and Hallett, 1999).

CMC has been shown to be relevant for understanding motor control. It has been suggested that increased CMC occurs when higher level of control (measured as perceived task difficulty) is required, when maintaining a stable motor output, for instance (Divekar and John, 2013). Increased CMC has also been found to be associated with more accurate motor performance (i.e., motor precision) in certain scenarios, suggesting more effective communication between the brain and the muscles (Kristeva-feige et al., 2002; Kristeva et al., 2007; Witte et al., 2007).

Previous research has shown that CMC is sensitive to surrounding environmental stimuli, even if an individual is not moving and is required to maintain a steady isometric contraction. Piitulainen et al. (2015) found pronounced increases in CMC following the presentation of unexpected auditory and visual distractors. Changes in CMC have also been shown during the observation of human actions (Hari et al., 2014) and the presentation of simple predictable audio-visual sequences (Piitulainen et al., 2015; Safri et al., 2006, 2007; Varlet et al., 2020). These results suggest that music, especially high-groove music characterised by stronger movement induction, might spontaneously modulate the strength of cortico-muscular synchronisation even if there is no intended movement.

Transcranial Magnetic Stimulation (TMS) research supports this possibility, revealing enhanced cortico-muscular facilitation with music compared to white noise, as indicated by larger Motor Evoked Potentials (MEP) in EMG recordings following TMS pulses during passive music listening (Stupacher et al., 2013) and foot tapping to music (Wilson and Davey, 2002). In these studies, cortico-muscular facilitation was stronger for high-groove than low-groove music and was found for both upper and lower limbs, in line with previous behavioural research that showed similar effects of groove levels on movement entrainment for both the hands and the feet, although the absolute amount of movement or synchronisation performance to the beat might differ between hands and feet (Janata et al., 2012; Tranchant et al., 2016). These results are particularly relevant here because it has been previously shown that the amplitude of TMS-induced MEPs is linked to the magnitude of beta band CMC (Schulz et al., 2014), suggesting that the connectivity between the brain and the muscles for upper and lower limbs might be modulated by music, especially high-groove music.

The current study tested this hypothesis in order to better understand the effects of music on the motor system by examining the strength of CMC between EEG and EMG recordings from the upper and lower limbs of participants listening to either no music, low-groove music, or high-groove music while instructed to maintain a steady isometric contraction. Because groove induces feelings of wanting to move and because this spontaneous movement planning may act as a time-keeping mechanism allowing temporal prediction and actual spontaneous movement, groove was expected to modulate the strength of the cortico-muscular coupling even if participants were not moving and were instructed to maintain an isometric contraction. More specifically, because high-groove music results in stronger motor engagement and higher motor excitability, it was hypothesised that listening to high-groove music would result in stronger CMC than listening to low-groove music and no music. This effect was expected to occur for both lower and upper limbs and to be stronger in participants with musical experience due to increased motor engagement and enhanced temporal predictions.

## 2. Method

### 2.1. Participants

Eighteen healthy right-handed participants volunteered in this study (age: 18–45 years old, M = 26.7±6.1; 13 females, 5 males). The sample size was chosen based on an a priori power analysis to detect medium effect sizes ($f = 0.25$) with at least 80% power, in line with effect sizes previously reported in CMC and groove studies (e.g., Safri et al., 2006; Stupacher et al., 2013; Varlet et al., 2020).

None of the participants had any history of hearing, motor, neurological, or psychiatric disorders. This study was approved by the Human Research Ethics Committee of Western Sydney University and was performed in accordance with the ethical standards of the Declaration of Helsinki. All participants gave written informed consent prior to participation and were debriefed after the study.

To control for the effect of musical experience, a dichotomous between-subject factor Musical Experience (high and low) was used where participants were assigned to one of the two groups post-hoc depending on whether they had more or less than five years of combined musical and dance experience, as self-reported (Grahn and Rowe, 2009; Zhang et al., 2018). The low Musical Experience group had an average of 1.000 ± 1.483 years of musical experience, whereas the high Musical Experience group had an average of 8.571 ± 2.370 years of musical experience.

### 2.2. Musical stimuli

The stimuli consisted of 50 musical excerpts of 30 s each, from which 25 were categorised as high-groove and 25 were categorised as low-groove. Forty excerpts were derived from the Janata et al. (2012) database. Twenty high-groove excerpts were chosen from the forty highest rated excerpts and twenty low-groove excerpts were derived from the forty lowest rated excerpts from this database. An extra ten musical excerpts (5 high-groove and 5 low-groove) from contemporary music (2010–2018) were also included (i.e., high-groove: Uptown Funk, Call Me Maybe, Shape of You, Despacito, Sorry – low-groove: Lovely London Sky, Opposite of Loving Me, I Miss Her, Mark My Words, Love Drought). These new contemporary excerpts were pilot tested on 9 participants, asking how much participants felt like moving on a 7-point Likert scale ("very much" - "not at all"), to confirm that the newly selected high-groove and low-groove excerpts differed significantly in perceived groove ($p < .001$). All the musical excerpts were obtained from the previews accessible on the iTunes Music Store.

The musical excerpts in this study varied in their genre (rock, soul, jazz) and had a wide range of tempi (from 66 to 159 bpm). The high-groove (M = 106, SD = 16 bpm) and low-groove (M = 113, SD = 26 bpm) excerpts were balanced as closely as possible for their tempo, as operationalised by the beats per minute. The excerpts were also matched for perceived loudness using adobe audition CS6. The musical stimuli were presented at a comfortable hearing level using ER-1 in-ear phones (Etymotic Research Inc, Illinois, USA).

In addition to the 50 musical excerpts, 25 control trials consisting of 30 s of silence were presented. The 75 trials were presented to the participants in random order. To ensure an equal distribution of the excerpts over time, the presentation order was blocked into sets of three. In each block a random high-groove, low-groove and control trial was assigned in random order.

### 2.3. Apparatus

During the experiment participants were seated on an armless chair, in front of a computer screen, with their right forearm placed on a table adjacent to them, with their elbow joint making approximately a 90° angle and the hand palm facing down. Their right index finger was placed on a force sensor on the table. The left foot was placed on a pedal that measured plantar flexion force.

#### 2.3.1. Force

The force exerted by the participant's right index finger and left foot was recorded at a sampling frequency of 60 Hz using two wide bar load cells (HTC-Sensor TAL201, Colorado, USA), one on the table and one for the foot pedal. The cells were connected to an Arduino Duemilanove board (Arduino, Ivrea, Italy) via an amplifier shield (Load Cell/Wheatstone Amplifier Shield, RobotShop, Mirabel, Quebec, Canada). The Arduino board was connected to a MacBook Pro laptop (Apple, Cupertino, CA, USA) via USB. The load cells were calibrated for linearity.

#### 2.3.2. EEG and EMG recording

EEG and EMG signals were recorded at a sampling rate of 2048 Hz using a BioSemi Active-Two system (BioSemi, Amsterdam, Netherlands). EEG was recorded with 64 Ag–AgCl electrodes placed over the scalp of the participant according to the international 10/20 system. EMG signals were recorded using BioSemi flat electrodes with a standard belly-tendon montage. After preparing the participant's skin using alcohol swabs, a pair of electrodes was placed on the right forearm to record the right Flexor Digitorum Superficialis (FDS) muscle, involved in maintaining continuous finger pressure (Cardellicchio et al., 2020; Kong et al., 2010). A second pair of electrodes was placed on the participant's Gastrocnemius Medialis (GM) muscle on the left calf, involved in maintaining the foot pressure (Hermens et al., 1999).

### 2.4. Procedure

Before commencing the experiment, participants were asked to complete a short questionnaire concerning demographic information including age, gender, handedness, and information regarding their level of expertise in music and dancing.

Prior to data collection, the force sensors for both hand and foot were calibrated for each participant by asking the participants to place their right index finger and their left foot on the sensors without applying any force, thereby subtracting the relative weight of participants' relaxed limbs on the sensors. Then, the participant's maximal voluntary contraction (MVC) was measured. The participants were instructed to put as much pressure on the sensors as they could for approximately 3 s. This was repeated three times and the average of the three maximum forces was considered to be the MVC, which was used in the following experimental trials.

#### 2.4.1. Task

Participants were instructed to sustain an isometric contraction of the right index finger and left foot throughout the 30 s trials, corresponding to the duration of the musical excerpts. The target force for the hand and the foot was calculated as 7% of the MVC (Kristeva-feige et al., 2002; Kristeva et al., 2007; Safri et al., 2006, 2007). Low-intensity isometric contraction was chosen to study CMC with line with previous research suggesting that the motor cortex is particularly involved with the coding of weak forces (Maier et al., 1993). It also provides the required level of muscular activity to gather EMG signals while preventing dynamic fluctuations in CMC related to movements (Halliday et al., 1995). Isometric contractions of both the hand and the foot enabled testing systemic effects of groove through the whole body, expected to propagate from central level to all distal body parts in line with previous research (e.g., Burger et al., 2013; Cameron et al., 2019; Matthews et al., 2020; Wilson and Davey, 2002).

Participants were instructed to focus on the musical excerpts and keep the pressure on the force sensors as stable as possible. Participants' force levels applied with the hand and the foot had to be within a 5% accuracy range of their respective target force defined as 7% of their MVC (Conway et al., 1995; Kristeva-feige et al., 2002; Kristeva et al., 2007; Safri et al., 2007; Witte et al., 2007; Varlet et al., 2020). Feedback of the participant's force level was visually presented between trials, and the following trial could only be started by the experimenter once the participant was within a 5% accuracy range of the target force for both the hand and the foot.

The visual feedback for each limb corresponded to a red bar that changed in length in real-time depending on participant's exerted force and turned green when the exerted force was within the 5% accuracy range of the target force. The target force was indicated by a white line on the bar. The force feedback disappeared as soon as the experimenter started the trials to avoid distracting the participants from focusing on the musical excerpts. Several practice trials were performed to familiarise participants with the experiment until they managed to hold steady forces of approximately 7% of MVC for both the hand and the foot.

#### 2.4.2. Survey items

Perceived groove, loudness, familiarity, effort to sit still, and enjoyment were evaluated on a seven-point scale (where 1 = "not at all" and 7 = "very much") via the computer display at the end of each musical excerpt. The following survey items were presented on the screen: 1) How much did you feel like moving? (groove); 2) How loud was the music? (loudness); 3) How familiar were you with the music? (familiarity); 4) How hard did you find it to sit still while listening to the music? (effort to sit still); and 5) How much did you enjoy the music you just heard? (enjoyment). Participants reported their answer to the experimenter who entered the values into the computer. Participants were also asked to report some lyrics to the experimenter at the end of each musical excerpt to make sure they paid attention to the stimuli. For this attention check, a dichotomous answer was used, participants either did (7) or did not (1) remember lyrics. When the excerpt had no lyrics, 7 was awarded when participants reported correctly that there were no lyrics.

