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Feel the Bass: Music Presented to Tactile and Auditory Modalities Increases Aesthetic Appreciation and Body Movement

Michael J. Hove
Fitchburg State University and Harvard Medical School

Steven A. Martinez
Fitchburg State University and Yale University

Jan Stupacher
Aarhus University

Music is both heard and felt—tactile sensation is especially pronounced for bass frequencies. Although bass frequencies have been associated with enhanced bodily movement, time perception, and groove (the musical quality that compels movement), the underlying mechanism remains unclear. In 2 experiments, we presented high-groove music to auditory and tactile senses and examined whether tactile sensation affected body movement and ratings of enjoyment and groove. In Experiment 1, participants ($N = 22$) sat in a parked car and listened to music clips over sound-isolating earphones (auditory-only condition), and over earphones plus a subwoofer that stimulated the body (auditory-tactile condition). Experiment 2 ($N = 18$) also presented music in auditory-only and auditory-tactile conditions, but used a vibrotactile backpack to stimulate the body and included 2 loudness levels. Participants tapped their finger with each clip, rated each clip, and, in Experiment 1, we additionally video recorded spontaneous body movement. Results showed that the auditory-tactile condition yielded more forceful tapping, more spontaneous body movement, and higher ratings of groove and enjoyment. Loudness had a small, but significant, effect on ratings. In sum, findings suggest that bass felt in the body produces a multimodal auditory-tactile percept that promotes movement through the close connection between tactile and motor systems. We discuss links to embodied aesthetics and applications of tactile stimulation to boost rhythmic movement and reduce hearing damage.

Keywords: rhythm, multisensory perception, vibrotactile, perception-action, groove

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When listening to loud music, for example, at a concert or in a car, we can feel sound vibrations on our skin. People commonly describe "feeling" the music and how it leads to swaying, singing, or dancing along. Moving to music can provide pleasure (Zatorre & Salimpoor, 2013), improve exercise (Karageorghis, Terry, Lane, Bishop, & Priest, 2012), aid rehabilitation (MacDonald, Kreutz, & Mitchell, 2013), and improve social bonding (Hagen & Bryant, 2003). With the many benefits of moving to music, it is unsurprising that some music strongly compels movement. Recent research has shown that movement is especially influenced by music's low frequencies (Stupacher, Hove, & Janata, 2016; van Dyck et al., 2013). What exactly drives this bass–movement connection remains unclear. One untested idea is that the bass frequencies are felt more in the body, and the resulting auditory-tactile percept provides a strong multisensory cue for the motor system. Here, we test whether presenting music to tactile and auditory modalities influences movement and ratings of music.

Music and Movement

Tight coupling between perception and action systems is evident in the compulsion to move to music (Iversen & Balasubramaniam, 2016; Keller, Novembre, & Hove, 2014; Repp & Su, 2013; Zatorre, Chen, & Penhune, 2007). The musical quality that compels body movement is termed *groove* and has garnered considerable research interest (e.g., Danielsen, 2006; Iyer, 2002; Janata, Tomic, & Haberman, 2012; Madison, 2006; Pressing, 2002; Senn, Kilchenmann, von Georgi, & Bullerjahn, 2016). Groove is associated with enjoyment (Janata et al., 2012) and can occur in many musical genres (Keil, 1995; Madison, Gouyon, Ullén, & Hörnström, 2011). High-groove songs induce spontaneous movement (Hurley, Martens, & Janata, 2014; Janata et al., 2012), affect

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Michael J. Hove, Department of Psychological Science, Fitchburg State University, and Department of Psychiatry, Harvard Medical School; Steven A. Martinez, Department of Psychological Science, Fitchburg State University, and Department of Psychology, Yale University; Jan Stupacher, Center for Music in the Brain, Aarhus University.
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Correspondence concerning this article should be addressed to Michael J. Hove, Department of Psychological Science, Fitchburg State University, 160 Pearl Street, Fitchburg, MA 01420. E-mail: michaeljhove@gmail.com

balance control (Ross, Warlaumont, Abney, Rigoli, & Balasubramaniam, 2016), and alter motor-system excitability even when listeners are not moving (Stupacher, Hove, Novembre, Schütz-Bosbach, & Keller, 2013).

Groove is a multifaceted phenomenon that relates to many musical factors. In addition to a strong beat, repetitive rhythm, and syncopation (Fitch, 2016; Madison et al., 2011; Pressing, 2002; Witek, Clarke, Wallentin, Kringelbach, & Vuust, 2014), groove ratings can be predicted by audio features extracted from the recordings. For example, groove ratings are associated with measures of variability in the audio signal, such as event density and root mean square (RMS). Although groove ratings correlate with RMS energy, previous work has showed that overall loudness was not considered an attribute of groove (Janata et al., 2012) and did not significantly affect groove ratings (Stupacher et al., 2016). Another audio feature commonly associated with groove ratings is change in the spectrum (i.e., spectral flux), especially in the low-frequency bands (0–200 Hz; Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2013; Madison et al., 2011; Stupacher et al., 2013, 2016). Low frequencies in music are associated with the bass drum and bass, instruments identified in musicology to drive musical pulse and groove (Butterfield, 2010; Iyer, 2002; Keil, 1995; Pressing, 2002).

Bass and Movement

The influence of low-frequency tones on movement has been established in many experimental studies. When finger tapping with streams of high- and low-pitched sounds presented together, the lower frequency tones have a greater influence on movement timing (Hove, Keller, & Krumhansl, 2007; Hove, Marie, Bruce, & Trainor, 2014). In a music study that manipulated frequencies of the bass and bass drum (two-octave difference), the lower bass yielded higher groove ratings and more forceful taps (Stupacher et al., 2016). Songs with higher fluctuation (i.e., spectral flux) of bass frequency content increasingly affected motor-system excitability (Stupacher et al., 2013). In dance, louder bass-drum levels increased dancers' activity and entrainment with the music (van Dyck et al., 2013), and dancers' head movements aligned with the music's low frequencies (50–100 Hz; Burger et al., 2013). In sum, research across many studies and methodologies has uncovered a close connection between low frequencies and movement. The exact mechanism, however, remains unclear.

