Move Your Body! Low-frequency Amplitude and Syncopation Increase Groove Perception in House Music

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Studies demonstrate that low frequencies and syncopation can enhance groove—the pleasurable urge to move to music. This study examined the simultaneous effect of low-frequency amplitude and syncopation on groove by manipulating basslines in house music, a subgenre of electronic dance music (EDM). One hundred and seventy-nine participants listened to 20 novel house music clips in which basslines were manipulated across two levels of low-frequency amplitude and syncopation. Music and dance-related experience, as well as genre preferences, were also assessed. Groove perception was most pronounced for house tracks combining high low-frequency amplitude (LFA) and high syncopation, and least pronounced for tracks with low LFA, irrespective of syncopation. Exploratory correlation analysis revealed that groove perception is influenced by listeners' preferences for energetic and rhythmic music styles, their urge to dance, and their propensity to experience an emotional connection to music. Our findings reveal that the urge to move when listening to music is shaped by the interplay of rhythmic complexity and sonic texture, and is influenced by dance and music experiences and preferences.

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Movement is a necessary component of creating and performing music (Clynes, 1986; Clynes & Nettheim, 1982; Jensenius & Wanderley, 2010; Keller & Rieger, 2009; Palmer, 2013; Repp, 1993; Todd, 1995; Zatorre et al., 2007). Yet, merely listening to music can also evoke the pleasurable urge to move (Farnell, 1999; Hodges, 2009; Levitin et al., 2018). Across cultures, music and dance are strongly related (Blacking, 1995; Kaeppler, 2000; Nettl, 2000; Savage et al., 2015; Trehub et al., 2015). Music can elicit movement before birth (López-Teijón et al., 2015) and, with sufficient exposure, can continue to do so throughout infancy and adulthood (Hargreaves & Lamont, 2017; Lamont, 2016; Parncutt, 2006, 2016; Trehub, 2016).

Moving to music involves the entrainment of neural oscillations to musical rhythm (Calderone et al., 2014; Chang et al., 2016; Fujioka et al., 2012; Trost et al., 2017; Trost & Vuilleumier, 2013). In groups listening to music, spontaneous movement takes many forms, including head-nodding (Swarbrick et al., 2018) and finger or foot tapping (Levitin et al., 2018; Zeiner-Henriksen, n.d.). Sensorimotor synchronization to auditory rhythms also occurs when people walk (Moumdjian et al., 2018; Styns et al., 2007) and during collaborative performance (Rasch, 2001) or exercise (Hallett & Lamont, 2017). Exercising to music can even increase stamina (Barney et al., 2012; Bigliassi et al., 2017; Karageorghis et al., 2012; Rendi et al., 2008)—particularly when the movements are intentionally synchronized to the music's pulse (Bacon et al., 2012; Bood et al., 2013) or when the music is familiar (Nakamura et al., 2010; Silva et al., 2021).

Overall, the relationship between music and movement is mediated by the synchronization of auditory and motor processing in the brain (Heckner et al., 2021; Kornysheva et al., 2010; Li et al., 2023; Lima et al., 2016; Nelson et al., 2013; Schneider & Mooney, 2015). This interplay is foundational to the phenomenon known as "groove," where music induces a pleasurable sensation that compels a listener to not only move, but also align their movements with the rhythm.

Groove

Groove (Janata et al., 2012; Madison, 2001; Senn et al., 2020; Witek, 2009) and music rated as groovy can engage reward networks (Matthews et al., 2020), evoke spontaneous body movement (Janata et al., 2012; Madison, 2001; Witek, 2009) and is modulated by rhythmic complexity, including syncopation (Madison & Sioros, 2014), harmonic complexity (Matthews et al., 2019), and beat salience (Madison et al., 2011). However, the findings of Senn et al. (2018) did not support

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a simple link between groove and beat saliency. Instead, the authors argue that this relationship is influenced by individual differences and music genre. They also noted that inconsistencies in existing groove research could stem from varying methodologies, musical repertoires, and participants' cultural backgrounds. For example, groove perception may be shaped by individual differences in dance experience (O'Connell et al., 2022).

Earlier studies claimed that microtiming deviations enhance groove (Alén, 1995; Keil, 1995; Monson, 2009; Prögler, 1995), whereas later research supported the contrary (Butterfield, 2010; Davies et al., 2013; Madison et al., 2011)—with only small micro-timing effects seen in participants categorized as musical experts (Kilchenmann & Senn, 2015). Additionally, music loudness does not appear to predict groove (Lenc et al., 2018; Stupacher et al., 2016). However, positive associations have been observed between groove and: 1) RMS energy (Tomic & Janata, 2008), 2) RMS variability (Stupacher et al., 2014), 3) spectral flux (Alluri & Toiviainen, 2010; Burger et al., 2012; Stupacher et al., 2013), and 4) low-frequency energy (Burger et al., 2013). Overall, studies have demonstrated that groove is attributable to specific rhythmic and frequency-based musical features, including syncopation and low-frequency amplitude (LFA).

SYNCOPATION

Early literature defined syncopation as "a violation of expectancy of rhythmical events over a perceived metre" (Longuet-Higgins & Lee, 1984). Alternatively, syncopation has been defined as the "absence of notes at strong metric locations and the presence of notes at weak metric locations" (Sadie & Tyrrell, 2000).

Syncopation has been shown to exhibit an inverted U-shape relationship with groove such that medium syncopation levels elicit the highest perceived groove scores. This relationship holds across different musical stimuli, for example, when listening to piano melodies (Sioros et al., 2014) or funk drum breaks (Witek et al., 2014). Using a variety of drum patterns from different musical styles, Senn et al. (2018) reported that syncopation-induced groove also depends on musical expertise, familiarity with the musical stimuli, and genre preferences.

Syncopation can be quantified as rhythmic complexity, (Gómez et al., 2007). Existing models of complexity include LHL (Longuet-Higgins & Lee, 1984), Keith's measure of syncopation (KTH: Keith, 1991), Pressing's Cognitive Complexity model (PRS: Jeffrey Pressing, 1999), Metric Complexity (TMC: Toussaint, 2002), Off-Beatness (TOB: Toussaint, 2005), Weighted Note-to-Beat Distance (WNBD: Gómez et al., 2005), SG (Sioros & Guedes, 2011), Syncopation Index (Witek et al., 2014), the Revised Syncopation Index (Hoesl & Senn, 2018), and Perceived Complexity (Senn et al. 2023). These models calculate complexity using algorithms based on one or more of the following metrics: 1) predefined weighting of strong/weak metric beats, 2) metric position of notes/rests, 3) metric position of neighbouring notes, 4) note length/velocity, and 5) perceived syncopation.

Research into the contextual influence of syncopation on groove suggests that its effects are modulated by musical harmony (Matthews et al., 2019) and that physiological and neural responses to groove are enhanced by rhythms with moderate complexity (Matthews et al., 2020). The predictive coding rhythmic incongruity (PCRI) model suggests that rhythmic discrepancies introduced by syncopation engage the brain's predictive mechanisms, evidenced by larger event-related potentials (Vuust et al., 2018). In line with previous studies, Vuust et al. (2018) found that moderate levels of syncopation offer an optimal challenge to these predictions, in turn enhancing positive affect.

In summary, current evidence supports the role of syncopation as a predictor of groove. However, its impact on groove may extend beyond simple rhythmic variation to involve interactions within a broader musical and perceptual context (Matthews et al., 2019). The present study focuses on the potential interaction between syncopation and low-frequency amplitude.

LOW-FREQUENCY AMPLITUDE (LFA)

Low-frequency amplitude (LFA) has also been linked to spontaneous movement. Stupacher et al. (2016) found that music incorporating lower frequency instruments resulted in higher reported groove, higher tapping velocities, and increased time-keeping accuracy. LFA has also been shown to enhance neural tracking of the musical beat (Hove et al., 2014; Lenc et al., 2018).

Van Dyck et al. (2013) observed that body movement increased as bass drum levels in dance music rose slowly. Furthermore, bass drum events positively correlated with the intensity and quantity of spontaneous movement. Similarly, Burger et al. (2013) observed a positive association between low-frequency flux and head movement speed when participants danced to popular music.