To minimise the source of artifacts in EEG signals during trials, participants were also instructed to focus their gaze on a cross at the centre of the screen, to relax their upper body and to refrain from moving their head, talking, swallowing, coughing, clenching their jaw, and blinking excessively. Participants were allowed to take as many breaks as necessary in between trials. The experimental task and procedure were explained to the participants in detail before the commencement of the experiment. The total experiment, including EEG and EMG preparation, lasted approximately 2 h.

### 2.5. Data analysis

The surface EEG and EMG were processed and analysed using MATLAB 2017a (The MathWorks, Inc., Natick, MA).

#### 2.5.1. EEG pre-processing

EEG signals were first (i) high-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 0.2 Hz to remove very slow drifts in the recorded signals and (ii) segmented into 30 s epochs locked to the onset of each trial.

After the initial filtering, EEG channels containing excessive artifacts or noise were identified based on visual inspection and interpolated with neighbouring channels (i.e., an average of 1.389 [SD = 1.253] interpolated electrodes per participant, and never more than 5 electrodes). The EEG signals were then decomposed by an independent component analysis (FastICA), as implemented in Fieldtrip (Oostenveld et al., 2011), to remove muscular activity related to eye movement artifacts. Based on visual inspection of the topography and time-course of independent components, components reflecting eye-blinks and lateralised eye movements were removed from the data. EEG data were then (i) re-referenced to the average of all scalp electrodes (Snyder et al., 2015), (ii) notch filtered to remove 50 Hz (and harmonics up to 200 Hz) electrical power contamination with a bandwidth of 1 Hz, and (iii) low-pass filtered at 195 Hz to exclude high frequency noise (de Cheveigné and Nelken et al., 2019; Kerrén et al., 2018).

#### 2.5.2. EMG pre-processing

EMG signals for FDS and GM muscles were first (i) high-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 0.2 Hz to remove very slow drifts in the recorded signals and (ii) segmented into 30 s epochs locked to the onset of each trial. The EMG signals were then re-referenced to their respective reference electrode, notch filtered to remove 50 Hz (and harmonics up to 200 Hz) electrical power contamination with a bandwidth of 1 Hz, and high-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 10 Hz to remove movement artifacts (De Luca et al., 2010; de Vries et al., 2016; Merletti and Di Torino, 1999; Tomiak et al., 2015). The EMG signals were then rectified and low-pass filtered at 195 Hz to remove high frequency noise in line with previous EMG and EEG/MEG-EMG coherence studies (Bourguignon et al., 2017; Piitulainen et al., 2015; Varlet et al., 2020). Although its benefits remain debated, rectifying EMG signals has been shown to be particularly appropriate to examine CMC for low exerted forces (Boonstra and Breakspear, 2012; Farina et al., 2013; McClelland et al., 2012; Ward et al., 2013). We also examined EMG broadband amplitude in separate analyses to investigate overall amplitude of muscular activity across conditions. EMG broadband amplitude was computed as the mean envelope of the rectified EMG (10–195 Hz) signals using the Hilbert transform. Finally, the pre-processed EEG and EMG signals were down-sampled to 500 Hz to reduce computational load.

#### 2.5.3. Cortico-muscular coherence analysis

Cortico-muscular coherence (CMC) and the time-frequency spectra required for coherence analysis were both calculated using the FieldTrip toolbox (Oostenveld et al., 2011). For each participant, CMC was calculated between all EEG electrodes and the FDS muscle (hand-EEG coherence), and the GM muscle (foot-EEG coherence). To do so, the EEG and EMG power spectra and their cross-spectrum were calculated over the whole 30 s trial using a Fast-Fourier transform based time-frequency analysis between 0 and 50 Hz. The time-frequency analysis was computed using fixed-length windows of 1000 ms giving a frequency resolution of 1 Hz with 800 ms overlap (Bourguignon et al., 2013; Piitulainen et al., 2018). A multitaper approach was used in order to improve CMC estimation using 3 Slepian tapers, resulting in ±1.5 Hz frequency smoothing for the computation of power- and cross-spectra (Reyes et al., 2017). Then, coherence was calculated from the cross-spectrum, normalised by the auto-spectrum as described by Halliday et al. (1995). This operation results in coherence values between 0 and 1 for each frequency bin, where 1 corresponds to perfect synchrony and 0 corresponds to no synchrony between the EEG and EMG signal.

Further analyses of coherence focused on the beta range between 15 and 35 Hz. This relatively large range allowed variability within and between participants to be captured at the frequencies at which CMC usually occurs (Hansen and Nielsen, 2004; Mehrkanoon et al., 2014; Murthy and Fetz, 1992, 1996; Omlor et al., 2007; Salenius et al., 1997; Varlet et al., 2020). Beta range CMC for the hand has been shown to occur in contralateral motor regions with C3 electrode being most commonly reported, whereas the foot has a more central topographical distribution with Cz electrode being most commonly reported (Kristeva-feige et al., 2002; Mehrkanoon et al., 2014; Petersen et al., 2012; Safri et al., 2007). Therefore, the C3 electrode (hand) and the Cz electrode (foot) were selected for further analyses.

### 2.6. Statistical analysis

#### 2.6.1. Subjective ratings

2 × 2 mixed model ANOVAs with the within-subject factor Groove (high-groove and low-groove) and the between-subject factor Musical Experience (high and low) were used to test for differences between the high-groove and low-groove excerpts in subjective ratings of groove, loudness, familiarity, effort to sit still and enjoyment, as well as to test

the effect of Musical Experience on the subjective ratings. In addition, to check if the newly added excerpts were as effective at inducing groove as the high-groove excerpts retrieved from Janata et al. (2012), *t*-tests were used to examine differences in subjective ratings between the 5 new high-groove contemporary excerpts and the high-groove excerpts retrieved from Janata et al. (2012). Where necessary, *t*-tests were adjusted for unequal variances using the Welch test.

Groove, familiarity and enjoyment are strongly correlated and therefore thought to be part of the experience of groove (Janata et al., 2012). Thus, we attempted to capture an overall construct of "groove" by performing an orthogonal Principal Component Analysis (PCA) for each participant on all 5 subjective items and 50 excerpts. The first principal component (PC1) was then used for further analyses, as described below.

### 2.6.2. *Cortico-muscular coherence*

A 2 × 3 × 50 × 2 mixed model ANOVA with the factors Limb (hand and foot), Groove (high-groove, low-groove, and control), Frequency (1–50 Hz), and Musical Experience (high and low) was first used on the CMC frequency spectrum across all frequency bins to detect a peak in the spectrum (Hanslmayr et al., 2005). A 2 × 3 × 2 mixed model ANOVA with the factors Limb (hand and foot), Groove (high-groove, low-groove, and control), and Musical Experience (high and low) was then used to examine beta CMC (averaged coherence across the 15–35 Hz frequency range) more specifically. Because groove is a subjective experience, it was expected that the highest rated excerpts might differ for each participant. Hence, subjective high-groove and low-groove categories were also tested based on the average of individual's 20 highest and lowest rated excerpts for Groove, Loudness, Familiarity, Effort to sit still, Enjoyment, and PC1. To confirm that the changes in CMC were due to actual changes in synchronisation between EEG and EMG signals and did not originate from time-locked amplitude modulations in the EEG and/or EMG signals, CMC was also calculated on permuted data. For each participant and each condition, the EEG signals of each trial were randomly matched with the EMG signal from another trial (von Carlowitz-Ghori et al., 2014; Hesterberg et al., 2005; Yoshida et al., 2017a). Beta CMC was calculated for 1000 permutations of the 75 trials and compared to real coherence values in a 2 × 2 × 3 repeated-measures ANOVA with the factors Dataset (real, permuted), Limb (hand and foot) and Groove (high-groove, low-groove, and control).

### 2.6.3. *EEG and EMG*

A 2 × 3 × 2 mixed model ANOVA with the factors Limb (hand and foot), Groove (high-groove, low-groove, and control), and Musical Experience (high and low) was also used on beta EMG power, beta EEG power, and broadband EMG (envelope of the 10–195 Hz rectified signal) amplitude averaged over the duration of the trials.

### 2.6.4. *Mean and variability of force*

A 2 × 3 × 2 mixed model ANOVA was also used on Mean Force and Force variability computed as the mean and standard deviation of participant's exerted force over the duration of the trials and expressed as a percentage of the instructed target force.

### 2.6.5. *Correlation between subjective ratings and physiological measures*

To further explore the relation between the subjective ratings (i.e., groove, familiarity, loudness, effort to sit still, enjoyment, and PC1) and the physiological measures (i.e., beta CMC, beta EEG power, beta EMG power, broadband EMG amplitude, Mean Force, and Force variability), Pearson correlations between them were calculated, both across participants and across excerpts. For the between-subject correlations, all variables were averaged across the low-groove and high-groove conditions. For the between-excerpt correlations, all variables were averaged across the participants.

All statistical analyses were performed in JASP (0.12.2.0). In addition to the frequentist statistics, Bayes Factors were calculated for all analyses with the default priors in JASP. The Bayes factor is a likelihood ratio that compares the evidence in favour of a null hypothesis $H_0$ to an alternative hypothesis $H_1$, i.e., the adequacy of the null model prediction and the alternative model prediction (Berger, 2006; Schönbrodt and Wagenmakers, 2018). Depending on the order of numerator and denominator in the ratio, the Bayes factor is either denoted as $BF_{01}$ ("$H_0$ over $H_1$") or as its inverse $BF_{10}$ ("$H_1$ over $H_0$"). When the Bayes factor $BF_{01}$ equals 4, this indicates that the data are four times more likely under $H_0$ than under $H_1$, meaning that $H_0$ has issued a better probabilistic prediction for the observed data than did $H_1$. In contrast, when $BF_{01}$ equals 0.25, the data support $H_1$ over $H_0$. Specifically, the data are $1/BF_{01} = BF_{10} = 4$ times more likely under $H_1$ than under $H_0$ (Schönbrodt and Wagenmakers, 2018). In other words, any $BF_{01} < 1$ supports $H_1$ over $H_0$, whereas it is the opposite in case of $BF_{01} > 1$.

The benefit of Bayes factors is that their predictive underpinnings entail that neither $H_0$ nor $H_1$ need be "true" for the Bayes factor to be useful. The Bayes factor does not force an all-or-none decision, but instead coherently reallocates belief on a continuous scale, allowing the Bayes factor to distinguish between absence of evidence and evidence of absence (e.g., Dienes, 2014; 2016). Although Bayes factors are defined on a continuous scale, several papers have proposed to subdivide the scale in discrete evidential categories (Jeffreys, 1961; Lee and Wagenmakers, 2013). Evidence in favour of an effect is considered anecdotal for $BF < 3$, moderate for $3 < BF < 10$, strong for $10 < BF < 30$, very strong for $BF > 30$, and extremely strong for $BF > 100$.