Potential Mechanisms Underlying the Bass–Movement Connection

A number of factors could contribute to the connection between low-frequency tones and movement, timing, and groove. One explanation focuses on encoding of low-frequency tones in the auditory pathway. For example, greater sensitivity to timing deviations of the lower of two tones could stem from dynamics of the cochlea in the inner ear (e.g., lower complex tones stimulate across more frequency channels creating clearer spike trains on the auditory nerve; Hove et al., 2014). Recent modeling of the auditory nerve and midbrain neurons demonstrates a bias to synchronize with the tempo of lower audio frequencies; this likely stems from differences in the spread of excitation in the basilar membrane and could impact beat perception (Zuk, Carney, & Lalor, 2018). Another study showed that the lower pitched tone of a chord had enhanced response in the brain stem and could support the low-tone/timing connection (Nozaradan, Schönwiesner, Caron-Desrochers, & Lehmann, 2016). Finally, loud low-frequency tones (70–260 Hz) have been shown to stimulate the vestibular apparatus (Todd & Cody, 2000), and this vestibular activation could play a role in the sound-movement connection and in beat perception (Todd & Lee, 2015; Trainor, Gao, Lei, Lehtovaara, & Harris, 2009).

Tactile Sensation in Music

Another potential factor linking bass and movement is music's ability to stimulate the tactile sense. Moving sound sources cause vibrations in air molecules and objects, which can displace eardrums and mechanoreceptors on the body (Merchel & Altinsoy, 2014; Verrillo, 1992). Consequently, loud music can be heard through the ears and felt as vibrations on the skin. Touch is sensitive to range of vibration frequencies, with peak sensitivity around 250 Hz (Verrillo, 1992), but a variety of factors make it more common to feel music's low frequencies (as is commonly experienced when feeling the bass in a club or concert). First, low frequencies require greater sound pressure level (SPLs) to sound as loud as higher frequencies (Fletcher & Munson, 1933), so are often played at considerably greater SPL; in concert or club settings, the low frequencies might be 10 to 30 dB higher than midband energy (Dibble, 1995; Todd & Cody, 2000). In addition, the body has natural resonances to low frequencies—for example, the chest has a resonant vibration in the region of 50 to 80 Hz (Leventhall, 2009). Together, factors such as increased SPL and bodily resonances can lead to an increased feeling of vibrations from the music's low-frequency pulse.

Tactile stimulation is important in musical performance and perception (Verrillo, 1992). Participants can use vibrotactile stimulation to discriminate musical timbre (Russo, Ammirante, & Fels, 2012) and, to some extent, pitch (Verrillo, 1992). In the rhythm domain, people can use tactile stimulation to discriminate musical meter (Huang, Gamble, Sarnlertsophon, Wang, & Hsiao, 2012) and to synchronize body movements (Ammirante, Patel, & Russo, 2016; Tranchant et al., 2017). Tactile and auditory rhythms are integrated to produce a coherent rhythmic percept (Huang et al., 2012; Roy, Lagarde, Dotov, & Dalla Bella, 2017) and recruit a common beat-detection network in the brain (Araneda, Renier, Ebner-Karestinos, Dricot, & De Volder, 2017). In a music-perception study, seat vibrations (low-pass filtered from the music) increased judgments of the overall quality of music (Merchel & Altinsoy, 2014). Although people can clearly use tactile information in music perception, it remains unclear whether tactile stimulation increases musical engagement and enjoyment and contributes to the bass–movement connection. In two experiments, we investigated whether tactile stimulation from low-frequency vibrations influenced music ratings and body movement.

Experiment 1

Experimental Overview

In Experiment 1, participants listened to high-groove musical clips. Each clip was presented twice—once over sound-isolating earphones (auditory-only condition) and once over the earphones plus a subwoofer that stimulated the body (auditory-tactile condition). Experiment 1 was run in a parked car—an ecologically valid listening space, with a small enclosed volume meant to heighten the tactile feeling produced by the subwoofer. We used both "old" and "new" musical clips, as new clips could be more engaging to the student participants and new songs tend to have higher bass levels (Hove, Vuust, & Stupacher, 2019). Participants tapped their finger along with each clip; we recorded body movement; and participants rated each clip for groove and enjoyment. We analyzed the effects of modality (auditory only vs. auditory-tactile presentation) and era (old vs. new) on tapping stability and pressure, amount of spontaneous head movement, and ratings.

Method

Participants. Experiment 1 included 22 undergraduate students (17 female, five male; mean age = 21.4 years, *SD* = 3.6). Participants were recruited from the psychology subject pool and by word of mouth. They were compensated with course credit. Participants were not selected based on musical experience and had a variety of musical backgrounds (nine of 22 had some musical training [*M* = 5.3 years, *SD* = 4.0]; the average musical training across all participants was 2.2 years [*SD* = 3.6]). All participants reported normal hearing. One additional participant was an outlier (ratings 3–5 *SD*s below the mean), reported "not really liking music," and was excluded. Participants provided written informed consent and the study protocol was approved by the local institutional review board.

Stimuli. The experiment used 10 musical clips with a high groove—some clips were selected from stimuli previously rated as high groove in Janata et al. (2012), and other clips were selected from recent pop and dance chart hits (see Table 1). Five "old" clips were originally released in the 1970s or 1980s, and five "new" clips were from the 2000s or 2010s. We included new clips for two reasons: (a) new clips should be more familiar and potentially more engaging for the undergraduate participants; and (b) bass levels have increased over time (Hove et al., 2019), and higher levels of bass in the new clips could yield stronger effects. Audio feature analyses revealed that the new clips had higher bass levels, and are presented in the online supplemental materials along with relations between audio features and other dependent measures. Each clip lasted 60 s and was taken from the iTunes preview (except for the song "Flash Light," which was taken from an earlier part of the song to avoid the breakdown section in the iTunes preview).