Low frequencies can be both heard and felt. Hove et al. (2020) found that bass frequencies within the 5–130 Hz range, presented via vibrotactile stimulation, led to increased body movement, forceful tapping, and higher ratings of groove and enjoyment compared to a control condition in which listeners only received auditory input. Similarly, Cameron et al. (2022) showed that low-frequency sounds within the 8–37 Hz range in a live concert setting, activated via very low frequency (VLF) speakers, increase audience dance movements, even when they cannot be perceived auditorily. These findings underline the role of bass in music as a catalyst for movement, leveraging both its audible and physical sensations to foster an embodied connection to rhythm and enhance musical engagement.

Interestingly, high bass levels have also been associated with an increased sense of power, a greater likelihood to take initiative, and heightened illusory control (Hsu et al., 2015). Furthermore, such levels correlate with elevated risk-taking behaviours and bolstered self-confidence (Brodsky et al., 2018), which Lovatt (2018) identifies as a key element in acting upon dance impulses.

These findings highlight the importance of a band's rhythm section—typically comprising low-frequency producing instruments—to convey groove and entice dancing (Hove et al., 2014; Sadie & Tyrrell, 2000). Moreover, a positive association between low-frequency amplitude and groove may explain the steady increase in popular music bass levels (Hove et al., 2019). Overall, evidence supports the idea that increased low-frequency amplitude enhances groove and movement-to-music synchronization.

To study how LFA and syncopation influence groove perception, we focus on house music, a subgenre of electronic dance music where LFA and syncopation typically feature as prominent characteristics (Hawkins, 2003; Papenburg & Schulze, 2016).

ELECTRONIC DANCE MUSIC (EDM)

Electronic dance music (EDM)—a music style encompassing several subgenres and typically created using drum machines, synthesisers, samplers, oscillators, and filters (Snoman, 2012)—is a compelling genre for studying groove perception. Electronic instruments can create a broader range of frequencies, greater spectral flux, and more dynamic sound shaping than acoustic instruments (Dayal & Ferrigno, 2012). Furthermore, electronic instruments can produce more precise rhythmic timing—a factor shown to enhance groove (Butterfield, 2010; Davies et al., 2013; Madison et al., 2011).

Interestingly, the development of the breakdown, buildup, and drop are notable musical features in EDM that shape listeners' expectations through a structured journey of tension and release (Solberg, 2014). The application of these sonic advancements and music devices in EDM has been shown to elicit energizing and uplifting experiences marked by increased skin conductance activity, bodily sensations of pleasure, and body movement (Solberg & Dibben, 2019; Solberg & Jensenius, 2017).

In a motion analysis groove study, Burger and Toiviainen (2020) observed that EDM generated significantly more body movement in young people (mean age 24 years, $SD = 3.3$) than jazz, funk, and Latin. When comparing audio filters applied to EDM basslines, Lustig and Tan (2020) found that participants rated low-pass and non-filtered basslines significantly higher (than high-pass and band-pass filters) for pleasure and groove. Interestingly, when incorporating EDM music clips covering a variety of subgenres, Wesolowski and Hofmann (2016) found that increased bass did not always correlate with increased groove. Specifically, higher groove-related ratings were reported for items featuring "non-isochronous" basslines compared to "isochronous" basslines.

In summary, evidence suggests that music with greater low-frequency amplitude and syncopation of basslines can enhance listener groove perception, which is defined as the urge to move. However, Wesolowski and Hofmann (2016) suggest an interplay between low frequencies and rhythm in EDM basslines, demonstrating that mere bass presence, especially when characterised by low rhythmic complexity, does not necessarily enhance groove.

In this study, we examine how the combination of LFA and syncopation influences groove perception by using carefully designed music clips in the style of the popular EDM genre house music (Ayres, 2014; Bidder, 1999). First, we predict groove perception will increase with higher LFA and more syncopation. Second, high LFA might heighten the perceptual salience of syncopation, thereby increasing its effect. Alternatively, syncopation and LFA might influence groove perception independently. Finally, we predict that perceived groove in house music will be influenced by individual differences, specifically by listeners' preference for EDM music styles (Lustig & Tan, 2020; Senn et al., 2018) and their prior experience with dance (Rose et al., 2020) and music (Müllensiefen et al., 2014a).

Method

PARTICIPANTS

Following approval from Goldsmiths University of London's ethics committee, we recruited participants via social media. All participants were entered into a prize draw for one of four £50 Amazon gift vouchers. In total, 179 people participated in the study, including 76 women, 98 men, two non-binary individuals, and three who did not disclose their gender. Ages ranged from 18 to 70 years ($M = 34.1$, $SD = 12.3$). Music ($M = 3.35$, $SD = 1.7$) and dance training scores ($M = 2.08$, $SD = 1.45$) were calculated from the Gold-MSI (Müllensiefen et al., 2014b) and Gold-DSI (Rose et al., 2020), respectively. Eight people reported minor hearing problems but were not excluded from the study.

DESIGN

This study used a fully-factorial, randomized 2 x 2 within-subject design in preparation for a repeated measures ANOVA. The two within-subject factors, *low-frequency amplitude (LFA)* and *syncopation*, were manipulated across two levels to create four experimental conditions: 1) *high LFA + high syncopation*, 2) *high LFA + low syncopation*, 3) *low LFA + high syncopation*, and 4) *low LFA + low syncopation*. Factor manipulations were solely applied to the basslines of custom-designed house music stimuli. The dependent variable—*urge to move*—was reported by participants via a 5-point Likert scale. Additionally, to explore the role of individual differences, we computed correlations between groove scores from the highest-rated experimental condition with musical preference (STOMP: Rentfrow & Gosling, 2003), music sophistication (Gold-MSI: Müllensiefen et al., 2014b), and dance sophistication (Gold-DSI: Rose et al., 2020).

POWER ANALYSIS

Power analysis was performed using G*Power Version 3.1.9.6. assuming statistical analysis using a 2 x 2 within-subject ANOVA. Partial eta squared was estimated at $\eta_p^2 = .01$ based on results from one bass-related (Stupacher et al., 2016) and one syncopation-related (Witek et al., 2014) groove study. A small effect size was calculated from Stupacher et al. (2016), who showed that participants exposed to low-frequency stimuli reported higher groove scores than those exposed to high-frequency stimuli ($d = 0.13$). Cohen's d was calculated as $d = \bar{x}1 - \bar{x}2 / SD_{\text{pooled}}$ (Cohen, 1992). Additionally, using an online effect size calculator (Uanhoro, 2017), a large effect size ($\eta_p^2 = .24$) was obtained from Witek et al. (2014), who reported a significant main effect of syncopation on groove, $F(1.62, 79.15) = 15.73$, $p < .001$. Thus, G* Power calculated a minimum sample size of 137 ($\alpha = .05$, power $= .8$).

MATERIALS

Twenty short house-style music clips were created in Logic Pro X. A Roland TR-8S drum machine (preset TR-909) was used to produce an authentic, house-style drum sound (Felton, 2016; Snoman, 2012). Furthermore, consistent with house music, clips featured constant quarter-note bass drum events, a 4/4 time signature at 126 bpm—within an optimal range for groove perception (Etani et al., 2018), and were quantized to a 16th note grid (Felton, 2016; Snoman, 2012).

We created five music clips for each experimental condition, beginning with the factor-level combination: *high LFA + high syncopation*. Each clip included three instruments: drums, bass, and piano. Piano sounds varied across clips, while drum and bass sounds remained consistent. Audio files of stimuli, spectrograms illustrating LFA manipulations, and MIDI piano rolls illustrating syncopation manipulations are available in the Supplementary Material accompanying this paper at online.ucpress.edu/mp.

High syncopation was achieved by placing bass notes on weak metric positions and rests on strong metric positions (Fitch & Rosenfeld, 2007; London, 2004, p. 107; Sadie & Tyrrell, 2000). *Low syncopation* was achieved by shifting off-beat notes to positions of stronger metric weight (Gómez et al., 2007). *Low LFA* was achieved by applying a 200 Hz low-frequency cut (48 dB/Oct, 0.71 Q) to basslines. This frequency choice was guided by the recognised definition of low frequencies – 60 to 250 Hz. Moreover, using 200 Hz—approximately G3, the uppermost string on a bass guitar—reinforced ecological validity by ensuring the experimental manipulations reflected frequencies commonly encountered in musical contexts.