## 3. Results

### 3.1. *Groove ratings*

The perceived groove ratings were significantly higher for musical stimuli in the high-groove condition (M = 4.280) than for the low-groove condition (M = 2.798), $F(1,16) = 38.121$, $p < .001$, partial $\eta^2 = 0.704$, $BF_{10} > 100$, indicating that the manipulation of induced groove was successful (see Fig. 1). The subjective groove ratings were not affected by musical experience, no main effect of Musical Experience was found, $F(1,16) = 1.824$, $p = .196$, partial $\eta^2 = 0.102$, $BF_{01} = 0.940$ and no interaction with Groove was found $F(1,16) = 2.455$, $p = .137$, partial $\eta^2 = 0.133$, $BF_{01} = 0.573$.

The results also indicated that high-groove conditions scored higher than low-groove conditions on their subjective ratings of familiarity

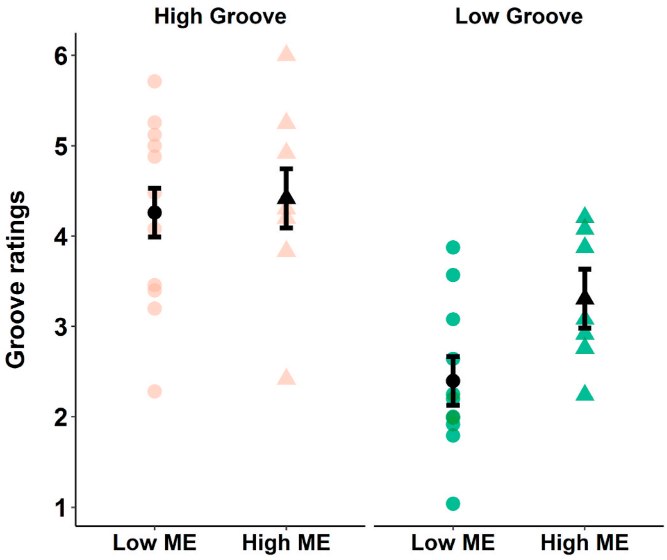


**Fig. 1.** Mean subjective groove ratings across the high-groove and low-groove conditions for the low Musical Experience (Low ME) and high Musical Experience group (High ME).

(high-groove; M = 3.651, low-groove; M = 1.689), $F(1,16) = 193.952$, $p < .001$, partial $\eta^2 = 0.924$, $BF_{10} > 100$, perceived effort to sit still (high-groove; M = 4.212, low-groove; M = 3.274), $F(1,16) = 21.097$, $p < .001$, partial $\eta^2 = 0.569$, $BF_{10} > 100$, enjoyment (high-groove; M = 4.676, low-groove; M = 3.910), $F(1,16) = 21.474$, $p < .001$, partial $\eta^2 = 0.573$, $BF_{10} > 100$, and $PC_1$ (high-groove; M = 1.546, low-groove; M = −1.106), $F(1,16) = 60.188$, $p < .001$, partial $\eta^2 = 0.817$, $BF_{10} > 100$, but not on perceived loudness (high-groove; M = 3.649, low-groove; M = 3.433), $F(1,16) = 3.488$, $p = .08$, partial $\eta^2 = 0.179$, $BF_{01} = 0.806$. No main effect of Musical Experience was found on any of the subjective ratings, nor did the effect of Groove interact with Musical Experience for any of the subjective ratings ($p$-values > .05, see Fig. 2).

The average groove ratings for each excerpt as well as the familiarity, loudness, effort to sit still, and enjoyment ratings are shown in Fig. 3.

### 3.1.1. New excerpts

The results also suggest that the five new contemporary excerpts scored higher for perceived groove, $t(23) = 3.963$, $p < .001$, $d = 1.982$, familiarity $t(19.585) = 8.950$, $p < .001$, $d = 2.847$, effort to sit still $t(23) = 3.935$, $p < .001$, $d = 1.967$, enjoyment, $t(23) = 2.918$, $p = .008$, $d = 1.459$, the first principal component $PC_1$, $t(23) = 2.738$, $p = .012$, $d = 1.369$, and even perceived loudness, $t(18.619) = 5.011$, $p < .001$, $d = 1.853$, than the other high-groove excerpts previously used by Janata et al. (2012).

### 3.1.2. Exerted force

A 2 × 3 × 2 mixed model ANOVA on the mean force and force variability (expressed as the percentage of instructed force), with the within-subject factors Limb (hand and foot) and Groove (high-groove, low-groove, and control), and between-subject factor Musical Experience (high and low), indicated a significant main effect of Limb on mean force, $F(1,16) = 35.962$, $p < .001$, partial $\eta^2 = 0.692$, $BF_{10} > 100$, and force variability, $F(1,16) = 19.026$, $p < .001$, partial $\eta^2 = 0.543$, $BF_{10} > 100$. As depicted in Fig. 4, the foot showed significantly higher force and lower force variability. There was no main effect of Groove on the mean force, $F(1.417,22.669) = 1.436$, $p = .254$, partial $\eta^2 = 0.082$, $BF_{01} = 20.843$, and force variability, $F(1.490,23.847) = 0.901$, $p = .392$, partial $\eta^2 = 0.053$, $BF_{01} = 17.050$, nor was there an interaction between the factors Groove and Limb for mean force, $F(2,32) = 0.066$, $p = .936$, partial $\eta^2 = 0.004$, $BF_{01} = 30.149$, and force variability, $F(2,34) = 1.056$, $p = .360$, partial $\eta^2 = 0.062$, $BF_{01} = 21.762$. No main effect of Musical Experience was observed for mean force, $F(1,16) = 0.022$, $p = .883$, partial $\eta^2 = 0.001$, $BF_{01} = 2.830$, and force variability, $F(1,16) = 0.696$, $p = .417$, partial $\eta^2 = 0.042$, $BF_{01} = 2.718$, nor were there any significant

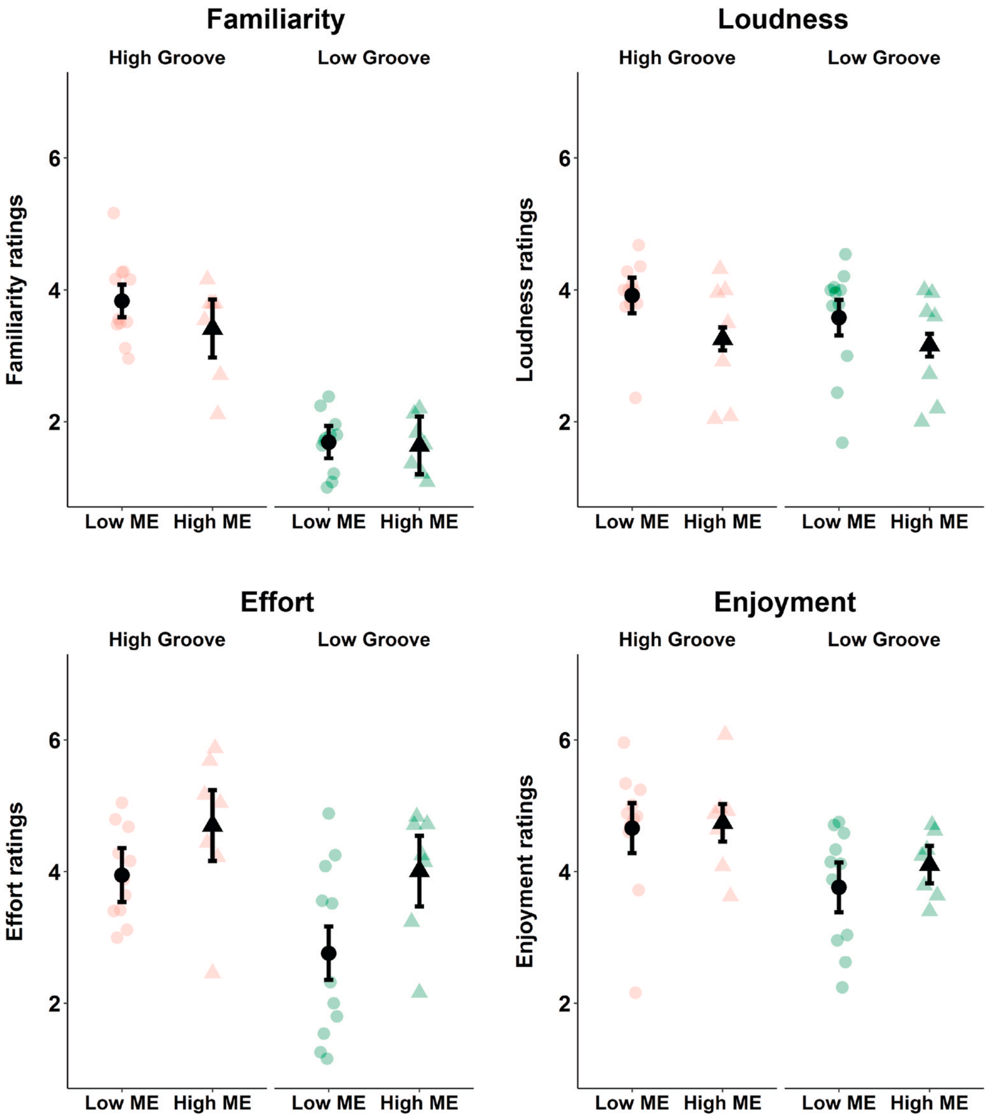


**Fig. 2.** Mean subjective familiarity, loudness, effort, and enjoyment ratings across the high-groove and low-groove conditions for the low Musical Experience (Low ME) and high Musical Experience group (High ME).