Table 1
Song Clips

Song	Artist	Year of release	Era
"Superstition"	Stevie Wonder	1972	Old
"Lady Marmalade"	LaBelle	1974	Old
"Straight From the Gate"	The Headhunters	1977	Old
"Flash Light"	Parliament	1978	Old
"Word Up!"	Cameo	1986	Old
"Goodies"	Ciara	2004	New
"Uptown Funk"	Mark Ronson feat. Bruno Mars	2014	New
"I Took a Pill in Ibiza"	Mike Posner–Seeb remix	2015	New
"Roses"	The Chainsmokers	2015	New
"Can't Feel My Face"	The Weeknd	2015	New

Apparatus. Participants were tested individually while seated in the passenger seat of a parked car (a 2012 Subaru Outback). The experiment was run in a car because it is an ecologically valid space where people often listen to loud music, and the small volume of the enclosed car interior heightens the tactile feeling produced by the subwoofer. We did not systematically query the participants on sensations felt from the subwoofer, so as to not reveal the experimental manipulation. However, the subwoofer was set to a level that created discernable tactile sensation in extensive pilot testing, and a separate group of participants ($n = 4$) corroborated that they could feel tactile sensations from the subwoofer. Tactile sensations were predominantly felt in the back, chest, and gut, and to a lesser extent in other areas, including face, hands, arms, and feet.

Stimuli were presented at a comfortable loudness over noise-isolating in-ear earphones with triple flange eartips (MC5; Etymotic Research). These earphones have a relatively flat frequency response and an estimated noise isolation of 35 to 42 dB (http://www.etymotic.com/consumer/earphones/mc5.html). Over the noise-isolating earphones, participants wore hearing-protector earmuffs (3M, AOSafety Peltor; 29-dB noise-reduction rating). The earphones and earmuffs provided noise isolation, so external sounds (including the subwoofer) could not be heard through the ears over the concurrent earphone-stimulus presentation (see Figure 1).

On half the trials, the stimuli were also presented over an external PA system (90-W Behringer Ultratone K900FX) placed on the floor of backseat facing the participant's back. The speaker, referred to as the *subwoofer*, had a 12-in. woofer and a 1-in. tweeter, and the five-band graphic equalizer was set to maximize the low frequencies (equalizer settings: +12 dB at the lowest 60-Hz band, and −12 dB at the four higher frequency bands). The unweighted SPL of the subwoofer playback was in the 90 to 95 dB range, as measured with a calibrated microphone (MicW i436) and an iPhone with the SPLnFFT app (Version 6.2 [Lefebvre, 2016]; Kardous & Shaw, 2014).

The experiment was controlled via MAX 7 software (Cycling '74) running on a Macbook Air laptop. Sound presentation was routed to the earphones and subwoofer via a two-channel USB interface (Applied Research and Technology). Participants tapped on a Roland SPD-6 drum machine, and the tap onset times and velocities (a measure of tap pressure ranging from 1 to 127) were recorded in MAX.

Video of each participant (in side view) was recorded using the camera in an iPhone 6s fixed to the armrest of the driver-side door. Video was recorded at 30 frames per second and a 1280 × 720 pixel resolution and was down-sampled to 640 × 360 pixels for analysis.

Procedure. The experimenter described the study and defined *groove* as the aspect of music that "compels the body to move" (Hurley et al., 2014; Janata et al., 2012; Madison, 2006). Participants held a drum machine (Roland SPD-6) on their laps and tapped with their right index finger along with the music's pulse (quarter-note level). Participants were told that they could engage with the music and it was okay to move if so compelled.

The experiment consisted of 20 total trials. The 10 musical clips were each played twice—once over earphones only, and once over earphones and the subwoofer. The stimuli were presented in quasi-

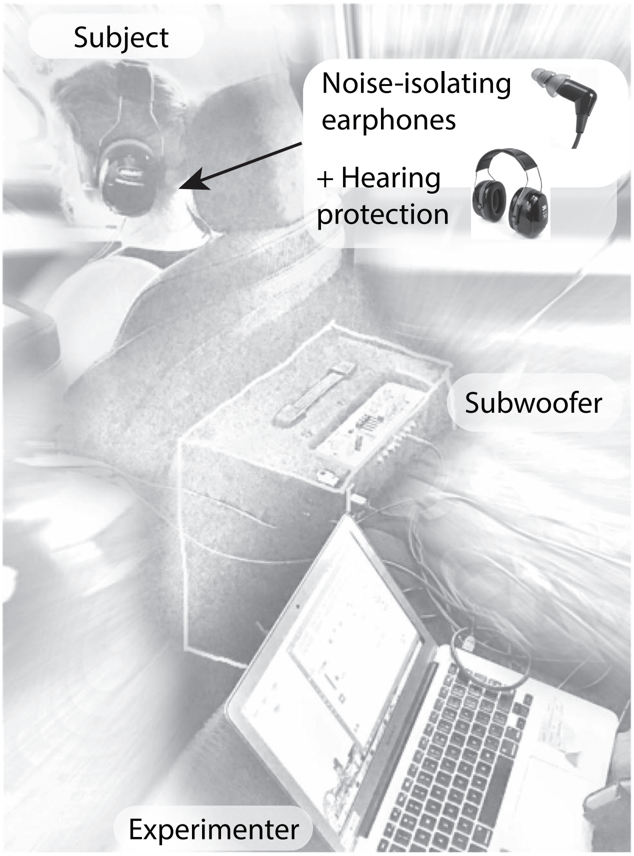

Figure 1. Experimental apparatus. The participant sat in the passenger seat of a parked car, and wore sound isolating in-ear earphones and over-ear hearing protection. A subwoofer was placed in the backseat. Songs clips were each presented twice—once over the earphones only (auditory condition) and once over earphones and the subwoofer (auditory-tactile condition).

random order (the same song could not play back-to-back). After the experiment, participants answered questions about their experience in the study. The entire session took approximately 45 min.

Dependent measures.