All 20 clips, each 15 seconds long, were exported from Logic Pro as 44.1 kHz, 160 kbps mp3 files. Ecological validity was further enhanced by five music experts' verification of the authentic house style of the clips. Diagrams of MIDI syncopation manipulations, spectrograms of LFA and syncopation manipulations, and four example stimuli (one for each condition) are available in the Supplementary Material. Quantitative values reflecting syncopation manipulations were calculated using SynPy (Song et al., 2015); see Table 1. All house music clips are openly available at OSF (https://osf.io/4nc53/?view_only=833df7920c1c4a7788f074b2cfff8c8f).

PROCEDURE

The online experiment was delivered using Qualtrics. At the beginning of the session, participants completed three demographic questions followed by an audio device test. The test aimed to confirm the suitability of their chosen listening device and facilitate setting appropriate volume levels. Participants were instructed to use earphones or headphones instead of their

TABLE 1. *Quantification of High and Low Syncopation*

		LHL	PRS	SG	TMC	TOB	WNDB
A	High	4	9.62	1.61	4.25	3	0.33
	Low	−1	3.25	0	0	1.5	0.06
B	High	5	10.72	1.3	5.25	2.75	0.52
	Low	−1	4.56	−0.29	0	2.25	0.18
C	High	4	9.25	1.36	4.5	3	0.46
	Low	−1	4	−0.08	0	2	0.21
D	High	6.25	15	2.52	7	4	0.5
	Low	−1	2	0	0	2	0
E	High	5	9.28	1.84	5.25	1.25	0.52
	Low	−1	3.69	0	0	1.25	0.11

Note. A - E represent the five music clips where syncopation manipulations were performed. LHL = Longuet-Higgins & Lee, 1984; PRS = Pressing, 1997; TMC = Metric Complexity - Toussaint, 2002; SG = Sioros & Guedes, 2011; TOB = Off-Beatness - Toussaint, 2005; WNBD = Weighted Note-to-Beat Distance - Gómez 2005.

smartphone speaker to better differentiate the presence of low frequencies (Villalba & Lleida, 2011). The test audio consisted of a one-minute sequence comprising two alternating sine waves (32.7 Hz and 43.65 Hz at −8 dBFS). The lower tone (C1) represented the lowest frequency to which participants would be exposed. The second tone (F1) was used to prevent monotony and maintain participant engagement, enhancing the test's reliability. Gain was set to −8 dBFS to reflect the *high LFA* manipulation. Participants were instructed to follow a four-step procedure: 1) connect their earphones or headphones to their device, 2) turn down the device volume, 3) press play on the media bar, and 4) slowly increase the volume until the tones could be heard at a moderately loud yet comfortable level.

The main part of the experiment consisted of 20 fully randomized music clips, five per experimental condition. *Urge to move* was assessed using the question, "How much do you agree with the following statement? This music evokes the sensation of wanting to move some part of my body." This question was selected from Senn et al.'s (2020) three-item scale for "urge to move" as it directly addresses the core aspect of groove under investigation. Senn et al. (2020) explicitly endorsed the use of a single question to measure the "urge to move," highlighting that this, along with the other two statements ("This music is good for dancing" and "I cannot sit still while listening to this music") demonstrated strong correlations with the sub-construct in their confirmatory factor analysis ($\alpha \geq .91$). Participants responded on a 5-point Likert scale (1 = *strongly disagree*, 5 = *strongly agree*).

After rating the *urge to move* for all clips, participants completed the Gold-MSI (Müllensiefen et al., 2014b) and the Gold-DSI (Rose et al., 2020) to assess individual differences in dance and music experience. The Gold-MSI comprises six subscales: *active engagement*, *perceptual abilities*, *music training*, *singing abilities*, *emotional engagement with music*, and *general music sophistication*. The Gold-DSI consists of five subscales: *body awareness*, *social dancing*, *urge to dance*, *dance training*, and *observational dance experience*. Finally, participants completed the Short Test of Music Preferences (STOMP: Rentfrow & Gosling, 2013), which comprises four subscales: *reflective & complex*, *intense & rebellious*, *upbeat & conventional*, and *energetic & rhythmic*.

DATA SCREENING AND ANALYSES

Urge to move scores for each participant were obtained by averaging responses across the five house clips for all four experimental conditions. Subsequently, data were imported into Jamovi 2.0.0.0 for statistical analysis. Missing data ($n = 13$) accounted for 0.07% of total data and only occurred in Gold-MSI responses. Missing data was replaced using mean substitution of participant scores from the relevant item (Downey & King, 1998; Roth & Switzer, 1995). Additionally, data from participants who scored uniformly across all items or completed the study in under five minutes were excluded from analysis, as this indicated a lack of careful engagement with the experiment, which was necessary to obtain meaningful results.

Parametric analysis was deemed suitable given that the processed Likert scale data comprised multiple related items (Carifio & Perla, 2008; Pell, 2005). In preparation for performing a two-way repeated-measures ANOVA, the assumption of a normally distributed dependent variable was checked. The assumption of sphericity was automatically met since this was a repeated measure design with only two levels (Hinton et al., 2004; Minke, 1997).

A visual inspection of histograms for *urge to move* across all four experimental conditions revealed negative skew. However, skewness across conditions ($min = -1.21$, $max = 1.44$, $M = -0.32$, $SD = 0.61$) fell within an acceptable range (Byrne, 2013; George & Mallery, 2010; Hair et al., 2009; Orcan, 2020). Attempts to improve skewness through log-transform were unsuccessful, so were not preserved. Moreover, some authors advise against using log transformation for skewed Likert data (Feng et al., 2014; Games & Lucas, 1966; Glass et al., 1972; O'Hara & Kotze, 2010). Kurtosis values ($min = -1.08$, $max = 2.82$, $M = 0.2$, $SD = 0.94$) were also deemed acceptable (Hair et al., 2009).

TABLE 2. *Descriptive Statistics for Groove Across LFA and Syncopation*

			95% CI					
	M	*SD*	Lower	Upper	Min	Max	*Skew*	*β2*
High LFA + high sync	4.18	0.63	4.09	4.28	2	5	−0.82	−0.58
High LFA + low sync	4.06	0.7	3.96	4.17	1.8	5	−0.67	−0.2
Low LFA + high sync	3.93	0.77	3.81	4.04	1.4	5	−0.67	0.15
Low LFA + low sync	3.89	0.75	3.78	4	1.6	5	−0.6	0.04

Note. LFA = *low-frequency amplitude*, sync = *syncopation*, *β2* = kurtosis.

In any case, it has been documented that parametric tests such as ANOVAs are robust against violations of normality, ordinal scale data, and small sample sizes (Gaito, 1980; Glass et al., 1972; Harwell et al., 1992; Lindquist, 1953; Lix et al., 1996; Norman, 2010; Pearson, 1931; Schmider et al., 2010; Srivastava, 1959).

In line with the primary hypotheses, a two-way repeated-measures ANOVA was performed to test for main and interaction within-subject effects of *LFA* and *syncopation* factors on *urge to move*. See Table 2 for descriptive statistics for *urge to move* across *LFA* and *syncopation*. Generalized eta squared was calculated to facilitate the comparison of effect sizes with studies using different designs (Bakeman, 2005; Lakens, 2013; Olejnik & Algina, 2003). Finally, to explore the role of individual differences in groove perception of house music, we conducted a simple Pearson correlation between *urge to move* scores in the *high syncopation* + *high LFA* condition, dance and music experience, and genre preferences. All Gold-DSI, Gold-MSI, and STOMP subscales were included.

Results

In line with our hypotheses, *urge to move* increased with LFA and syncopation. The ANOVA revealed both a significant main effect of *LFA*, $F(1, 178) = 42.19$, $p < .001$, $\eta_p^2 = .192$, $\eta^2_G = .022$) and a main effect of *syncopation*, $F(1, 178) = 11.88$, $p < .001$, $\eta_p^2 = .063$, $\eta^2_G = .003$. The interaction between *LFA* and *syncopation* on *urge to move*, $F(1, 178) = 4.29$, $p = .04$, $\eta_p^2 = .024$, $\eta^2_G = .001$, was marginally significant. See Figure 1. Post hoc Tukey tests were performed to explore the significance and direction of simple effects and pairwise comparisons.