| Musical Excerpt | | Groove | Familiarity | Loudness | Effort | Enjoyment | PC$_1$ |
|---|---|---|---|---|---|---|---|
| High Groove | Uptown Funk | 5.50 | 6.21 | 3.91 | 4.94 | 5.59 | 4.33 |
| | Call me maybe | 4.94 | 6.41 | 3.76 | 4.71 | 4.65 | 3.95 |
| | Shape of You | 5.06 | 6.50 | 4.00 | 4.78 | 5.44 | 4.55 |
| | Despacito | 5.31 | 6.19 | 3.88 | 5.06 | 6.00 | 4.55 |
| | Sorry | 4.76 | 6.41 | 3.94 | 4.76 | 5.00 | 4.22 |
| | Yeah | 4.92 | 6.14 | 3.83 | 4.51 | 5.15 | 4.04 |
| | Lay Down the Law | 3.73 | 1.27 | 3.40 | 3.87 | 4.13 | -0.24 |
| | Sco-mule | 3.65 | 1.32 | 3.32 | 3.79 | 3.71 | -0.93 |
| | Music | 3.25 | 1.67 | 3.28 | 4.00 | 4.06 | -0.87 |
| | Mama Cita | 4.31 | 1.97 | 3.76 | 4.16 | 4.10 | 0.20 |
| | Sing Sing Sing | 5.00 | 4.36 | 3.83 | 4.61 | 5.50 | 2.70 |
| | Sabrosa | 3.35 | 1.47 | 3.59 | 3.59 | 3.65 | -0.89 |
| | Outa-space | 3.69 | 1.69 | 3.50 | 3.53 | 3.94 | -0.34 |
| | Superstition | 4.41 | 4.69 | 3.63 | 3.97 | 5.16 | 2.41 |
| | Lose My Breath | 4.71 | 5.65 | 3.94 | 5.00 | 4.94 | 3.62 |
| | Lady Marmelade | 4.19 | 4.97 | 3.66 | 4.25 | 4.97 | 2.67 |
| | It's a Wrap | 3.94 | 1.75 | 3.75 | 4.06 | 4.31 | 0.31 |
| | In the mood | 4.85 | 3.35 | 3.57 | 4.15 | 5.47 | 1.86 |
| | I used to love someone | 3.50 | 1.56 | 3.44 | 3.94 | 3.81 | -0.34 |
| | Goodies | 4.57 | 4.65 | 3.65 | 4.67 | 4.45 | 2.57 |
| | Cheeck to Cheek | 4.36 | 3.11 | 3.83 | 4.08 | 5.08 | 1.06 |
| | Bring the Funk | 3.75 | 1.34 | 3.38 | 3.88 | 4.19 | -0.33 |
| | Bad Tune | 3.81 | 1.69 | 3.88 | 4.00 | 4.19 | -0.36 |
| | Angela | 2.94 | 1.50 | 3.19 | 3.19 | 3.94 | -1.00 |
| | If I ain't got you | 3.94 | 4.50 | 3.38 | 4.31 | 4.59 | 1.94 |
| Low Groove | Lovely London Sky | 3.14 | 2.81 | 3.44 | 3.56 | 4.81 | 0.07 |
| | Opposite of loving me | 2.81 | 1.50 | 3.31 | 3.25 | 4.13 | -0.80 |
| | I miss her | 3.33 | 1.78 | 3.59 | 3.75 | 3.61 | -0.78 |
| | Mark my words | 3.12 | 3.03 | 3.56 | 3.53 | 3.85 | 0.20 |
| | Love Drought | 2.19 | 1.75 | 3.25 | 2.69 | 3.75 | -1.18 |
| | Sweet Thing | 2.62 | 1.50 | 3.24 | 3.41 | 3.74 | -1.44 |
| | Thugamar | 2.18 | 1.41 | 3.71 | 3.29 | 4.18 | -1.50 |
| | Stupid stupid rain | 2.50 | 1.59 | 3.44 | 2.82 | 4.06 | -1.47 |
| | Strong, strong wind | 2.38 | 1.59 | 3.31 | 2.91 | 3.09 | -1.59 |
| | Ray Dawn Balloon | 2.71 | 1.24 | 3.24 | 3.24 | 3.71 | -1.62 |
| | Orange Sky | 2.80 | 1.60 | 3.13 | 2.87 | 4.07 | -0.82 |
| | Just to be near you | 2.25 | 1.56 | 3.16 | 2.97 | 3.84 | -1.29 |
| | I get the Blues when it rains | 3.71 | 1.59 | 3.76 | 3.59 | 3.53 | -0.87 |
| | Hymn for Jaco | 2.12 | 1.18 | 3.41 | 2.88 | 3.50 | -2.07 |
| | Ghost | 2.56 | 1.63 | 3.47 | 3.16 | 3.38 | -1.31 |
| | Fortuna | 3.06 | 1.38 | 3.16 | 3.50 | 4.31 | -0.79 |
| | Flandyke Shore | 2.41 | 1.24 | 3.53 | 3.06 | 3.24 | -1.81 |
| | Fire in the Brain | 2.63 | 1.19 | 3.06 | 3.00 | 3.56 | -1.69 |
| | Druid Fluid | 3.12 | 1.29 | 3.53 | 3.53 | 4.18 | -1.01 |
| | Dawn Star | 2.53 | 1.29 | 3.35 | 3.00 | 3.88 | -1.62 |
| | Bryter Layter | 2.67 | 1.72 | 3.39 | 3.17 | 4.61 | -1.40 |
| | Better Man | 2.49 | 2.39 | 3.35 | 3.35 | 3.12 | -0.98 |
| | Beauty of the Sea | 2.85 | 1.41 | 3.32 | 3.03 | 3.68 | -1.57 |
| | Aural Oasis | 2.31 | 1.59 | 3.50 | 3.03 | 4.34 | -1.00 |
| | All Things Reconsidered | 3.13 | 1.60 | 3.33 | 3.53 | 3.93 | -0.30 |

**Fig. 3.** Subjective ratings (on a 7-point Likert scale) for high-groove excerpts (above the line) and low-groove excerpts (below the line). The cell colour is scaled according to the values of the dependent variable, ranging from minimum to maximum for each column. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interactions with Musical Experience ($p$-values >.05).

ANOVAs conducted on high-groove and low-groove force data selected based on each participant's subjective ratings (i.e., groove, loudness, familiarity, effort, enjoyment, and PC1) also did not show any significant effects of Groove on mean force and force variability ($p$-values $> .05$ and $BF_{01} > 3$).

### 3.2. *Cortico-muscular coherence*

A 2 × 3 × 50 × 2 mixed model ANOVA on coherence values at the respective electrodes for each limb (i.e., C3 and Cz), with the within-subject factors Limb (hand and foot), Groove (high-groove, low-groove, and control) and Frequency (0–50 Hz in 1 Hz bins), and the between-subject factor Musical Experience (high and low), indicated a significant main effect of Frequency, $F(49,833) = 6.201$, $p < .001$, partial $\eta^2 = 0.267$, $BF_{10} > 100$, but not of Groove, $F(2,34) = 2.221$, $p = .124$, partial $\eta^2 = 0.013$, $BF_{01} > 100$, or Limb, $F(1,17) < 0.001$, $p = .765$, partial $\eta^2 < 0.001$, $BF_{01} = 8.962$, and no significant interactions between the factors Limb, Groove, and Frequency ($p$-values $> .05$; see Fig. 5 for individual's coherence spectra and Fig. 6 for coherence spectra in the different Groove conditions). Musical Experience did not have a significant effect on CMC, $F(1,16) = 0.304$, $p = .589$, partial $\eta^2 = 0.019$, $BF_{01} = 5.685$, nor did Musical Experience interact with the factors Limb, Groove, and Frequency ($p$-values $> .05$). However, the three-way interaction between Limb, Groove, and Musical Experience was significant, $F(1,16) = 4.138$, $p = .025$, partial $\eta^2 = 0.205$, but post-hoc testing with Bonferroni correction did not show any significant comparisons ($p$-values $> .05$) and Bayesian analysis indicated extremely strong evidence for the exclusion of the three-way interaction, $BF_{01} > 100$ in favour of the null hypothesis.

#### 3.2.1. *Beta CMC*

A 2 × 2 × 3 repeated measures ANOVA on CMC in the beta (15–35 Hz) frequency range, with the factors Dataset (real and permuted), Limb (hand and foot) and Groove (high-groove, low-groove, and control), indicated a significant main effect of Dataset, $F(1,17) = 14.128$, $p =$

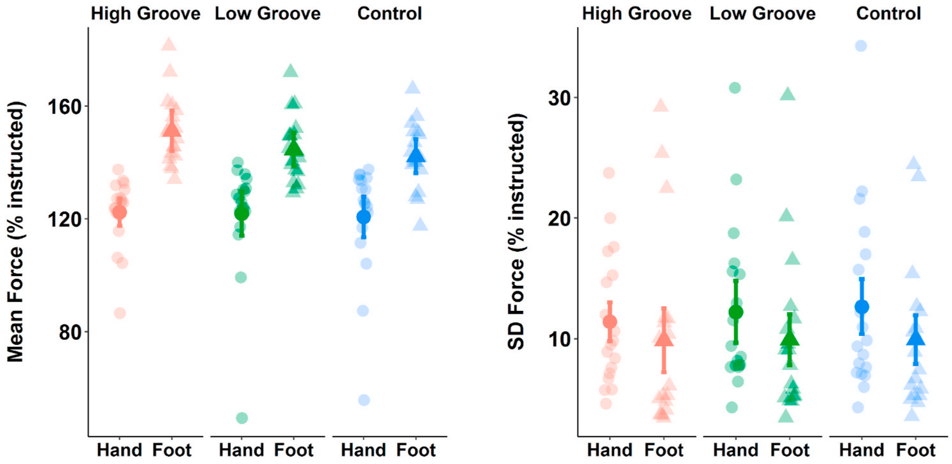


**Fig. 4.** Mean (A) and Standard Deviation (B) of the instructed force (7% of an individual's maximum force) for the hand and the foot across the different groove conditions.

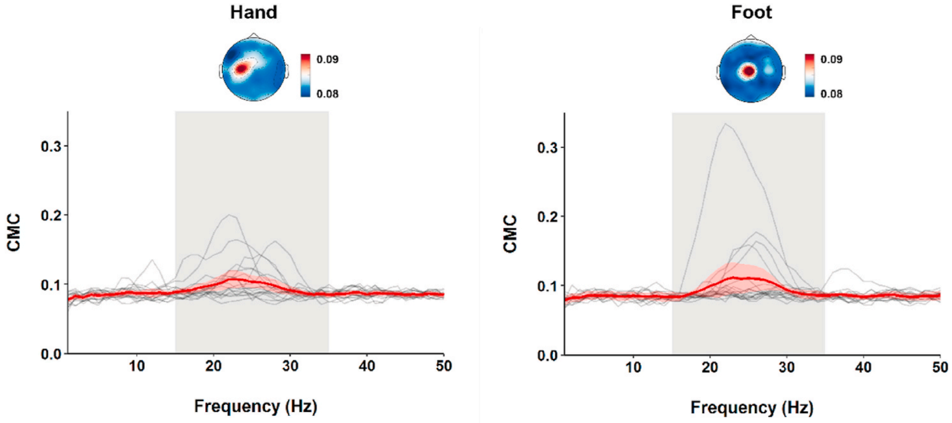


**Fig. 5.** EEG-EMG coherence spectra averaged across conditions for the hand and foot. Red lines represent the average of the three Groove conditions with shading representing 95% confidence intervals (CI) and grey lines representing individual participants. Grey shaded areas represent the selected beta range (15–35 Hz) and the topographical maps show the distribution of coherence values averaged within this range across participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

.002, partial $\eta^2 = 0.454$, $BF_{10} > 100$, showing that coherence captures genuine synchronisation between EEG and EMG activity.