Ratings. After each trial, participants rated each musical clip using 7-point Likert scales on following questions:

- How much did the music "groove" (1 = *low groove*; 7 = *extremely high groove*)?
- How much did you enjoy that excerpt (1 = *not at all*; 7 = *very much*)?
- How easy was it to tap along with the music (1 = *very difficult;* 7 = *very easy*)?

Tapping data. Tap data from the drum machine were analyzed in terms of the coefficient of variation (standard deviation/mean intertap interval [ITI]), a measure of the consistency of tap timing (controlling for rate); and tap pressure (i.e., Musical Instrument Digital Interface [MIDI] velocity), a measure of how hard participants tapped (MIDI values ranging from 1 to 127).

Body movement in the video recordings. Body movements in the video recordings were analyzed using optical flow analysis. The analysis, implemented in FlowAnalyzer software (https://www.cefala.org/FlowAnalyzer), computes pixel displacements between consecutive frames in a video to infer the amount of body movement in a region of interest (Barbosa, Yehia, & Vatikiotis-Bateson, 2008). The main variable for each trial was the overall amount of movement (i.e., the sum of frame-to-frame movement).

Analysis.

Normality. All variables were assessed for normality with Shapiro-Wilk tests. If not normally distributed (Shapiro Wilk, $p <$ .05), the data were transformed to meet the assumption of normality.

Ratings. The means of each participant's ratings on groove, enjoyment, and ease of tapping were analyzed in repeated measures ANOVAs with the factors Modality (auditory-only, auditory-tactile) and Era (new, old). For effect sizes, partial eta squared (η_p^2) and generalized eta squared (η_G^2) are calculated and reported following recommendations by Lakens (2013). In contrast to η_p^2, η_G^2 removes design-dependent factors, making the effect size comparable between studies and with Cohen's (1988) benchmarks, which define small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) effects.

Tapping data. ITIs were calculated by subtracting the absolute time of a tap from the absolute time of the following tap. Taps in the first 2.5 s and last 2.5 s of each trial were not analyzed. ITIs more than 50% longer or shorter than the target ITI were excluded (3.5%; Semjen, Schulze, & Vorberg, 2000). Trials averaged 94 ITIs per trial. Trials with fewer than 50 valid taps were not included (2.7%). Mean velocity in each trial was calculated from the taps that were included in the timing analyses.

The participants' mean coefficient of variation and mean velocities were log transformed to meet the assumption of normality, and were analyzed in repeated-measures ANOVAs, with the factors Modality (auditory-only, auditory-tactile) and Era (new, old).

Body movement in the video recordings. For each participant's video, a region of interest was defined that encompassed the head and neck. FlowAnalyzer was run on the video of the entire experimental session (~30 min/subject); then, the frame-to-frame output was parsed for each trial. The 5 s at the beginning and end of each trial were not included, leaving 50 s analyzed for each trial. The video from one participant was not recorded because of a technical problem. The remaining movement data contained some outliers. Five of the 420 trials (1.2%) had extreme values (more than Quartile3 [Q3] + 1.5*Interquartile Range [IQR]; Tukey, 1977) that, upon inspection, were clearly artifactual (e.g., the subject moved very little throughout the trial but had high movement scores produced by wiping or itching the face). The five outlier data points were replaced by that subject's mean movement score (Tabachnick & Fidell, 2007). The movement data were log transformed to meet normality, and the participants' mean values were analyzed in a repeated-measures ANOVA with the factors Modality (auditory-only, auditory-tactile) and Era (new, old).

Results

Ratings.

Groove ratings. Groove ratings were significantly higher in the auditory-tactile condition than the auditory-only condition, as indicated by the main effect of modality, $F(1, 21) = 12.72$, $p =$ .002, $\eta_p^2 = .38$, $\eta_G^2 = .03$. There was no difference in groove ratings for old versus new clips, $F(1, 21) = 2.35$, $p = .141$, $\eta_p^2 =$

.10, $\eta^2_G = .04$, and no Modality × Era interaction ($p = .27$; see Figure 2A).

Enjoyment ratings. Participants rated songs as more enjoyable in the auditory-tactile condition than in the auditory-only condition, as indicated by the main effect of modality, $F(1, 21) = 4.89$, $p = .038$, $\eta^2_p = .19$, $\eta^2_G = .01$. The new songs were rated significantly more enjoyable, as indicated by the main effect of era, $F(1, 21) = 6.86$, $p = .016$, $\eta^2_p = .25$, $\eta^2_G = .15$. The Modality × Era interaction was not significant ($p = .22$; see Figure 2B).

Ease of tapping ratings. There were no significant effects on ease of tapping ratings. Perceived ease of tapping did not differ between auditory-only and auditory-tactile conditions, $F(1, 21) = 0.38$, $p = .542$, $\eta^2_p = .02$, $\eta^2_G < .01$, or between new and old songs, $F(1, 21) = 0.06$, $p = .807$, $\eta^2_p < .01$, $\eta^2_G < .01$, and there was no Modality × Era interaction ($p = .341$).

Tapping data.

Tapping pressure. Analysis of participants' tapping force on the drum machine showed that participants tapped significantly harder for clips in the auditory-tactile condition than the auditory-only condition, $F(1, 21) = 6.35$, $p = .020$, $\eta^2_p = .23$, $\eta^2_G < .01$. There was no effect of era, $F(1, 21) = 1.14$, $p = .30$, $\eta^2_p = .05$, $\eta^2_G < .01$, and no interaction ($p = .88$).

Tapping variability. Tapping variability did not differ between auditory-only and auditory-tactile conditions, $F(1, 21) = 1.59$, $p = .22$, $\eta^2_p = .07$, $\eta^2_G < .01$. Higher tapping variability occurred with the new songs, as indicated by the significant main effect of era, $F(1, 21) = 7.15$, $p = .014$, $\eta^2_p = .25$, $\eta^2_G = .01$. The interaction was not significant ($p = .75$).