Post hoc tests confirmed that *urge to move* scores for *high LFA* and *low LFA* were significantly different, ($MD = 0.216$, $SE = 0.033$), $t(178) = 6.50$, $p_{tukey} < .001$. *Urge to move* scores for *high syncopation* and *low syncopation* were also significantly different, ($MD = 0.08$, $SE = 0.02$), $t(178) = 3.45$, $p_{tukey} < .001$. In support of the hypotheses, the largest mean across factor-level combinations was *high LFA* + *high syncopation*, ($M = 4.18$, $SD = 0.63$) $\pm$ 0.05, 95% *CI* [4.09, 4.28]. Additionally, the largest mean difference of the four factor-level combinations was between *high LFA* + *high syncopation* and *low LFA* + *low syncopation*, ($MD = 0.3$, $SE = 0.04$), $t(178) = 7.11$, $p < .001$. Conversely, the smallest difference was between *low LFA* + *high syncopation* and *low LFA* + *low syncopation*, ($MD = 0.04$, $SE = 0.03$), $t(178) = 1.24$, $p < .604$. See Table 3 for pairwise comparisons.

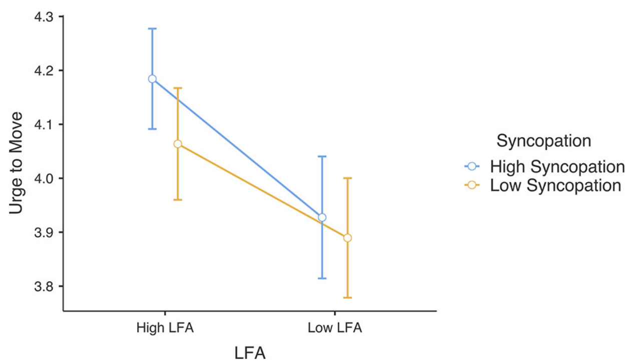

FIGURE 1. Interaction of LFA and syncopation on groove.
Note: LFA = low-frequency amplitude. Error bars represent confidence intervals.

Nonparametric Durbin-Conover pairwise comparisons revealed a corroboratory pattern of results. In particular, the largest difference between conditions was observed between *high LFA* + *high syncopation* and *low LFA* + *low syncopation*, $DC = 7.81$, $p < .001$. The smallest absolute difference was between *low LFA* + *high syncopation* and *low LFA* + *low syncopation;* and was not significant, $DC = 1.12$, $p = .265$. See Table 4 for a complete list of nonparametric pairwise comparisons.

Finally, we conducted exploratory correlational analyses to assess the strength of association between *urge to move* scores in the *high-LFA* + *high syncopation* condition and Gold-MSI, Gold-DSI and STOMP subscales. A Bonferroni-corrected significance level was

TABLE 3. *Tukey Pairwise Comparisons for LFA and Syncopation*

Comparison					*MD*	*SE*	*t*	*p*
high LFA	high sync	-	low LFA	low sync	0.3	0.04	7.11	< .001
high LFA	high sync	-	low LFA	high sync	0.26	0.04	6.98	< .001
high LFA	low sync	-	low LFA	low sync	0.17	0.04	4.29	< .001
high LFA	high sync	-	high LFA	low sync	0.12	0.03	3.99	< .001
low LFA	high sync	-	high LFA	low sync	0.14	0.04	3.47	.004
low LFA	high sync	-	low LFA	low sync	0.04	0.03	1.24	.604

Note. LFA = low-frequency amplitude, sync = syncopation, *MD* = mean difference, *SE* = standard error.
p-values adjusted for multiple comparisons using Tukey correction.

TABLE 4. *Durbin-Conover Pairwise Comparisons*

Comparison					*DC*	*p*
High LFA	high sync	–	low LFA	low sync	7.81	< .001
High LFA	high sync	–	low LFA	high sync	6.69	< .001
High LFA	high sync	–	high LFA	low sync	4.12	< .001
High LFA	low sync	–	low LFA	low sync	3.69	< .001
High LFA	low sync	–	low LFA	high sync	2.57	.01
Low LFA	high sync	–	low LFA	low sync	1.12	.265

Note. LFA = low-frequency amplitude, sync = syncopation, *DC* = Durbin-Conover statistic. *p values* adjusted for multiple comparisons using Bonferroni correction.

TABLE 5. *Pearson Correlations for High LFA + High Syncopation-Induced Urge to Move*

	M	*SD*	*r*	*p*
STOMP-ER	5.59	0.98	0.465	< .001*
MSI-EM	5.81	0.87	0.324	< .001*
DSI-UD	4.68	1.22	0.321	< .001*
DSI-BA	4.46	1.2	0.27	< .001*
STOMP-RC	5.21	1.05	0.25	< .001*
MSI-PA	5.34	0.95	0.244	< .001*
DSI-SD	4.32	1.5	0.243	.001*
MSI-SA	4.36	0.96	0.239	.001*
MSI-GM	4.32	1.09	0.236	.001*
STOMP-UC	4.51	1.19	0.215	.004
MSI-AE	4.29	1.06	0.213	.004
DSI-ODE	3.71	1.24	0.122	.104
MSI-MT	3.35	1.71	0.099	0.189
STOMP-IR	4.76	1.38	0.073	0.331
DSI-DT	2.06	1.45	−0.02	0.787

Note. Dance Sophistication Index (DSI): BA = *body awareness*, DT = *dance training*, ODE = *observational dance experience*, SD = *social dancing*, UD = *urge to dance*. STOMP: ER = *energetic & rhythmic*, IR = *intense & rebellious*, RC = *reflective & complex*, UC = *upbeat & conventional.* Musical Sophistication Index (MSI): AE = *active engagement*, GM = *general musical sophistication*, PA = *perceptual abilities*, MT = *music training*, SA = *singing ability*, EM = *emotional engagement with music*.
* Significant at Bonferroni-corrected significance level ($p < (.05 /16) = .003125$)

applied at $p < (.05 /16) = .003125$. Subscales that exhibited the highest positive association with the *urge to move* as induced by house music featuring *high LFA + high syncopation* basslines were STOMP: *energetic & rhythmic*, $r = .456$, Gold-MSI: *emotional engagement with music*, $r = .324$, Gold-DSI: *urge to dance*, $r = .321$, Gold-DSI: *body awareness*, $r = .27$. See Table 5 for a full list of Gold-DSI, Gold-MSI, and STOMP descriptive statistics and Pearson's correlations with *high LFA + high syncopation*-induced *urge to move*, corrected for multiple comparisons.

Discussion

This study aimed to understand if and how low-frequency amplitude (LFA) and syncopation impact groove perception in electronic dance music (EDM), specifically house music. Groove—the urge to move—was operationally defined as "the sensation of wanting to move some part of one's body in response to music" (Senn et al., 2020).

Our findings show that a combination of high LFA (Lustig & Tan, 2020) and high syncopation (Wesolowski & Hofmann, 2016) produces the highest perceived groove scores in our house music clips. Moreover, LFA and syncopation show a tendency to interact: greater LFA appears to heighten the saliency of syncopation, as groove perception for house tracks with low LFA was unaffected by our syncopation manipulation. Our results thus help explain why bass instruments often convey rhythmic aspects of music (Sadie & Tyrrell, 2000) and how increasing bass levels in popular music may be linked to production techniques used to entice dancing (Hove et al., 2019).

Additionally, we explored the role of individual differences in groove perception and found that groove perception is associated with a preference for energetic and rhythmic styles of music (Lustig & Tan, 2020; Senn et al., 2018), a general urge to dance (Janata et al., 2012; Witek et al., 2014), and an emotional connection to music (Huron, 2006; Senn et al., 2020; Solberg & Dibben, 2019; Solberg & Jensenius, 2017). Dance experience, in particular, is rarely assessed in research on music perception. Yet, in keeping with more recent work, our study suggests that the urge to dance, social dancing, and body awareness may be important predictors of groove experience (Foster Vander Elst et al., 2021; Nave-Blodgett et al., 2021; O'Connell et al., 2022). However, given that we did not include covariates in our power analysis, our findings are exploratory. More research is needed to confirm the role of individual trait differences in groove perception.