A 2 × 3 × 2 mixed model ANOVA on beta CMC, with the within-subject factors Limb (hand and foot) and Groove (high-groove, low-groove, and control) and the between-subject factor Musical Experience (high and low) indicated no significant effect of Limb, $F(1,16) < 0.001$, $p = .995$, partial $\eta^2 = 0.004$, $BF_{01} = 4.512$, Groove, $F(2,32) = 0.785$, $p = .477$, partial $\eta^2 = 0.045$, $BF_{01} = 26.911$, or Musical Experience, $F(1,16) = 0.221$, $p = .645$, partial $\eta^2 = 0.014$, $BF_{01} = 4.352$. No interaction between Limb and Groove was observed, $F(2,32) = 1.138$, $p = .333$, partial $\eta^2 = 0.066$, $BF_{01} = 6.587$ (see Figs. 6 and 8A). The average beta CMC for each excerpt can be found in Fig. 7.

No interaction between Limb and Musical experience, $F(1,16) = 1.138$, $p = .259$, partial $\eta^2 = 0.079$, $BF_{01} = 86.143$, or Groove and Musical Experience was observed, $F(1,16) = 0.482$, $p = .622$, partial $\eta^2 = 0.029$, $BF_{01} = 62.695$. The three-way interaction between Limb, Groove, and Musical Experience, however, was significant, $F(1,16) = 4.601$, $p = .018$, partial $\eta^2 = 0.223$, but post-hoc tests with Bonferroni correction did not show any significant comparisons ($p$-values $> .05$) and Bayesian analysis indicated extremely strong evidence for the exclusion of the three-way interaction ($BF_{01} > 100$).

ANOVAs conducted on high-groove and low-groove CMC data selected based on each participant's subjective ratings (i.e., groove, loudness, familiarity, effort, enjoyment, and PC1) also did not reveal any significant effects of Groove ($p$-values $> .05$ and $BF_{01} > 3$).

### *3.3. EMG*

A 2 × 3 × 2 mixed model ANOVA, with the within-subject factors Limb (hand and foot) and Groove (high-groove, low-groove, and control) and the between-subject factor Musical Experience (high and low), indicated a significant main effect of Limb on the mean beta EMG power, $F(1,16) = 5.201$, $p = .037$, partial $\eta^2 = 0.245$, $BF_{10} > 100$, and broadband EMG, $F(1,16) = 13.227$, $p = .002$, partial $\eta^2 = 0.453$, $BF_{10} > 100$. No effect of Groove was found on the mean beta EMG power, $F(2,32) = 1.794$, $p = .183$, partial $\eta^2 = 0.101$, $BF_{01} = 24.597$, and broadband EMG, $F(1.441,23.049) = 0.292$, $p = .677$, partial $\eta^2 = 0.018$, $BF_{01} = 9.439$. The average broadband EMG and beta EMG power for each excerpt can be found in Fig. 7. No effect of Musical Experience was found on mean beta EMG power, $F(1,16) = 0.006$, $p = .937$ partial $\eta^2 < 0.001$, $BF_{01} = 4.876$, and broadband EMG, $F(1,16) = 0.508$, $p = .486$, partial $\eta^2 = 0.031$, $BF_{01} = 9.429$. No interaction between Limb and Groove was observed either for mean beta EMG power, $F(2,32) = 0.574$, $p = .569$, partial $\eta^2 = 0.035$, $BF_{01} = 32.981$, and the broadband EMG, $F(1.335,21.367) = 0.302$, $p = .654$, partial $\eta^2 = 0.019$, $BF_{01} = 6.178$ (see Fig. 8C and D). No interactions with Musical Experience were observed ($p$-values $> .05$).

ANOVAs conducted on high-groove and low-groove EMG data selected based on each participant's subjective ratings (i.e., groove, loudness, familiarity, effort, enjoyment, and PC1) also did not show any significant effects of Groove on broadband EMG or mean beta EMG power ($p$-values $> .05$ and $BF_{01} > 3$).

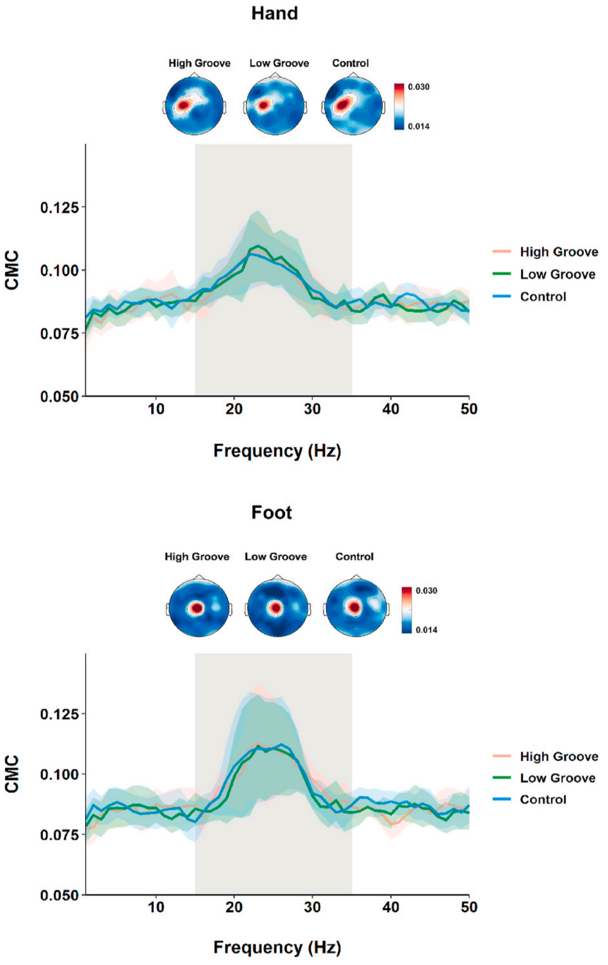


**Fig. 6.** Coherence spectra for the hand (top) and foot (bottom). Coloured lines represent the coherence values for the different experimental conditions averaged across participants with the corresponding 95% confidence intervals. Grey shaded areas represent the selected beta range (15–35 Hz) with the corresponding topographical map for each groove condition.

### 3.4. *EEG*

Similar to the EMG beta power, a 2 × 3 × 2 mixed model ANOVA on the mean beta EEG power, with the within-subject factors Limb (hand and foot) and Groove (high-groove, low-groove, and control), and the between-subject factor Musical experience (high and low) indicated a significant main effect of Limb, $F(1,16) = 14.535$, $p = .002$, partial $\eta^2 = 0.476$, $BF_{10} > 100$. No effect of Groove on mean beta EEG power was found, $F(2,32) = 0.191$, $p = .827$ partial $\eta^2 = 0.012$, supported by strong evidence in favour of the null-hypothesis, $BF_{01} = 24.075$. The average beta EEG power for each excerpt can be found in Fig. 7. No effect of Musical Experience on mean beta EEG power was found, $F(1,16) = 0.183$, $p = .183$ partial $\eta^2 = 0.108$, $BF_{10} = 4.285$. No interaction between Groove and Limb was observed either, $F(2,32) = 0.545$, $p = .585$, partial $\eta^2 = 0.033$, $BF_{01} = 28.980$ (see Fig. 8B). No significant interactions with Musical Experience were observed ($p$-values > .05).

Although ANOVAs conducted on high-groove and low-groove EEG data selected based on each participant's subjective ratings (i.e., groove, loudness, familiarity, effort, enjoyment, and PC1) did show significant main effects of Groove on mean beta EEG power for the subjective excerpt selection based on groove ($p = .014$), familiarity ($p = .011$), and enjoyment ($p = .006$) ratings, all of them yielded evidence in favour of the null-hypothesis ($p$ ($BF_{01} > 3$).

### 3.5. *Correlations between subjective ratings and physiological measures*

To explore the relation between subjective ratings and physiological measures across participants, Pearson correlations were calculated to address whether participants who perceived higher levels of Groove also had higher CMC. Out of the 60 correlations only three were significant, as depicted in Fig. 9. CMC for the hand was negatively correlated with the effort to sit still, $\rho(17) = -\ 0.564$, $p = .009$, but CMC for the foot was not, $\rho(17) = -\ 0.372$, $p = .116$. Additionally, a significant negative correlation between EMG beta power and familiarity was observed for the foot, $\rho\ (17) = 0.520$, $p = .024$, but not for the hand, $\rho(17) = 0.070$, $p = .702$. In addition to the lack of consistency of these significant effects across effectors, it can be noted that none of these correlations remains significant when corrected for multiple comparisons using Bonferroni correction, which brings the significance threshold to 0.0008.