Bodily motion from video recordings. Analysis of the amount of body movement in the video recordings revealed no significant main effects of modality, $F(1, 20) = .28$, $p = .605$, $\eta^2_p = .01$, $\eta^2_G < .01$, or era, $F(1, 20) = .91$, $p = .352$, $\eta^2_p = .04$, $\eta^2_G < .01$. However, there was a significant Modality × Era interaction, $F(1, 20) = 6.76$, $p = .017$, $\eta^2_p = .25$, $\eta^2_G < .01$ (see Figure 3).

Breaking down this interaction, for the new clips, participants tended to move more in the auditory-tactile condition than auditory-only condition, $t(20) = 2.21$, $p = .039$, $d = .11$ (Bonferroni-corrected $\alpha = .025$). For the old clips, body movement did not differ between auditory-tactile and auditory-only conditions, $t(20) = 1.26$, $p = .223$, $d = .06$.

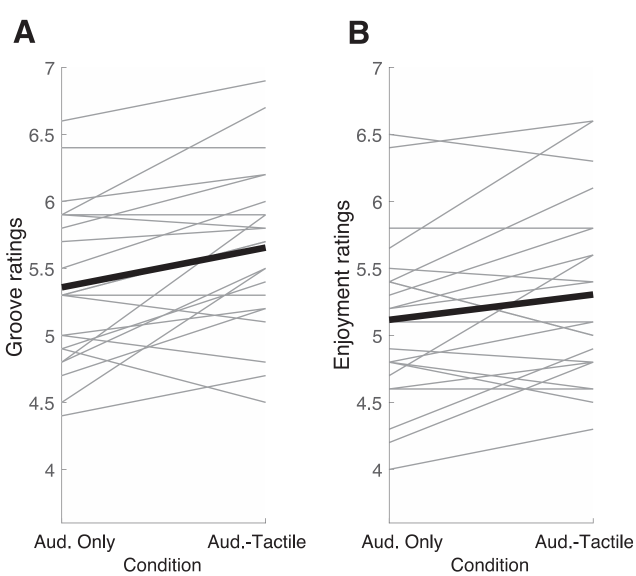

Figure 2. Average groove and enjoyment ratings for the auditory (aud.) only and auditory-tactile (subwoofer) conditions. Overall averages are in black and individual participants are in gray. (A) Groove ratings were significantly higher in the auditory-tactile condition ($p = .002$). (B) Enjoyment ratings were significantly higher in the auditory-tactile condition ($p = .038$).

Summary

To summarize Experiment 1, the auditory-tactile condition yielded higher groove and enjoyment ratings, more forceful tapping, and more spontaneous movement. Here, the tactile stimulation was produced by a subwoofer. Pilot testing suggested that the additional sound produced by the subwoofer was not heard over the stimulus in the noise-isolating headphones and hearing protection. However, these pilot tests were based on subjective evaluations. Therefore, we ran a similar experiment that manipulated audio loudness and directly stimulated the tactile sense with a vibrating backpack.

Experiment 2

Experimental Overview

Experiment 2 examined the effects of music loudness and vibrotactile stimulation on tapping performance and ratings. Experiment 2 used the same 10 music clips (shortened from 60 s to 15 s) and employed a 2 (headphone loudness: moderate, loud) × 2 (modality: auditory only, auditory-tactile) within-subjects design. Here, vibrotactile stimulation was delivered via a tactile-stimulating backpack (Subpac M2X; www.subpac.com) that translates low sound frequencies into vibrations that directly stimulate the body. Participants tapped with each clip and rated each clip for groove, enjoyment, and ease of tapping. We analyzed the effects of modality (auditory only vs. auditory-tactile presentation) and loudness (moderate vs. loud) on tapping variability and pressure and ratings.

Method

Participants. Experiment 2 included 18 undergraduate participants (13 female, five male; mean age = 22.7 years, $SD = 2.9$). Participants were recruited from the psychology subject pool and by word of mouth. To be eligible, participants could not be pregnant, be diabetic, have a pacemaker, or have other health concerns. Six participants had experience playing a musical instrument; these participants averaged 5.0 years of playing a musical instrument. Some participants were compensated with extra credit or $8.00.

Apparatus. For vibrotactile stimulation, participants wore a Subpac M2X backpack that translated low sound frequencies (Subpac response range = 5–130 Hz) to vibrations that stimulated the body. The backpack's elastic straps were tightened for a snug fit. Participants were seated, and the backpack did not touch the

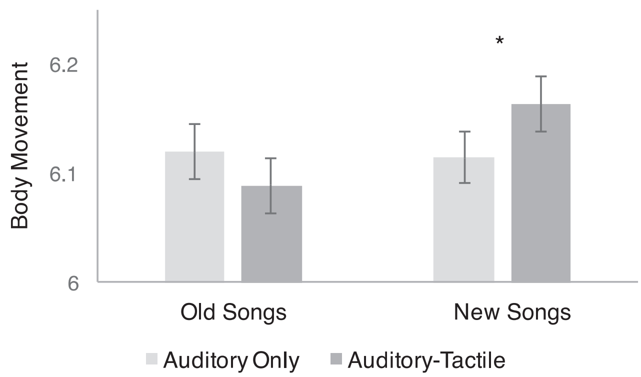

Figure 3. Amount of body movement of the head and neck region extracted from video recordings for the old and new songs in the auditory-only and auditory-tactile (subwoofer) conditions, with single standard error bars. Participants moved significantly more in the auditory-tactile condition solely for the new songs (p = .039).

seatback. The Subpac was set to a moderate setting, which created clear vibrotactile stimulation in the tactile condition.

Participants wore over-ear headphones (Sennheiser HD280 Pro). Each song clip was played in two loudness conditions—moderate and loud. The unweighted dB levels measured by a calibrated microphone (MicW i436) and SPLnFFT app (Version 6.2; Lefebvre, 2016) on the "slow" response setting (Kardous & Shaw, 2014) were approximately 81 to 84 dB in the moderate loudness condition, and 85 to 89 dB in the loud condition.

The experiment was controlled via MAX 7 software. Music was routed to the headphones and Subpac backpack via the headphone outputs on a USB audio interface (Focusrite Scarlett 6i6 2nd Gen). Levels were manually set to the specified levels using headphone gain knobs before each trial. Level settings were not visible, and the manipulation was not described to the participants. Participants tapped on a Roland SPD-6 drum machine, and we recorded tap onset times and velocities (a measure of tap pressure).