Our findings align with previous research demonstrating the significant impact of LFA on enhancing groove. Specifically, studies have demonstrated 1) increased groove and tapping velocities through exposure to instruments producing low frequencies (Stupacher et al., 2016), 2) that bass drums in dance music are likely to elicit spontaneous movement (Van Dyck et al., 2013), and 3) a positive correlation between low-frequency energy and head movement speed during dance (Burger et al., 2013). Additionally, LFA has been observed to improve neural entrainment to musical rhythms (Lenc et al., 2018) and augment rhythmic accuracy (Hove et al., 2014). These findings support our conclusion that EDM basslines with higher LFA significantly contribute to an increased sense of groove.

Regarding syncopation, our findings align with previous literature showing that varying levels of rhythmic complexity enhance groove perception. Specifically, our results corroborate studies indicating that non-isochronous EDM basslines (Wesolowski & Hofmann, 2016), highly syncopated drum beats (Senn et al., 2018; Witek et al., 2014), and syncopated piano melodies (Sioros et al., 2014) contribute to increased groove compared to their isochronous or less syncopated counterparts.

However, previous studies have shown that syncopation exhibits an inverted-U shape on groove, such that medium syncopation levels elicit higher groove scores than low or high syncopation (Sioros et al., 2014; Witek et al., 2014, 2017). As our primary research interest was to understand the relationship between LFA and syncopation, we only used two levels of syncopation. It is, therefore, possible that groove perception would have been lower had we included more extreme levels of syncopation. However, in house music, where a quarter-note bass drum consistently emphasises strong beats, it is also possible that a highly syncopated bassline would not exceed the optimal groove threshold as defined by Witek et al.'s (2014) inverted-U curve theory. Furthermore, more extreme variations of syncopation might have led participants to not classify the musical excerpts as representative of the genre, house. However, as confirmed by independent experts, our syncopation manipulations were within the range to be classified as house music.

Arguably, our findings do not easily map onto other studies with more than two syncopation levels; however, we calculated and documented syncopation levels (Song et al., 2015) using six different models (Gómez et al., 2005; Longuet-Higgins & Lee, 1984; Pressing, 1999; Sioros & Guedes, 2011; Toussaint, 2002, 2005). Together with reported generalized effect sizes (Olejnik & Algina, 2003), these measures of syncopation support comparing our findings to other existing and future studies.

We would like to highlight a few limitations of our study. First, during the listening task, participants could proceed to the following music clip before the current clip had finished playing. This aspect increased the potential for participants to not listen to the complete track. However, we excluded data from participants who scored the same for all items or completed the study in under five minutes, as these patterns suggested a lack of careful engagement with the musical stimuli.

Second, we did not include aesthetic or pleasure ratings in this study, as we wanted to avoid the influence of aesthetic judgements on groove ratings; people might have rated individual excerpts as groovier because they liked them, not because they perceived more groove. Moreover, a positive relationship between groove perception and pleasure is already well established (Matthews et al., 2020); for example, syncopation alone can evoke powerfully positive emotions (Huron, 2006; Witek, 2017; Witek et al., 2014), and increased bass correlates with positive aesthetic appreciation (Hove et al., 2020; Lustig & Tan, 2020). Nonetheless, the influence of emotional musical connection, the urge to dance, and the trait preference for energetic music on groove perception in our study support a link between groove and pleasure (Solberg, 2014; Solberg & Dibben, 2019) and are in keeping with findings that participating in EDM events can enhance social, musical, and emotional experiences (Cannon & Greasley, 2021).

A third limitation is the binary nature of our syncopation manipulation. This design means we cannot produce a predictive groove model that links objective rhythmic complexity to subjective groove. Fourth, we used a 5-point Likert scale instead of the 7-point scale used by Senn et al. (2020). This decision was made to reduce respondent time and survey fatigue, aiming to keep the study duration within the advertised 20 minutes. This design choice may have limited our capacity for direct comparisons with research employing the original scale; however, evidence suggests that five and seven-point scales are highly correlated (Colman et al.,

1997) and produce the same mean scores once re-scaled (Dawes, 2008).

Additionally, our study manipulated bassline syncopation, whereas previous studies manipulated the syncopation of snare and bass drums (Witek et al., 2014, 2017) or piano melodies (Sioros et al., 2014). Future work could use a more fine-grained syncopation manipulation in EDM to more precisely predict how variations in syncopation influence the groove experience across different musical genres and musical timbre.

Finally, we observed only a weak interaction between LFA and syncopation. Arguably, participants in our online study used a variety of headphones and earphones with unique specifications to complete this study, introducing variability into our LFA amplitude manipulation. While this may have reduced the overall interaction effect, the pattern of results across all pairwise comparisons is consistent and robust; that is, the same in both parametric and nonparametric comparisons. Our results clearly show a mutually enhancing effect of high LFA and high syncopation on groove perception, even under the relatively unconstrained conditions of an online study and relatively liberal inclusion criteria. Therefore, follow-up studies under more controlled lab conditions are needed to confirm that LFA modulates the effect of syncopation on groove perception.

In conclusion, our study shows that higher LFA and syncopation of basslines in house music increase the urge to dance. Furthermore, perceived groove showed significant positive associations with a preference for energetic and rhythmic music styles, a general desire to dance, and an emotional connection to music. We conclude that the interplay of highly syncopated basslines, accompanied by a steady, low-syncopated rhythmic foundation not only maintains but enhances the sensation of groove, especially in people who enjoy dancing to music, thereby highlighting the close yet often understudied connection between music and dance.

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References

Alén, O. (1995). Rhythm as duration of sounds in Tumba Francesa. *Ethnomusicology*, *39*(1), 55–71.

Alluri, V., & Toiviainen, P. (2010). Exploring perceptual and acoustical correlates of polyphonic timbre. *Music Perception*, *27*(3), 223–242.

Ayres, D. (2014). *Historical seeds and worldwide dissemination of house music*. [Self-published]

Bacon, C. J., Myers, T. R., & Karageorghis, C. I. (2012). Effect of music-movement synchrony on exercise oxygen consumption. *The Journal of Sports Medicine and Physical Fitness*, *52*(4), 359–365.

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, *37*(3), 379–384.

Barney, D., Gust, A., & Liguori, G. (2012). College students' usage of personal music players (PMP) during exercise. *ICHPER-SD Journal of Research*. https://eric.ed.gov/?id=EJ973952

Bidder, S. (1999). *House: The rough guide*. Rough Guides.

Bigliassi, M., Karageorghis, C. I., Wright, M. J., Orgs, G., & Nowicky, A. V. (2017). Effects of auditory stimuli on electrical activity in the brain during cycle ergometry. *Physiology and Behavior*, *177*, 135–147.

Blacking, J. (1995). *Music, culture and experience: Selected papers of John Blacking*. University of Chicago Press.

Bood, R. J., Nijssen, M., van der Kamp, J., & Roerdink, M. (2013). The power of auditory-motor synchronization in sports: Enhancing running performance by coupling cadence with the right beats. *PLOS One*, *8*(8), e70758.

Brodsky, W., Olivieri, D., & Chekaluk, E. (2018). Music genre induced driver aggression: A case of media delinquency and risk-promoting popular culture. *Music and Science*, *1*, 2059204317743118.

Burger, B., Thompson, M. R., Luck, G., Saarikallio, S., & Toiviainen, P. (2012). *Music moves us: Beat-related musical features influence regularity of music-induced movement*. https://www.semanticscholar.org/paper/fe1c36c3b329c8811b35d341a674ea24683870be

Burger, B., Thompson, M. R., Luck, G., Saarikallio, S., & Toiviainen, P. (2013). Influences of rhythm- and timbre-related musical features on characteristics of music-induced movement. *Frontiers in Psychology*, *4*, 183.

Burger, B., & Toiviainen, P. (2020). Embodiment in electronic dance music: Effects of musical content and structure on body movement. *Musicae Scientiae: The Journal of the European Society for the Cognitive Sciences of Music*, *24*(2), 186–205.

Butterfield, M. (2010). Participatory discrepancies and the perception of beats in jazz. *Music Perception*, *27*(3), 157–176.

Byrne, B. M. (2013). *Structural equation modeling with AMOS: Basic concepts, applications, and programming* (2nd ed.). Routledge.

Calderone, D. J., Lakatos, P., Butler, P. D., & Castellanos, F. X. (2014). Entrainment of neural oscillations as a modifiable substrate of attention. *Trends in Cognitive Sciences*, *18*(6), 300–309.