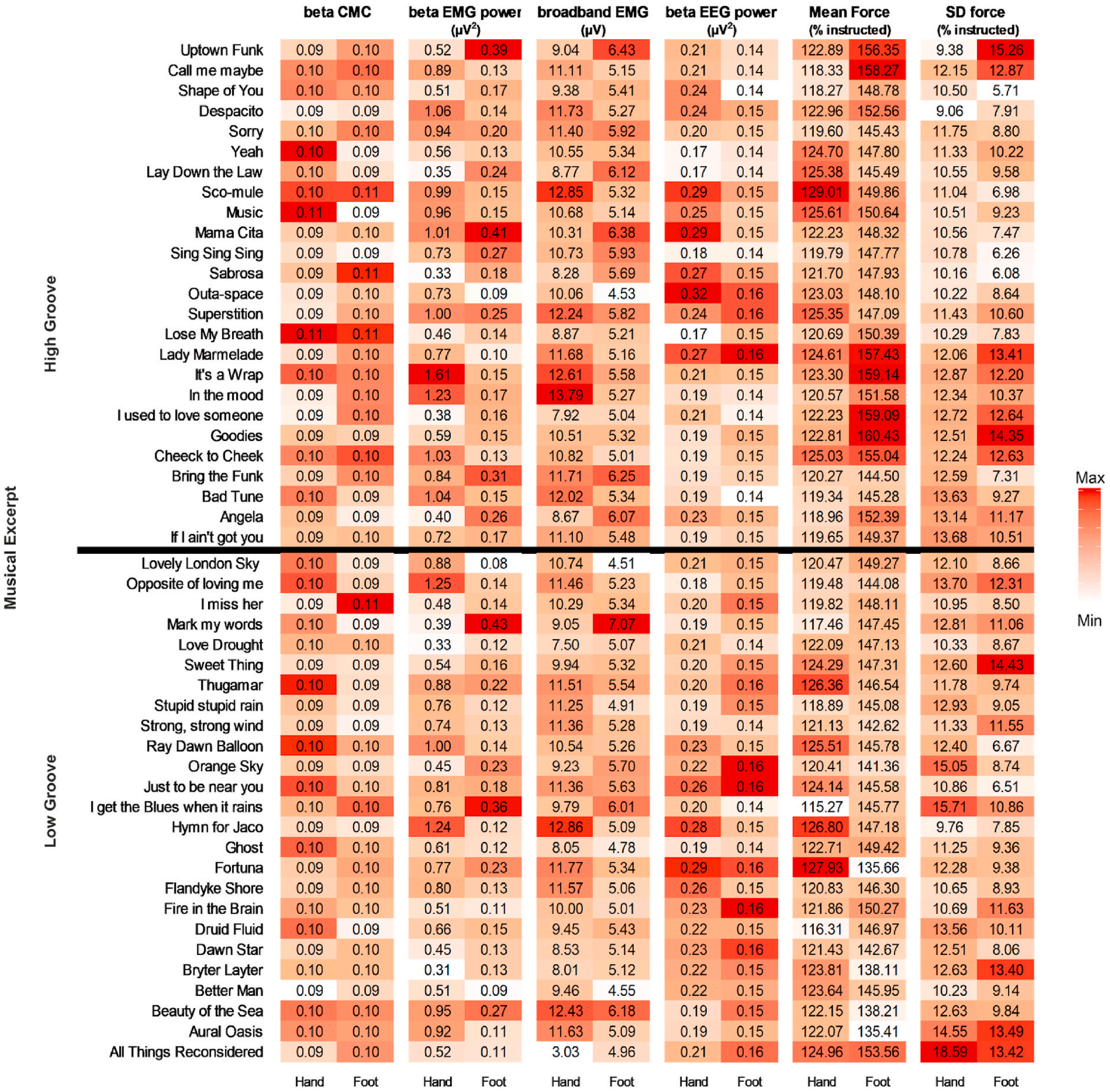
Additionally, Pearson correlations were calculated between excerpts to address whether excerpts that scored higher on subjective Groove ratings were associated with higher CMC. Out of the 60 correlations, eight were significant, but no consistency across the hand and foot was found. Furthermore, none of these correlations remained significant when corrected for multiple comparisons (which brings the significance threshold to 0.0008). Groove, familiarity, effort to sit still, and PC1 were all negatively correlated with the EEG beta power of the foot, $\rho(49) = -\ 0.319$, $p = .024$, $\rho(49) = -\ 0.304$, $p = .031$, $\rho(49) = -\ 0.340$, $p = .016$, $\rho(49) = -\ 0.360$, $p = .010$, respectively, but not with EEG beta power of the hand, $\rho(49) = -\ 0.136$, $p = .347$, $\rho(49) = -\ 0.209$, $p = .145$, $\rho(49) = -0.227$, $p = .113$, $\rho(49) = -0.167$, $p = .246$, respectively (see Fig. 10). Additionally, familiarity and effort to sit still were positively correlated with broadband EMG of the foot, $\rho(49) = 0.280$, $p = .048$, $\rho(49) = 0.324$, $p = .022$, respectively, but not for the hand, $\rho(49) = -0.031$, $p = .829$, $\rho(49) = 0.140$, $p = .332$, respectively. Finally, the subjective ratings of groove, effort to sit still and PC1 were significantly correlated with the Mean Force of the hand, $\rho(49) = 0.373$, $p = .008$, $\rho(49) = 0.355$, $p = .011$, and $\rho(49) = 0.310$, $p = .029$, respectively, but not with the Mean Force of the foot, $\rho(49) = -0.078$, $p = .592$, $\rho(49) = -0.045$, $p = .754$, and $\rho(49) = -0.046$, $p = .751$, respectively.

## 4. Discussion

The current study aimed to better understand the effects of music on the motor system by examining the strength of CMC between EEG and EMG recordings from the upper and lower limbs of participants listening to either no music, low-groove music, or high-groove music. It was hypothesised that listening to high-groove music would result in stronger CMC than listening to low-groove music and no music due to increased engagement of the motor system through predictive timing mechanisms and/or effort to sit still with high-groove music. Although different levels of groove were successfully induced while instructed to maintain an isometric contraction, no effect of groove was found on participants' CMC and capacity to maintain a steady force for both upper and lower limbs irrespective of participants' musical expertise.

The results show that the presented sounds successfully modulated the experience of groove but this occurs without actual changes in force and cortico-muscular coupling.

The five newly added high-groove excerpts also successfully led to higher experience of groove with even greater magnitude than the previous excerpts from Janata et al. (2012). This is likely due to their familiarity for our relatively young participant sample, as this is a well-established relationship (Janata et al., 2012; Leow et al., 2015; Senn et al., 2018, 2019). These new highly groovy excerpts would therefore make a useful contribution in future studies of groove. Musical excerpts that yield high-groove ratings have been previously associated with better movement entrainment and more spontaneous movement (Janata et al., 2012). However, high-groove excerpts in the current study did not invoke changes in the mean and variability of participants' force. Thus, regardless of different levels of 'wanting to move', people were



| | beta CMC | | beta EMG power (μV²) | | broadband EMG (μV) | | beta EEG power (μV²) | | Mean Force (% instructed) | | SD force (% instructed) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hand | Foot | Hand | Foot | Hand | Foot | Hand | Foot | Hand | Foot | Hand | Foot |
| Uptown Funk | 0.09 | 0.10 | 0.52 | 0.39 | 9.04 | 6.43 | 0.21 | 0.14 | 122.89 | 156.35 | 9.38 | 15.26 |
| Call me maybe | 0.10 | 0.10 | 0.89 | 0.13 | 11.11 | 5.15 | 0.21 | 0.14 | 118.33 | 158.27 | 12.15 | 12.87 |
| Shape of You | 0.10 | 0.10 | 0.51 | 0.17 | 9.38 | 5.41 | 0.24 | 0.14 | 118.27 | 148.78 | 10.50 | 5.71 |
| Despacito | 0.09 | 0.09 | 1.06 | 0.14 | 11.73 | 5.27 | 0.24 | 0.15 | 122.96 | 152.56 | 9.06 | 7.91 |
| Sorry | 0.10 | 0.10 | 0.94 | 0.20 | 11.40 | 5.92 | 0.20 | 0.15 | 119.60 | 145.43 | 11.75 | 8.80 |
| Yeah | 0.10 | 0.09 | 0.56 | 0.13 | 10.55 | 5.34 | 0.17 | 0.14 | 124.70 | 147.80 | 11.33 | 10.22 |
| Lay Down the Law | 0.10 | 0.09 | 0.35 | 0.24 | 8.77 | 6.12 | 0.17 | 0.14 | 125.38 | 145.49 | 10.55 | 9.58 |
| Sco-mule | 0.10 | 0.11 | 0.99 | 0.15 | 12.85 | 5.32 | 0.29 | 0.15 | 129.01 | 149.86 | 11.04 | 6.98 |
| Music | 0.11 | 0.09 | 0.96 | 0.15 | 10.68 | 5.14 | 0.25 | 0.15 | 125.61 | 150.64 | 10.51 | 9.23 |
| Mama Cita | 0.09 | 0.10 | 1.01 | 0.41 | 10.31 | 6.38 | 0.29 | 0.15 | 122.23 | 148.32 | 10.56 | 7.47 |
| Sing Sing Sing | 0.09 | 0.09 | 0.73 | 0.27 | 10.73 | 5.93 | 0.18 | 0.14 | 119.79 | 147.77 | 10.78 | 6.26 |
| Sabrosa | 0.09 | 0.11 | 0.33 | 0.18 | 8.28 | 5.69 | 0.27 | 0.15 | 121.70 | 147.93 | 10.16 | 6.08 |
| Outa-space | 0.09 | 0.10 | 0.73 | 0.09 | 10.06 | 4.53 | 0.32 | 0.16 | 123.03 | 148.10 | 10.22 | 8.64 |
| Superstition | 0.09 | 0.10 | 1.00 | 0.25 | 12.24 | 5.82 | 0.24 | 0.16 | 125.35 | 147.09 | 11.43 | 10.60 |
| Lose My Breath | 0.11 | 0.11 | 0.46 | 0.14 | 8.87 | 5.21 | 0.17 | 0.15 | 120.69 | 150.39 | 10.29 | 7.83 |
| Lady Marmelade | 0.09 | 0.10 | 0.77 | 0.10 | 11.68 | 5.16 | 0.27 | 0.16 | 124.61 | 157.43 | 12.06 | 13.41 |
| It's a Wrap | 0.10 | 0.10 | 1.61 | 0.15 | 12.61 | 5.58 | 0.21 | 0.15 | 123.30 | 159.14 | 12.87 | 12.20 |
| In the mood | 0.09 | 0.10 | 1.23 | 0.17 | 13.79 | 5.27 | 0.19 | 0.14 | 120.57 | 151.58 | 12.34 | 10.37 |
| I used to love someone | 0.09 | 0.10 | 0.38 | 0.16 | 7.92 | 5.04 | 0.21 | 0.14 | 122.23 | 159.09 | 12.72 | 12.64 |
| Goodies | 0.09 | 0.09 | 0.59 | 0.15 | 10.51 | 5.32 | 0.19 | 0.15 | 122.81 | 160.43 | 12.51 | 14.35 |
| Cheeck to Cheek | 0.10 | 0.10 | 1.03 | 0.13 | 10.82 | 5.01 | 0.19 | 0.15 | 125.03 | 155.04 | 12.24 | 12.63 |
| Bring the Funk | 0.09 | 0.10 | 0.84 | 0.31 | 11.71 | 6.25 | 0.19 | 0.15 | 120.27 | 144.50 | 12.59 | 7.31 |
| Bad Tune | 0.10 | 0.09 | 1.04 | 0.15 | 12.02 | 5.34 | 0.19 | 0.14 | 119.34 | 145.28 | 13.63 | 9.27 |
| Angela | 0.09 | 0.09 | 0.40 | 0.26 | 8.67 | 6.07 | 0.23 | 0.15 | 118.96 | 152.39 | 13.14 | 11.17 |
| If I ain't got you | 0.09 | 0.10 | 0.72 | 0.17 | 11.10 | 5.48 | 0.19 | 0.15 | 119.65 | 149.37 | 13.68 | 10.51 |
| Lovely London Sky | 0.10 | 0.09 | 0.88 | 0.08 | 10.74 | 4.51 | 0.21 | 0.15 | 120.47 | 149.27 | 12.10 | 8.66 |
| Opposite of loving me | 0.10 | 0.09 | 1.25 | 0.14 | 11.46 | 5.23 | 0.18 | 0.15 | 119.48 | 144.08 | 13.70 | 12.31 |
| I miss her | 0.09 | 0.11 | 0.48 | 0.14 | 10.29 | 5.34 | 0.20 | 0.15 | 119.82 | 148.11 | 10.95 | 8.50 |
| Mark my words | 0.10 | 0.09 | 0.39 | 0.43 | 9.05 | 7.07 | 0.19 | 0.15 | 117.46 | 147.45 | 12.81 | 11.06 |
| Love Drought | 0.10 | 0.10 | 0.33 | 0.12 | 7.50 | 5.07 | 0.21 | 0.14 | 122.09 | 147.13 | 10.33 | 8.67 |
| Sweet Thing | 0.09 | 0.09 | 0.54 | 0.16 | 9.94 | 5.32 | 0.20 | 0.15 | 124.29 | 147.31 | 12.60 | 14.43 |
| Thugamar | 0.10 | 0.09 | 0.88 | 0.22 | 11.51 | 5.54 | 0.20 | 0.16 | 126.36 | 146.54 | 11.78 | 9.74 |
| Stupid stupid rain | 0.09 | 0.09 | 0.76 | 0.12 | 11.25 | 4.91 | 0.19 | 0.15 | 118.89 | 145.08 | 12.93 | 9.05 |
| Strong, strong wind | 0.09 | 0.09 | 0.74 | 0.13 | 11.36 | 5.28 | 0.19 | 0.14 | 121.13 | 142.62 | 11.33 | 11.55 |
| Ray Dawn Balloon | 0.10 | 0.10 | 1.00 | 0.14 | 10.54 | 5.26 | 0.23 | 0.15 | 125.51 | 145.78 | 12.40 | 6.67 |
| Orange Sky | 0.09 | 0.09 | 0.45 | 0.23 | 9.23 | 5.70 | 0.22 | 0.16 | 120.41 | 141.36 | 15.05 | 8.74 |
| Just to be near you | 0.10 | 0.10 | 0.81 | 0.18 | 11.36 | 5.63 | 0.26 | 0.16 | 124.14 | 145.58 | 10.86 | 6.51 |
| I get the Blues when it rains | 0.10 | 0.10 | 0.76 | 0.36 | 9.79 | 6.01 | 0.20 | 0.14 | 115.27 | 145.77 | 15.71 | 10.86 |
| Hymn for Jaco | 0.09 | 0.09 | 1.24 | 0.12 | 12.86 | 5.09 | 0.28 | 0.15 | 126.80 | 147.18 | 9.76 | 7.85 |
| Ghost | 0.10 | 0.10 | 0.61 | 0.12 | 8.05 | 4.78 | 0.19 | 0.14 | 122.71 | 149.42 | 11.25 | 9.36 |
| Fortuna | 0.09 | 0.10 | 0.77 | 0.23 | 11.77 | 5.34 | 0.29 | 0.16 | 127.93 | 135.66 | 12.28 | 9.38 |
| Flandyke Shore | 0.09 | 0.10 | 0.80 | 0.13 | 11.57 | 5.06 | 0.26 | 0.15 | 120.83 | 146.30 | 10.65 | 8.93 |
| Fire in the Brain | 0.10 | 0.10 | 0.51 | 0.11 | 10.00 | 5.01 | 0.23 | 0.16 | 121.86 | 150.27 | 10.69 | 11.63 |
| Druid Fluid | 0.10 | 0.09 | 0.66 | 0.15 | 9.45 | 5.43 | 0.22 | 0.15 | 116.31 | 146.97 | 13.56 | 10.11 |
| Dawn Star | 0.09 | 0.10 | 0.45 | 0.13 | 8.53 | 5.14 | 0.23 | 0.16 | 121.43 | 142.67 | 12.51 | 8.06 |
| Bryter Layter | 0.10 | 0.10 | 0.31 | 0.13 | 8.01 | 5.12 | 0.22 | 0.15 | 123.81 | 138.11 | 12.63 | 13.40 |
| Better Man | 0.09 | 0.09 | 0.51 | 0.09 | 9.46 | 4.55 | 0.22 | 0.15 | 123.64 | 145.95 | 10.23 | 9.14 |
| Beauty of the Sea | 0.10 | 0.10 | 0.95 | 0.27 | 12.43 | 6.18 | 0.19 | 0.15 | 122.15 | 138.21 | 12.63 | 9.84 |
| Aural Oasis | 0.10 | 0.10 | 0.92 | 0.11 | 11.63 | 5.09 | 0.19 | 0.15 | 122.07 | 135.41 | 14.55 | 13.49 |
| All Things Reconsidered | 0.09 | 0.10 | 0.52 | 0.11 | 3.03 | 4.96 | 0.21 | 0.16 | 124.96 | 153.56 | 18.59 | 13.42 |