Procedure. Participants put on the backpack and headphones and were presented with a musical sample to familiarize with the vibrotactile stimulation. Participants were instructed to tap their right index finger along with the music's pulse (quarter-note level) on the drum machine on the table.

The experiment consisted of 40 total trials. The 10 musical clips were played in each of the four conditions (2 [loudness: moderate, loud] × 2 [modality: auditory only, auditory-tactile]). The stimuli were presented in quasi-random order (the same song could not play back-to-back).

After each trial, participants rated each clip using a 9-point Likert scale on the following questions:

- How much did that clip groove? (1 = *low groove*; 9 = *extremely high groove*)
- How much did you enjoy that clip? (1 = *not at all*; 9 = *very much*)
- How easy was that clip to tap along to? (1 = *difficult*; 9 = *very easy*)

The study was approved by the local institutional review board, and the entire session lasted approximately 40 min.

Analysis.

Ratings. Participants' mean ratings on groove, enjoyment, and ease of tapping were analyzed in repeated measures ANOVAs with the factors Modality (auditory-only, auditory-tactile) and Loudness (moderate, loud).

Tapping data. Taps in the first 2.5 s of the 15-s trials were not analyzed. ITIs more than 50% longer or shorter than the target ITI were excluded (4.0%; Semjen et al., 2000). Trials averaged 20.9 ITIs per trial, and trials with fewer than nine valid taps were not included (3.6%).

Tapping variability was measured as coefficient of variation. Two participants tapped with excessively high variability (more than Q3 + 1.5*IQR; Tukey, 1977), and were excluded from tap-timing analyses. Mean velocity data were not normally distributed and were square-root transformed to meet the assumption of normality. Mean velocity and coefficient of variation were analyzed in repeated measures ANOVAs, with the factors Modality (auditory-only, auditory-tactile) and Loudness (moderate, loud).

Results

Ratings.

Groove ratings. Groove ratings were significantly higher when presented over the tactile-stimulating backpack and headphones compared with the auditory-only condition, as indicated by the main effect of modality, $F(1, 17) = 10.4$, $p = .005$, $\eta_p^2 = .38$, $\eta_G^2 = .19$. Groove ratings were also significantly higher in the loud condition than the moderate condition, as indicated by the main effect of loudness, $F(1, 17) = 21.0$, $p < .001$, $\eta_p^2 = .55$, $\eta_G^2 = .01$. The Modality × Loudness interaction was not significant, $F(1, 17) = 1.96$, $p = .180$ (see Figure 4).

As can be seen in Figure 4, the difference between moderate and loud appears largely in the auditory-only condition. As the purpose of this experiment was to probe potential loudness effects in the observed auditory-tactile effect, it is noteworthy that there was no significant difference between moderate and loud in the auditory-tactile condition, $t(17) = 1.32$, $p = .20$, $d = .15$, whereas the loudness effect was significant in the auditory-only condition, $t(17) = 2.83$, $p = .011$, $d = .28$ (Bonferroni-corrected $\alpha = .025$).

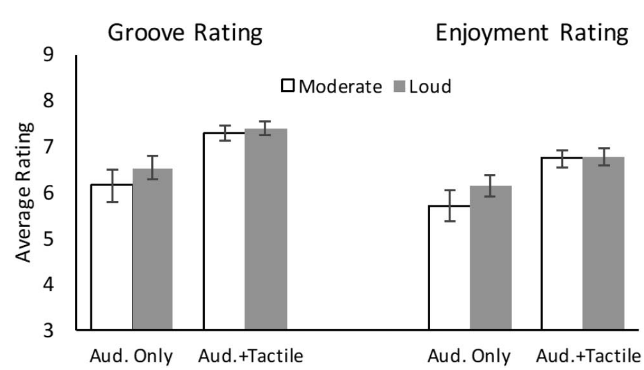

Figure 4. Average groove and enjoyment ratings for the auditory-only and auditory-tactile conditions while played at moderate or loud levels. Error bars depict standard error of the mean.

Enjoyment ratings. Enjoyment ratings yielded similar results: Enjoyment ratings were higher in the auditory-tactile condition than the auditory-only condition, $F(1, 17) = 10.9$, $p = .004$, $\eta^2_p = .39$, $\eta^2_G = .15$, and higher in the loud condition than the moderate condition, $F(1, 17) = 14.6$, $p = .001$, $\eta^2_p = .46$, $\eta^2_G = .01$. The interaction was not significant, $F(1, 17) = 2.79$, $p = .113$.

Again, Figure 4 shows that the loudness differences were more apparent in the auditory-only condition. There was no difference between moderate and loud conditions in the auditory-tactile condition, $t(17) = .48$, $p = .639$, $d = .06$, whereas the loudness difference was significant in the auditory-only condition, $t(17) = 2,76$, $p = .013$, $d = .37$ (Bonferroni-corrected $\alpha = .025$).

Ease of tapping ratings. Ease of tapping ratings yielded no significant effects. Ease of tapping ratings did not differ between the auditory-only and auditory-tactile conditions, $F(1, 17) = 1.13$, $p = .302$, $\eta^2_p = .06$, $\eta^2_G = .01$, or between the moderate and loud conditions, $F(1, 17) = .16$, $p = .694$, $\eta^2_p = .01$, $\eta^2_G < .01$, and there was no Modality $\times$ Loudness interaction ($p = .854$).

Tapping data.

Tapping pressure. Analysis of participants' tapping force showed that participants tapped significantly harder in the auditory-tactile condition ($M = 49.2$, $SE = 5.7$) than the auditory-only condition ($M = 46.5$, $SE = 5.5$), $F(1, 17) = 4.47$, $p = .050$, $\eta^2_p = .21$, $\eta^2_G < .01$ (see Table 2). No difference occurred between the moderate ($M = 47.2$, $SE = 5.6$) and loud ($M = 48.6$, $SE = 5.7$) conditions, $F(1, 17) = 3.93$, $p = .064$, $\eta^2_p = .19$, $\eta^2_G < .01$, and there was no Modality $\times$ Loudness interaction ($p = .203$).