Cameron, D. J., Dotov, D., Flaten, E., Bosnyak, D., Hove, M. J., & Trainor, L. J. (2022). Undetectable very-low frequency sound increases dancing at a live concert. *Current Biology: CB*, *32*(21), R1222–R1223.

Cannon, J. W., & Greasley, A. E. (2021). Exploring relationships between electronic dance music event participation and well-being. *Music and Science*, *4*, 2059204321997102.

Carifio, J., & Perla, R. (2008). Resolving the 50-year debate around using and misusing Likert scales. *Medical Education*, *42*(12), 1150–1152.

Chang, A., Bosnyak, D. J., & Trainor, L. J. (2016). Unpredicted pitch modulates beta oscillatory power during rhythmic entrainment to a tone sequence. *Frontiers in Psychology*, *7*, 327.

Clynes, M. (1986). Music beyond the score. *Communication and Cognition*, *19*(2), 169–194.

Clynes, M., & Nettheim, N. (1982). The living quality of music. In M. Clynes (Ed.), *Music, mind, and brain: The neuropsychology of music* (pp. 47–82). Springer.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155–159.

Colman, A. M., Norris, C. E., & Preston, C. C. (1997). Comparing rating scales of different lengths: Equivalence of scores from 5-point and 7-point scales. *Psychological Reports*, *80*(2), 355–362.

Davies, M., Madison, G., Silva, P., & Gouyon, F. (2013). The effect of microtiming deviations on the perception of groove in short rhythms. *Music Perception*, *30*(5), 497–510.

Dawes, J. (2008). Do data characteristics change according to the number of scale points used? An experiment using 5 point, 7 point and 10 point scales. *International Journal of Market Research*, *51*(1).

Dayal, G., & Ferrigno, E. (2012). Electronic dance music. In *Oxford Music Online*. Oxford University Press. https://doi.org/10.1093/gmo/9781561592630.article.a2224259

Downey, R. G., & King, C. (1998). Missing data in Likert ratings: A comparison of replacement methods. *The Journal of General Psychology*, *125*(2), 175–191.

Etani, T., Marui, A., Kawase, S., & Keller, P. E. (2018). Optimal tempo for groove: Its relation to directions of body movement and Japanese nori. *Frontiers in Psychology*, *9*, 462.

Farnell, B. (1999). Moving bodies, acting selves. *Annual Review of Anthropology*, *28*, 341–373.

Felton, D. (Ed.) (2016). *The secrets of dance music production* (1st ed.). Jake Island Limited.

Feng, C., Wang, H., Lu, N., Chen, T., He, H., Lu, Y., & Tu, X. M. (2014). Log-transformation and its implications for data analysis. *Shanghai Archives of Psychiatry*, *26*(2), 105–109.

Fitch, W. T., & Rosenfeld, A. J. (2007). Perception and production of syncopated rhythms. *Music Perception*, *25*(1), 43–58.

Foster Vander Elst, O., Vuust, P., & Kringelbach, M. L. (2021). Sweet anticipation and positive emotions in music, groove, and dance. *Current Opinion in Behavioral Sciences*, *39*, 79–84.

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *32*(5), 1791–1802.

Gaito, J. (1980). Measurement scales and statistics: Resurgence of an old misconception. *Psychological Bulletin*, *87*(3), 564–567.

Games, P. A., & Lucas, P. A. (1966). Power of the analysis of variance of independent groups on non-normal and normally transformed data. *Educational and Psychological Measurement*, *26*(2), 311–327.

George, D., & Mallery, P. (2010). *SPSS for Windows step by step: A simple guide and reference* (17.0 Update). Allyn and Bacon.

Glass, G. V., Peckham, P. D., & Sanders, J. R. (1972). Consequences of failure to meet assumptions underlying the fixed effects analyses of variance and covariance. *Review of Educational Research*, *42*(3), 237–288.

Gómez, F., Melvin, A., & Rappaport, D. (2005). Mathematical measures of syncopation. *BRIDGES: Mathematical*. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.70.1979&rep=rep1&type=pdf

Gómez, F., Thul, E., & Toussaint, G. T. (2007). *An experimental comparison of formal measures of rhythmic syncopation*. ICMC. https://www.researchgate.net/profile/Francisco-Gomez-38/publication/279235158_An_Experimental_Comparison_of_Formal_Measures_of_Rhythmic_Syncopation/links/55ca605f08aebc967dfbe2e5/An-Experimental-Comparison-of-Formal-Measures-of-Rhythmic-Syncopation.pdf

Hair, J. F., Jr., Black, W. C., Babin, B. J., & Anderson, R. E. (2009). *Multivariate data analysis* (7th ed.). Pearson.

Hallett, R., & Lamont, A. (2017). Music use in exercise: A questionnaire study. *Media Psychology*, *20*(4), 658–684.

Hargreaves, D., & Lamont, A. (2017). *The psychology of musical development*. Cambridge University Press.

Harwell, M. R., Rubinstein, E. N., Hayes, W. S., & Olds, C. C. (1992). Summarizing Monte Carlo results in methodological research: The one- and two-factor fixed effects ANOVA cases. *Journal of Educational and Behavioral Statistics*, *17*(4), 315–339.

Hawkins, S. (2003). Feel the beat come down: House music as rhetoric. In A. F. Moore (Ed.), *Analyzing popular music*. Cambridge University Press.

Heckner, M. K., Cieslik, E. C., Küppers, V., Fox, P. T., Eickhoff, S. B., & Langner, R. (2021). Delineating visual, auditory and motor regions in the human brain with functional neuroimaging: A BrainMap-based meta-analytic synthesis. *Scientific Reports*, *11*(1), 9942.

Hinton, P., McMurray, I., & Brownlow, C. (2004). *SPSS explained* (1st ed.). Routledge.

Hodges, D. A. (2009). Bodily responses to music. In S. Hallam, I. Cross, & M. H. Thaut (Eds.), *The Oxford handbook of music psychology*. Oxford Academic. https://doi.org/10.1093/oxfordhb/9780199298457.001.0001/oxfordhb-9780199298457

Hoesl, F., & Senn, O. (2018). Modelling perceived syncopation in popular music drum patterns: A preliminary study. *Music and Science*, *1*, 2059204318791464.

Hove, M. J., Marie, C., Bruce, I. C., & Trainor, L. J. (2014). Superior time perception for lower musical pitch explains why bass-ranged instruments lay down musical rhythms. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(28), 10383–10388.

Hove, M. J., Martinez, S. A., & Stupacher, J. (2020). Feel the bass: Music presented to tactile and auditory modalities increases aesthetic appreciation and body movement. *Journal of Experimental Psychology. General*, *149*(6), 1137–1147.

Hove, M. J., Vuust, P., & Stupacher, J. (2019). Increased levels of bass in popular music recordings 1955-2016 and their relation to loudness. *Journal of the Acoustical Society of America*, *145*(4), 2247.

Hsu, D. Y., Huang, L., Nordgren, L. F., Rucker, D. D., & Galinsky, A. D. (2015). The music of power: Perceptual and behavioral consequences of powerful music. *Social Psychological and Personality Science*, *6*(1), 75–83.

Huron, D. (2006). *Sweet anticipation: Music and the psychology of expectation*. MIT Press.

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology. General*, *141*(1), 54–75.

Jensenius, A. R., & Wanderley, M. M. (2010). Musical gestures: Concepts and methods in research. *Musical gestures*. Routledge.

Kaeppler, A. L. (2000). II. Dance ethnology and the anthropology of dance. *Dance Research Journal*, *32*(1), 116–125.

Karageorghis, C. I., Terry, P. C., Lane, A. M., Bishop, D. T., & Priest, D.-L. (2012). The BASES expert statement on use of music in exercise. *Journal of Sports Sciences*, *30*(9), 953–956.

Keil, C. (1995). The theory of participatory discrepancies: A progress report. *Ethnomusicology*, *39*(1), 1–19.

Keith, M. (1991). *From polychords polya: Adventures musical combinatorics*. Vinculum Press.

Keller, P. E., & Rieger, M. (2009). Special issue—Musical movement and synchronization. *Music Perception*, *26*(5), 397–400.

Kilchenmann, L., & Senn, O. (2015). Microtiming in swing and funk affects the body movement behavior of music expert listeners. *Frontiers in Psychology*, *6*, 1232.