**Fig. 7.** Physiological measures for high-groove excerpts (above the line) and low-groove excerpts (below the line). The cell colour is scaled to the values of the dependent variable, ranging from minimum to maximum for each column. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

rather successful at suppressing spontaneous behavioural motor responses when asked to. Hence, these results support theories of groove induction through active listening that propose that moving to the rhythm is not a necessary component of experiencing different levels of groove (Levitin et al., 2017; Madison, 2006; Madison et al., 2011; Witek et al., 2014).

The lack of an effect of groove on CMC could be related to the general lack of modulation in participants' force in response to the groove conditions. CMC has been shown to vary during dynamic movement or changes in exerted force (Kilner et al., 2000; Petersen et al., 2012; Reyes et al., 2017; Ushiyama et al., 2017; Yoshida et al., 2017a). CMC correlates with force levels and fluctuations (Conway et al., 1995; Baker et al., 1997; Kilner et al., 1999, 2000, 2003; Baker, 2007; Kristeva et al., 2007; Ushiyama et al., 2017; Witte et al., 2007). Specifically, CMC increases when force levels and/or fluctuation increases. In addition, Stupacher et al. (2013) also argued that Motor Evoked Potentials elicited by TMS could be lower for high groove stimuli than low groove stimuli in non-musicians due to the effort that they invested in suppressing movement. Although we did not find an effect of musical experience, participants in our study's high Musical Experience group still had significantly less experience than the musicians in the study by Stupacher et al. (2013) and the current task constraints may have annulled the effect of musical experience. Therefore, the successful suppression of force modulations in the current study, despite different levels of experienced groove, might have led to the current null-effects on CMC.

However, with the successful induction of groove, even without spontaneous modulation in participants' force, it remains possible that CMC could have been increased with high-groove music for two main reasons. The first is the increased effort to maintain a stable force output whilst 'wanting to move'. Several studies support the hypothesis that the effort required to maintain stable motor output correlates with CMC magnitude (Divekar and John, 2013; Safri et al., 2006), suggesting top-down regulation of CMC. Divekar and John (2013) proposed that CMC is not directly dependent on the precision of the motor output, but rather on the (perceived) task difficulty and the required effort to perform the task. In addition, cognitive factors such as attention to the

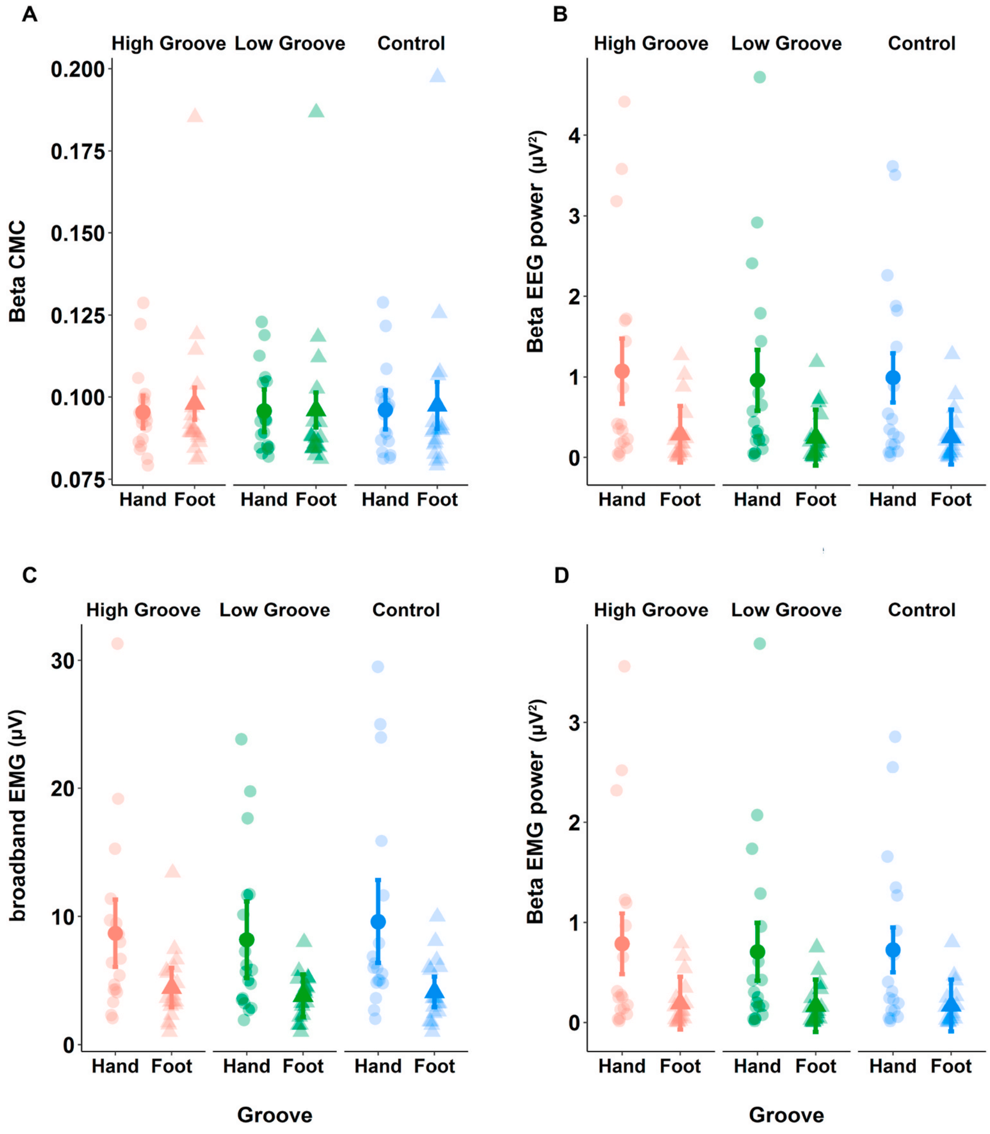
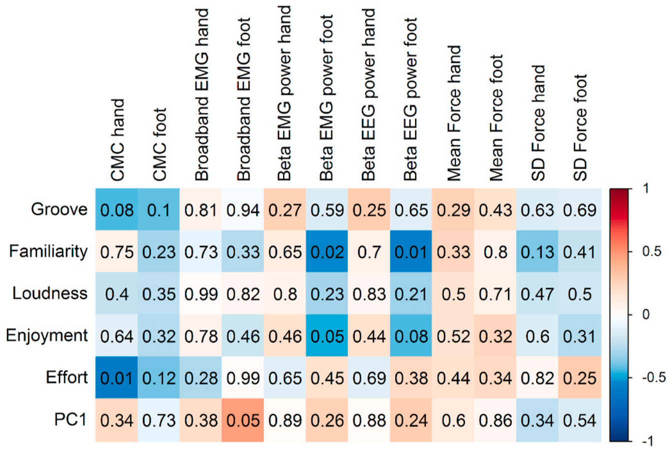


**Fig. 8.** Mean beta (15–35 Hz) CMC (A), Mean beta (15–35 Hz) EEG power (B), Mean broadband EMG (C), and Mean beta (15–35 Hz) EMG power (D) as a function of the limb and experimental conditions. Error bars represent 95% confidence intervals (CI). Individual data points are shaded.

task have been shown to affect CMC magnitude (Kristeva-feige et al., 2002; Safri et al., 2006, 2007). Here we found no differences in the mean and variability of participants' force but it remains possible that maintaining a stable force with high-groove excerpts was more difficult, as indicated by the increased subjective urge to move and effort to sit still. Therefore, according to the top-down view of CMC being driven by subjective task difficulty, CMC could have increased for the high-groove excerpts compared to low-groove and silence. Yet we did not find such results; no difference in CMC was found between conditions, even though participants did report they found it more difficult to sit still during the high-groove excerpts. These results do not support strong top-down influence on CMC mediated by task difficulty or effort.