Tapping variability. No differences in the coefficients of variation were observed. There were no effects of modality (auditory only: $M = .057$, $SE = .003$ vs. auditory-tactile: $M = .061$, $SE = .004$), $F(1, 15) = 1.85$, $p = .194$, $\eta^2_p = .11$, $\eta^2_G = .00$, or loudness (loud: $M = .058$, $SE = .004$ vs. moderate: $M = .060$, $SE = .004$), $F(1, 15) = .34$, $p = .571$, $\eta^2_p = .02$, $\eta^2_G < .01$, and no interaction ($p = .470$).

Summary

To summarize Experiment 2, music presented over headphones and the additional vibrotactile backpack yielded higher groove ratings, higher enjoyment ratings, and more forceful tapping. The louder presentation level received significantly higher groove and enjoyment ratings compared with the moderate level, especially in the auditory-only condition. When considering effect sizes (Cohen, 1988; Lakens, 2013), the loudness manipulation on ratings had very small effects ($\eta^2_G = .01$), whereas the auditory-tactile modality manipulation had large effects ($\eta^2_G = .15$–$.19$).

Discussion

In music, low frequencies play a predominate role in laying down the rhythm, and are strongly linked to groove ratings, body movement, and timing (Burger et al., 2013; Hove et al., 2007, 2014; Lenc, Keller, Varlet, & Nozaradan, 2018; Novembre, Varlet, Muawiyath, Stevens, & Keller, 2015; Stupacher et al., 2013, 2016; van Dyck et al., 2013). The underlying mechanism, however, has remained elusive. Music vibrations, especially from low frequencies, can be felt in the body, so we examined whether tactile sensation could play a role in bass–movement links. Participants were presented with music over earphones only or earphones plus vibrotactile stimulation from a subwoofer or a vibrating backpack.

With tactile stimulation, participants rated the songs higher on groove and enjoyment, tapped their fingers harder, and moved more. The subwoofer effects on spontaneous movement were stronger for the more bass-heavy new songs. Songs with more bass produced more subwoofer output (see the online supplemental materials) and more tactile stimulation (a separate group of participants corroborated that the newer bass-heavy songs yielded greater tactile sensation). Together, results from the vibrotactile manipulation and natural variation in bass indicate that tactile stimulation from bass led to increased experiences of groove, enjoyment, and body movement. Although music is often considered a purely auditory experience, tactile stimulation, especially from bass, transforms music perception and engagement.

Tactile Stimulation, Movement, and Music Perception

After establishing links between tactile sensation, movement, and music perception, the next question is, what drives this connection? We discuss three potential mechanisms: (a) a multisensory advantage, (b) the close connection between tactile and motor systems, and (c) embodied aesthetics.

Multimodal advantage. Combining earphones with a subwoofer or vibrating backpack in our experiments created multisensory auditory-tactile stimulation. Multisensory encoding is thought to minimize variance in the perceptual estimate of a stimulus, and accordingly can improve performance in a variety of tasks (Elliott, Wing, & Welchman, 2010; Ernst & Bülthoff, 2004). Auditory-tactile multisensory stimulation (compared with unimodal stimulation) can improve movement timing in gait (Roy et al., 2017), spatiotemporal variability in arm movements (Zelic, Mottet, & Lagarde, 2012), and quality judgments of music (Merchel & Altinsoy, 2014). Auditory and tactile rhythmic information are integrated into a coherent multisensory percept (Huang et al., 2012) and are coded in a common brain network (Araneda et al., 2017). Thus, multisensory encoding of auditory and tactile streams in music could minimize encoding variance and lead to a more stable coherent percept for the motor system to act upon.

Tactile and motor connections. Participants in our study tapped harder and moved more with stronger tactile stimulation. Somatosensory and motor systems have close functional and anatomical links. Due to their close connections and parallel structure, somatosensory and motor cortices are often referred to to-

Table 2
Tapping Data by Condition (Standard Error in Parentheses)

Tapping measure	Modality: Auditory only	Modality: Auditory-tactile	Era: Old songs	Era: New songs
Timing variability (coefficient of variation)	.071 (.005)	.070 (.006)	.065 (.005)	.075 (.006)
Tap pressure (mean MIDI velocity)	39.4 (3.7)	41.0 (3.6)	40.3 (3.6)	40.0 (3.9)

gether as the *sensorimotor cortex*. Somatosensory areas project heavily to a cerebellar loop critical for tuning and executing movement, and thus can impact motor output timing (Bear, Connors, & Paradiso, 2016; Bijsterbosch et al., 2011). Additionally, somatosensory stimulation of the body increases the excitability of motor-cortex projections to those stimulated body parts and affects their propensity to move (Kaelin-Lang et al., 2002). Thus, somatosensory stimulation from music could plausibly increase the motor excitability and the propensity to move.

Embodied aesthetics. In our study, when participants felt the music in their bodies, they moved more with the music and reported greater aesthetic appreciation of the music. These findings support an embodied approach to aesthetics, which proposes that sensorimotor coupling and bodily states can shape cognition and perception (e.g., Leman, 2008). Neuroimaging research shows that aesthetic appreciation involves brain areas involved in bodily and interoceptive processing. In a meta-analysis of 93 neuroimaging studies on positive aesthetic appraisal, the most concordant area of activation was the anterior insula, an area associated with touch, visceral, and interoceptive perception (Brown, Gao, Tisdelle, Eickhoff, & Liotti, 2011). In our study, vibrotactile stimulation was applied to body areas including the chest and gut; this would presumably increase insula activation and could drive the increased aesthetic ratings. If aesthetic appraisal is rooted in interoceptive processing (Brown et al., 2011), then bodily stimulation from bass in music could be perceived as an interoceptive experience and influence aesthetic interpretation.