Kornysheva, K., von Cramon, D. Y., Jacobsen, T., & Schubotz, R. I. (2010). Tuning-in to the beat: Aesthetic appreciation of musical rhythms correlates with a premotor activity boost. *Human Brain Mapping*, *31*(1), 48–64.

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*, 863.

Lamont, A. (2016). Musical development from the early years onwards. In S. Hallam, I. Cross, & M. H. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd ed.). Oxford University Press.

Lenc, T., Keller, P. E., Varlet, M., & Nozaradan, S. (2018). Neural tracking of the musical beat is enhanced by low-frequency sounds. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(32), 8221–8226.

Levitin, D. J., Grahn, J. A., & London, J. (2018). The psychology of music: Rhythm and movement. *Annual Review of Psychology*, *69*, 51–75.

Li, L., Zhang, Y., Fan, L., Zhao, J., Guo, J., Li, C., Wang, J., & Liu, T. (2023). Activation of the brain during motor imagination task with auditory stimulation. *Frontiers in Neuroscience*, *17*, 1130685.

Lima, C. F., Krishnan, S., & Scott, S. K. (2016). Roles of supplementary motor areas in auditory processing and auditory imagery. *Trends in Neurosciences*, *39*(8), 527–542.

Lindquist, E. F. (1953). *Design and analysis of experiments in psychology and education*. Houghton Mifflin Company.

Lix, L. M., Keselman, J. C., & Keselman, H. J. (1996). Consequences of assumption violations revisited: A quantitative review of alternatives to the one-way analysis of variance F test. *Review of Educational Research*, *66*(4), 579–619.

London, J. (2004). *Hearing in time: Psychological aspects of musical meter*. Oxford University Press.

Longuet-Higgins, H. C., & Lee, C. S. (1984). The rhythmic interpretation of monophonic music. *Music Perception*, *1*(4), 424–441.

López-Teijón, M., García-Faura, Á., & Prats-Galino, A. (2015). Fetal facial expression in response to intravaginal music emission. *Ultrasound*, *23*(4), 216–223.

Lovatt, P. (2018). *Dance psychology*. [Self-published].

Lustig, E., & Tan, I. (2020). All about that bass: Audio filters on basslines determine groove and liking in electronic dance music. *Psychology of Music*, *48*(6), 861–875.

Madison, G. (2001). Different kinds of groove in jazz and dance music as indicated by listeners' ratings. In *Proceedings of the VII International Symposium on Systematic and Comparative Musicology* (pp. 108–112).

Madison, G., Gouyon, F., Ullén, F., & Hörnström, K. (2011). Modeling the tendency for music to induce movement in humans: First correlations with low-level audio descriptors across music genres. *Journal of Experimental Psychology. Human Perception and Performance*, *37*(5), 1578–1594.

Madison, G., & Sioros, G. (2014). What musicians do to induce the sensation of groove in simple and complex melodies, and how listeners perceive it. *Frontiers in Psychology*, *5*, 894.

Matthews, T. E., Witek, M. A. G., Heggli, O. A., Penhune, V. B., & Vuust, P. (2019). The sensation of groove is affected by the interaction of rhythmic and harmonic complexity. *PLOS One*, *14*(1), e0204539.

Matthews, T. E., Witek, M. A. G., Lund, T., Vuust, P., & Penhune, V. B. (2020). The sensation of groove engages motor and reward networks. *NeuroImage*, *214*(116768), 116768.

Minke, A. (1997). *Conducting repeated measures analyses: Experimental design considerations*. http://files.eric.ed.gov/fulltext/ED407415.pdf

Monson, I. (2009). *Saying something*. University of Chicago Press.

Moumdjian, L., Buhmann, J., Willems, I., Feys, P., & Leman, M. (2018). Entrainment and synchronization to auditory stimuli during walking in healthy and neurological populations: A methodological systematic review. *Frontiers in Human Neuroscience*, *12*, 263.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014a). Measuring the facets of musicality: The Goldsmiths Musical Sophistication Index (Gold-MSI). *Personality and Individual Differences*, *60*, S35.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014b). The musicality of non-musicians: An index for assessing musical sophistication in the general population. *PLOS One*, *9*(2), e89642.

Nakamura, P. M., Pereira, G., Papini, C. B., Nakamura, F. Y., & Kokubun, E. (2010). Effects of preferred and nonpreferred music on continuous cycling exercise performance. *Perceptual and Motor Skills*, *110*(1), 257–264.

Nave-Blodgett, J. E., Snyder, J. S., & Hannon, E. E. (2021). Auditory superiority for perceiving the beat level but not measure level in music. *Journal of Experimental Psychology. Human Perception and Performance*, *47*(11), 1516–1542.

Nelson, A., Schneider, D. M., Takatoh, J., Sakurai, K., Wang, F., & Mooney, R. (2013). A circuit for motor cortical modulation of auditory cortical activity. *The Journal of Neuroscience*, *33*(36), 14342–14353.

Nettl, B. (2000). An ethnomusicologist contemplates universals in musical sound and musical culture. *The Origins of Music*, *3*(2), 463–472.

Norman, G. (2010). Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education: Theory and Practice*, *15*(5), 625–632.

O'Connell, S. R., Nave-Blodgett, J. E., Wilson, G. E., Hannon, E. E., & Snyder, J. S. (2022). Elements of musical and dance sophistication predict musical groove perception. *Frontiers in Psychology*, *13*, 998321.

O'Hara, R. B., & Kotze, D. J. (2010). Do not log-transform count data. *Methods in Ecology and Evolution / British Ecological Society*, *1*(2), 118–122.

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: measures of effect size for some common research designs. *Psychological Methods*, *8*(4), 434–447.

Orcan, F. (2020). Parametric or non-parametric: Skewness to test normality for mean comparison. *International Journal of Assessment Tools in Education*, *7*(2), 255–265.

Palmer, C. (2013). Music performance: Movement and coordination. *The psychology of music* (Vol. *3*, pp. 405–422). Elsevier.

Papenburg, J. G. (2016). Enhanced bass: On 1970s disco culture's listening devices. In J. G. Papenburg & H. Schulze (Eds.), *Sound as popular culture: A research companion*. (pp. 373–385). MIT Press.

Parncutt, R. (2006). Prenatal development. In G. E. McPherson (Ed.), *The child as musician: A handbook of musical development* (Vol. *501*, pp. 1–31). Oxford University Press.

Parncutt, R. (2016). Prenatal development and the phylogeny and ontogeny of musical behavior. In S. Hallam, I. Cross, & M. H. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd ed.). Oxford University Press.

Pearson, E. S. (1931). The analysis of variance in cases of non-normal variation. *Biometrika*, *23*, 114–133.

Pell, G. (2005). Use and misuse of Likert scales [Review of *Use and misuse of Likert scales*]. *Medical Education*, *39*(9), 970; author reply 971.

Pressing, J. (1999). *Cognitive complexity and the structure of musical patterns*. In R. Heath, B. Hayes, A. Heathcote, & C. Hooker (Eds.), *Proceedings of the 4th Conference of the Australian Cognitive Science Society*, *4*, 1–8.

Prögler, J. A. (1995). Searching for swing: Participatory discrepancies in the jazz rhythm section. *Ethnomusicology*, *39*(1), 21–54.

Rasch, R. A. (2001). Timing and synchronization in ensemble performance. In J. A. Sloboda (Ed.), *Generative processes in music: The psychology of performance, improvisation, and composition* (pp. 70–90). Oxford University Press.

Rendi, M., Szabo, A., & Szabó, T. (2008). Performance enhancement with music in rowing sprint. *Sport Psychologist*, *22*(2), 175–182.

Rentfrow, P. J., & Gosling, S. D. (2003). The do re mi's of everyday life: the structure and personality correlates of music preferences. *Journal of Personality and Social Psychology*, *84*(6), 1236–1256.

Rentfrow, P. J., & Gosling, S. D. (2013). *Short Test Of Music Preferences (STOMP). Measurement Instrument Database for the Social Science*. Retrieved from www.midss.ie

Repp, B. H. (1993). Music as motion: A synopsis of Alexander Truslit's (1938) gestaltung und bewegung in der musik. *Psychology of Music*, *21*(1), 48–72.