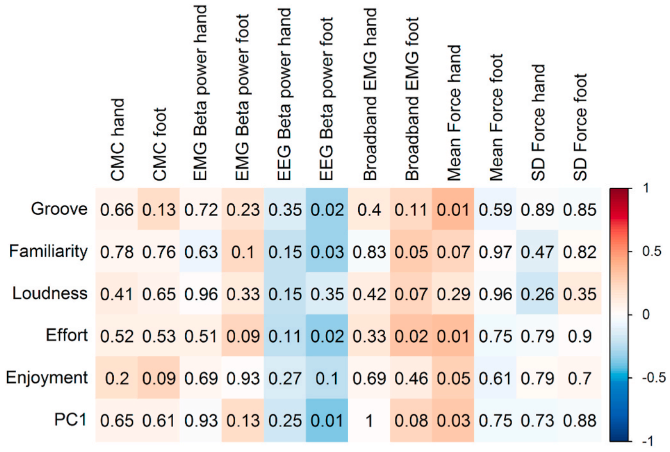
The second reason CMC was expected to increase with groove is the involvement of the motor system in predictive timing processes, which has been suggested to be stronger with high-groove music. Again, no effect of groove on CMC was found, including in participants with musical expertise despite them being known to have stronger temporal prediction and being better at time-keeping (e.g., Doelling and Poeppel, 2015; Repp, 2005). In the current study, however, subjective groove was induced without following any rhythmic instructions or allowing movement. Thus, the used task did not require the same degree of active temporal prediction as would be needed to move in time with music. The lack of difference in both EEG and CMC over motor areas in response to different levels of groove and silence, suggests that motor engagement or attention was not modulated by music listening, which might have contributed to the null-effects on CMC. The current control for vigilance was based on the lyrics to prevent artificial rhythmic interference if a specific counting or rhythmic task was given. Perhaps, participants' attention could have been drawn more to temporal structures of the music in a way that would require more active temporal prediction, i.e., a more active listening experience. This could have increased the covert predictive activity in the motor system, as observed by Matthews et al. (2020), leading in turn to amplitude modulations in beta EEG and increased CMC.

Alternatively, there might have been (enough) predictive motor engagement in the current design to affect cortico-muscular pathways, as indicated by the differences in subjective feelings of groove and effort to sit still. Instead, cortico-muscular responses could have been dynamic, rather than a static increase in CMC baseline. Dynamic modulations of CMC aligned with the beat, increased on the beat and decreased off the beat, for example, was not captured in this study. Dynamic cortico-muscular responses to audio-visual rhythms have previously been



| | CMC hand | CMC foot | Broadband EMG hand | Broadband EMG foot | Beta EMG power hand | Beta EMG power foot | Beta EEG power hand | Beta EEG power foot | Mean Force hand | Mean Force foot | SD Force hand | SD Force foot |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groove | 0.08 | 0.1 | 0.81 | 0.94 | 0.27 | 0.59 | 0.25 | 0.65 | 0.29 | 0.43 | 0.63 | 0.69 |
| Familiarity | 0.75 | 0.23 | 0.73 | 0.33 | 0.65 | 0.02 | 0.7 | 0.01 | 0.33 | 0.8 | 0.13 | 0.41 |
| Loudness | 0.4 | 0.35 | 0.99 | 0.82 | 0.8 | 0.23 | 0.83 | 0.21 | 0.5 | 0.71 | 0.47 | 0.5 |
| Enjoyment | 0.64 | 0.32 | 0.78 | 0.46 | 0.46 | 0.05 | 0.44 | 0.08 | 0.52 | 0.32 | 0.6 | 0.31 |
| Effort | 0.01 | 0.12 | 0.28 | 0.99 | 0.65 | 0.45 | 0.69 | 0.38 | 0.44 | 0.34 | 0.82 | 0.25 |
| PC1 | 0.34 | 0.73 | 0.38 | 0.05 | 0.89 | 0.26 | 0.88 | 0.24 | 0.6 | 0.86 | 0.34 | 0.54 |

**Fig. 9.** Correlation matrix between subjective ratings and physiological responses across participants. The colour scale represents the correlation coefficient ($\rho$), whereas the numbers represent $p$-values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



| | CMC hand | CMC foot | EMG Beta power hand | EMG Beta power foot | EEG Beta power hand | EEG Beta power foot | Broadband EMG hand | Broadband EMG foot | Mean Force hand | Mean Force foot | SD Force hand | SD Force foot |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groove | 0.66 | 0.13 | 0.72 | 0.23 | 0.35 | 0.02 | 0.4 | 0.11 | 0.01 | 0.59 | 0.89 | 0.85 |
| Familiarity | 0.78 | 0.76 | 0.63 | 0.1 | 0.15 | 0.03 | 0.83 | 0.05 | 0.07 | 0.97 | 0.47 | 0.82 |
| Loudness | 0.41 | 0.65 | 0.96 | 0.33 | 0.15 | 0.35 | 0.42 | 0.07 | 0.29 | 0.96 | 0.26 | 0.35 |
| Effort | 0.52 | 0.53 | 0.51 | 0.09 | 0.11 | 0.02 | 0.33 | 0.02 | 0.01 | 0.75 | 0.79 | 0.9 |
| Enjoyment | 0.2 | 0.09 | 0.69 | 0.93 | 0.27 | 0.1 | 0.69 | 0.46 | 0.05 | 0.61 | 0.79 | 0.7 |
| PC1 | 0.65 | 0.61 | 0.93 | 0.13 | 0.25 | 0.01 | 1 | 0.08 | 0.03 | 0.75 | 0.73 | 0.88 |

**Fig. 10.** Correlation matrix between subjective ratings and physiological responses across excerpts. The colour scale represents the correlation coefficient ($\rho$), whereas the numbers represent $p$-values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reported (Varlet et al., 2020), but examining CMC dynamically comes with some practical limitations. In order to calculate CMC reliably, a large number of time windows is required (Bastos and Schoffelen, 2016; Carter et al., 1973). Since the excerpts were pieces of music with variations in tempo, loudness and pitch, windows cannot be stacked within a single trial or excerpt and would require the excerpts to be played many times to generate multiple windows at each time-point. It was therefore not possible to capture CMC dynamic modulations with the current design. Future studies should consider testing rhythmic musical stimuli with a controlled period to explore CMC dynamics.

Although neither hand nor foot was affected by musical groove, some differences between the two limbs can be noted. The mean exerted force, expressed as the percentage of the target force, was significantly higher for the foot than the hand. This suggests that fine motor control at lower intensity with the foot might have been more challenging compared to the hand (Volz et al., 2015). Lower EMG and EEG activity for the foot compared to the hand was also observed, leaving unclear whether larger force was actually applied with the foot compared to the hand, although a wide range of factors, such as the absolute maximum recorded force, might have influenced these measures. Interestingly, these differences in force, EMG, and EEG amplitude did not transfer to beta CMC magnitude, which further supports that CMC is sensitive to the synchrony between EEG and EMG signals rather than their amplitude, as underscored by the permutation analyses. More generally, further investigation of CMC at the level of the hand and the foot will be needed in future research to better understand whether musical groove affects the coupling between the brain and muscles across the different body parts.

Particularly important for future research would be to further investigate the role of movement in the experience of groove and the modulation of the cortico-muscular coupling. Indeed, even if the experience of groove was successfully induced while participants maintained an isometric contraction, it remains possible that stronger effects of groove, including significant effects on CMC, might have occurred if participants were allowed to move with the music (Manning and Schutz, 2013). There are conflicting theories about the role of movement in the experience of groove, but some consider that moving in time with the music is an essential component of the groove experience (e.g., Roholt, 2014), and therefore, suggest that a steady isometric contraction might have limited groove induction and contributed to the current null-effect. However, investigating the effects of groove on CMC while moving in time with music will result in methodological challenges that future research will need to address. CMC is largely modulated when moving, which might involve bottom-up processes that differ from, and even mask, top-down control processes that were targeted in the current study (Nijhuis et al., 2021; Petersen et al., 2012; Yoshida et al., 2017a, 2017b).

Furthermore, the current motor task might also have worked against finding effects of groove due to constraints on motor-cortical activity in the beta-band resulting from isometric contraction (Engel and Fries, 2010; Khanna and Carmena et al., 2015; Kilner et al., 1999). Indeed, the isometric contraction might have favoured static motor-cortical activity in the beta-band and prevented or masked the effects of music and groove (Brown, 2000; Engel and Fries, 2010). Such constraints imposed by the current motor task need to be investigated in future research as it might explain in part these null findings. This constraint was not present in the TMS study of Stupacher et al. (2013), for instance, in which participants remained relaxed without performing any motor task. However, because there is at least some level of muscular activity required to collect meaningful EMG and measure CMC, testing lower intensity isometric contractions might be a promising avenue for future research. Force targets lower than the 7% of participant's maximal voluntary contraction used in the current study might help reduce the constraints on beta-band cortical activity, and thus, strengthening the effects of music and groove on the brain and its coupling with body muscles. Such experiments with further manipulations of the motor tasks, including more dynamic motor tasks as mentioned above, are critical to confirm that these null findings are not restricted to the current isometric contraction settings.

In sum, this study found no evidence for an effect of music listening, high-groove music in particular, on cortico-muscular coupling and participants' capacity to maintain a steady force despite an increase in participants' urge to move and difficulty to stay still. These results do not support a top-down influence of groove on cortico-muscular coupling, although it remains possible that such influence might have occurred in the form of dynamic modulations and/or with more active listening. Therefore, these results encourage further research to better understand the effects of groove on the motor system at central but also peripheral level and the exact function of cortico-muscular coherence.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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