Low-Frequency/Movement Links

Although the current study provides compelling evidence for the role of tactile sensation in bass–movement links, tactile sensation alone does not fully account for the links. Some previous studies establishing links between bass, movement, and timing have used loudspeakers (Burger et al., 2013; Hove et al., 2014; Stupacher et al., 2016, Study 1; van Dyck et al., 2013), whereas others used only headphones that would not produce bodily tactile sensation (e.g., Hove et al., 2007; Stupacher et al., 2013, 2016, Study 3). Tactile stimulation is one of multiple, non-mutually-exclusive factors in the low-frequency/movement-groove links. Other factors include vestibular processing (Todd & Lee, 2015), and encoding in the auditory pathway (Hove et al., 2014; Nozaradan et al., 2016; Zuk et al., 2018). Note that vestibular activation alone cannot account for the links because most studies showing bass–movement links played stimuli at loudness levels below the threshold for vestibular activation. Although auditory encoding is a promising factor, recent modeling work showed that bottom-up models of the auditory nerve and midbrain were insufficient to produce activity locked to the musical beat, suggesting that an additional mechanism is needed (Zuk et al., 2018; see also Lenc et al., 2018). Future work will help decipher the relative contributions of various factors.

Current and previous findings point to links between low frequencies, groove, and movement; however, bass is clearly not the only factor in the multifaceted phenomenon of groove (Wesolowski & Hofmann, 2016). For example, filtered music highlighting the bass received lower groove ratings and less pupil dilation than filtered music highlighting the mid- and high frequencies; strongest groove ratings occurred for unfiltered music, indicating the importance and interplay between pulse, rhythmic, and melodic information across all frequency bands (Bowling, Graf Ancochea, Hove, & Fitch, 2019; cf. Lustig & Tan, 2019).

Other open questions include whether the bass–movement link is learned through exposure to music that places rhythmic information in the bass; whether similar low-frequency effects exist in infants with limited musical exposure; and whether bass–movement associations are driven by evolutionary pressures—for example, low-frequency sounds might signify danger at a distance (e.g., from a larger animal, stampede, earthquake, or storm), and thus should alert and activate the motor system. Cross cultural, developmental, and comparative species studies could be illuminating.

Loudness

Finally, we consider loudness. In Experiment 1, the subwoofer in the auditory-tactile condition increased the overall loudness in the car. Participants wore sound-isolating in-ear earphones and over-ear hearing protection, and we did not notice increased loudness over the concurrent earphone presentation (whereas the tactile sensation was clear). However, we did not measure loudness in the ear canal, so increased loudness from the subwoofer is possible and might have affected groove ratings. In Experiment 2, we manipulated loudness and observed a small, but significant, effect of loudness on subjective groove ratings, especially in the auditory-only condition. This effect of loudness on groove ratings contrasts with previous work, wherein systematic manipulation of playback loudness (high, medium [-6 dB], and low [-12 dB] intensities) did not affect the subjective ratings of groove (Stupacher et al., 2016), and overall loudness was not considered an attribute of groove (Janata et al., 2012). Although the tactile effects were far more salient and pronounced than loudness effects, loudness should be considered and studied in future work on groove (Lustig & Tan, 2019). For example, dance music is often played at loud volumes, and it is hard to imagine dancers uncontrollably moving to quiet music. In contrast, subjective groove ratings might remain high for, say, Stevie Wonder's song "Superstition," played at a relatively quiet level. This suggests a close, but not one-to-one, relationship between actual movement induction and subjective groove ratings that could be affected by loudness.

Implications, Future Directions, and Conclusion

Our results suggest that tactile stimulation from music can be harnessed to increase engagement and movement in a variety of applications. A common method to induce movement in music is the bass drop, wherein the bass or drumbeat is "dropped" back into the music. After a drop in electronic dance music (EDM), dancers move more and synchronize more with each other (Solberg & Jensenius, 2017). Because EDM is among the most bass-heavy genres and is played at high volumes (Burton, Murphy, & Brereton, 2017; Dayal & Ferrigno, 2014), such bass drops are likely felt in the body. Adding tactile stimulation to auditory rhythms could boost movement induction, and therewith improve the efficacy of rhythmic stimulation in applications such as rehabilitation (Hove & Keller, 2015; MacDonald et al., 2013), exercise (Karageorghis et al., 2012), and increasing social cohesion (Keller et al., 2014; Rennung & Göritz, 2016; Stupacher, Maes, Witte, & Wood, 2017).

Any discussion of the importance of tactile sensation in music perception should consider deaf and hearing-impaired listeners. Deaf (and hearing) individuals listen to and enjoy dancing to music (Darrow, 1993), can perceive sound vibrations through the surface of their skin (Yamada, Ikuji, Fujikata, Watanabe, & Kosaka, 1983), and can synchronize with vibrotactile music (Tranchant et al., 2017). At concerts, hearing-impaired individuals commonly hold makeshift technologies such as plastic bottles or balloons or stand near loudspeakers to increase tactile sensation.

Hearing individuals may also attempt to intensify tactile sensation through loud levels, but such exposure can damage hearing. Risk of hearing damage could be reduced with vibrotactile reinforcement. Vibrotactile stimulation (e.g., via vibrational platforms or voice coils embedded in chairs or backpacks) is already popular in home-theater and gaming applications and is emerging in musical applications (Merchel & Altinsoy, 2014; Russo et al., 2012). Finally, work with high-powered infrasubwoofer systems (below 50 Hz) showed that increasing levels of low frequencies led to lower overall preferred loudness; such low frequency extension is felt in the body and could be used to reduce overall sound pressure at concerts and the risk of hearing damage (Burton et al., 2017).

In conclusion, we show that multisensory auditory-tactile stimulation from music can increase enjoyment and groove ratings and bodily movement. These effects could stem from a multisensory encoding advantage, close connections between tactile and motor systems, and embodied aesthetics. Reinforcing music with tactile stimulation could be used to induce movement in many applications and to reduce hearing loss. Although music is commonly considered a purely auditory experience, music is multisensory—in fact, "feeling the beat" can arise from sound pressure stimulating touch receptors on the body.

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