Rose, D., Müllensiefen, D., Lovatt, P., & Orgs, G. (2020). The Goldsmiths Dance Sophistication Index (Gold-DSI): A psychometric tool to assess individual differences in dance experience. *Psychology of Aesthetics, Creativity, and the Arts*. https://doi.org/10.1037/aca0000340

Roth, P. L., & Switzer, F. S. (1995). A Monte Carlo analysis of missing data techniques in a HRM setting. *Journal of Management*, *21*(5), 1003–1023.

Sadie, S., & Tyrrell, J. (2000). *The new Grove dictionary of music and msicians*. Groves Dictionaries, Incorporated.

Savage, P. E., Brown, S., Sakai, E., & Currie, T. E. (2015). Statistical universals reveal the structures and functions of human music. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(29), 8987–8992.

Schmider, E., Ziegler, M., Danay, E., Beyer, L., & Bühner, M. (2010). Is it really robust? Reinvestigating the robustness of ANOVA against violations of the normal distribution assumption. *Methodology: European Journal of Research Methods for the Behavioral and Social Sciences*, *6*(4), 147–151.

Schneider, D. M., & Mooney, R. (2015). Motor-related signals in the auditory system for listening and learning. *Current Opinion in Neurobiology*, *33*, 78–84.

Senn, O., Bechtold, T., Rose, D., Câmara, G. S., Düvel, N., Jerjen, R., et al. (2020). Experience of Groove Questionnaire: Instrument development and initial validation. *Music Perception*, *38*(1), 46–65.

Senn, O., Hoesl, F., Jerjen, R., Bechtold, T. A., Kilchenmann, L., Rose, D., & Alessandri, E. (2023). A stimulus set of 40 popular music drum patterns with perceived complexity measures. *Music and Science*, *6*. https://doi.org/10.1177/20592043231202576

Senn, O., Kilchenmann, L., Bechtold, T., & Hoesl, F. (2018). Groove in drum patterns as a function of both rhythmic properties and listeners' attitudes. *PLOS One*, *13*(6), e0199604.

Silva, N. R. D. S., Rizardi, F. G., Fujita, R. A., Villalba, M. M., & Gomes, M. M. (2021). Preferred music genre benefits during strength tests: Increased maximal strength and strength-endurance and reduced perceived exertion. *Perceptual and Motor Skills*, *128*(1), 324–337.

Sioros, G., & Guedes, C. (2011). *Complexity driven recombination of MIDI loops*. In A. Klapuri & C. Leider (Eds.), *Proceedings of the 12th International Society for Music Information Retrieval Conference*, (pp. 381–386).

Sioros, G., Miron, M., Davies, M., Gouyon, F., & Madison, G. (2014). Syncopation creates the sensation of groove in synthesized music examples. *Frontiers in Psychology*, *5*, 1036.

Snoman, R. (2012). *The dance music manual: tools, toys and techniques*. Routledge.

Solberg, R. T. (2014). "Waiting for the bass to drop": Correlations between intense emotional experiences and production techniques in build-up and drop sections of electronic dance music. *Dancecult*, *6*(1), 61–82.

Solberg, R. T., & Dibben, N. (2019). Peak experiences with electronic dance music. *Music Perception*, *36*(4), 371–389.

Solberg, R. T., & Jensenius, A. R. (2017). Pleasurable and intersubjectively embodied experiences of electronic dance music. *Empirical Musicology Review*, *11*(3-4), 301.

Song, C., Pearce, M., & Harte, C. (2015). *SynPy*: A python toolkit for syncopation modelling. In J. Timoney & F. Collender (Eds.), *Proceedings of the 12th International Conference on Sound and Music Computing* (pp. 295–300).

Srivastava, A. B. L. (1959). Effect of non-normality on the power of the analysis of variance test. *Biometrika*, *46*(1/2), 114–122.

Stupacher, J., Hove, M. J., & Janata, P. (2014). Decrypt the groove: Audio features of groove and their importance for auditory-motor interactions. *Proceedings of the 7th International Conference of Students of Systematic Musicology*. https://core.ac.uk/download/pdf/234135896.pdf

Stupacher, J., Hove, M. J., & Janata, P. (2016). Audio features underlying perceived groove and sensorimotor synchronization in music. *Music Perception*, *33*(5), 571–589.

Stupacher, J., Hove, M. J., Novembre, G., Schütz-Bosbach, S., & Keller, P. E. (2013). Musical groove modulates motor cortex excitability: A TMS investigation. *Brain and Cognition*, *82*(2), 127–136.

Styns, F., van Noorden, L., Moelants, D., & Leman, M. (2007). Walking on music. *Human Movement Science*, *26*(5), 769–785.

Swarbrick, D., Bosnyak, D., Livingstone, S. R., Bansal, J., Marsh-Rollo, S., Woolhouse, M. H., & Trainor, L. J. (2018). How live music moves us: Head movement differences in audiences to live versus recorded music. *Frontiers in Psychology*, *9*, 2682.

Todd, N. P. M. (1995). The kinematics of musical expression. *Journal of the Acoustical Society of America*, *97*(3), 1940–1949.

Tomic, S. T., & Janata, P. (2008). Beyond the beat: Modeling metric structure in music and performance. *Journal of the Acoustical Society of America*, *124*(6), 4024–4041.

Toussaint, G. (2002). A mathematical analysis of African, Brazilian and Cuban Clave rhythms.In R. Sarhangi (Ed.), *Proceedings of Bridges: Mathematical Connections in Art, Music, and Science* (pp. 157–168).

Toussaint, G. (2005). Mathematical features for recognizing preference in sub-Saharan African traditional rhythm timelines. *Pattern Recognition and Data Mining*, 18–27.

Trehub, S. E. (2016). Infant musicality. In S. Hallam, I. Cross, & M. H. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd ed.). Oxford University Press.

Trehub, S. E., Becker, J., & Morley, I. (2015). Cross-cultural perspectives on music and musicality. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *370*(1664), 20140096.

Trost, W., & Vuilleumier, P. (2013). Rhythmic entrainment as a mechanism for emotion induction by music: A neurophysiological perspective. In T. Cochrane, B. Fantini, & K. R. Scherer (Eds.), *The emotional power of music: Multidisciplinary perspectives* (pp. 213–225). Oxford University Press.

Trost, W. J., Labbé, C., & Grandjean, D. (2017). Rhythmic entrainment as a musical affect induction mechanism. *Neuropsychologia*, *96*, 96–110.

Uanhoro, J. O. (2017). *Effect size calculators*. https://effect-size-calculator.herokuapp.com/

Van Dyck, E., Moelants, D., Demey, M., Deweppe, A., Coussement, P., & Leman, M. (2013). The impact of the bass drum on human dance movement. *Music Perception*, *30*(4), 349–359.

Villalba, J., & Lleida, E. (2011). Detecting replay attacks from far-field recordings on speaker verification systems. *Biometrics and ID Management*, 274–285.

Vuust, P., Dietz, M. J., Witek, M., & Kringelbach, M. L. (2018). Now you hear it: A predictive coding model for understanding rhythmic incongruity. *Annals of the New York Academy of Sciences*, *1423*(1), 19–29.

Wesolowski, B. C., & Hofmann, A. (2016). There's more to groove than bass in electronic dance music: Why some people won't dance to techno. *PLOS One*, *11*(10), e0163938.

Witek, M. (2009). *Groove experience: Emotional and physiological responses to groove-based music*. In J. Louhivuori, T. Eerola, S. Saarikallio, & T. Himberg (Eds.), *Proceedings of the 7th Triennial Conference of European Society for the Cognitive Sciences of Music (ESCOM 2009)* (pp. 573–582).

Witek, M. (2017). Filling in: Syncopation, pleasure and distributed embodiment in groove. *Music Analysis*, *36*(1), 138–160.

Witek, M., Clarke, E. F., Wallentin, M., Kringelbach, M. L., & Vuust, P. (2014). Syncopation, body-movement and pleasure in groove music. *PLOS One*, *9*(4), e94446.

Witek, M., Popescu, T., Clarke, E. F., Hansen, M., Konvalinka, I., Kringelbach, M. L., & Vuust, P. (2017). Syncopation affects free body-movement in musical groove. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *235*(4), 995–1005.

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*(7), 547–558.

Zeiner-Henriksen, H. (n.d.). The significance of verticality for musical entrainment [Abstract]. *Frontiersin.org*. https://www.frontiersin.org/10.3389/conf.fnhum.2013.214.00015/event_abstract