CRACKING THE PITCH CODE OF MUSIC-MOTOR SYNCHRONIZATION USING DATA-DRIVEN METHODS

Léo Migotti[1], **Quentin Decultot**[2], **Pierre Grailhe**[2], and **Jean-Julien Aucouturier**[2]

[1]Institut Jean Nicod (CNRS - EHESS - ENS) - Département d'Etudes Cognitives, Ecole Normale Supérieure, Paris, France - PSL Research University

[2]Department of Robotics and Automation - FEMTO-ST Institute (CNRS/Université de Bourgogne Franche Comté), Besançon, France

ABSTRACT

The study of auditory-motor synchronization with music has been so far mostly concerned with timing. For instance, research has established that people are able to spontaneously coordinate with musical beat when walking or running [1]. Yet, music is more than a metronome, and the relation between the spectral dimension of music, i.e. parameters such as its pitch, timber, or harmonic structure, and simultaneous motion remains nearly unknown. Here, we introduce a novel data-driven paradigm in which participants were asked to walk on a treadmill while listening to a large variety of musical tones systematically varied in pitch. Using analysis techniques inspired by psychophysical reverse correlation, we show that participants' gait patterns while walking to music spontaneously encode pitch height: despite being instructed to simply synchronize in time, participants steps were both longer and heavier on tones with lower pitches. These findings reveal that, similarly to time perception, pitch cognition is not purely 'disembodied' and suggest that listeners' spontaneous motor reactions to pitch might ground their ability to mentally represent music.

***K*eywords** music | auditory-motor synchronization | pitch | walking | gait

Music in all human cultures is often experienced in motion, be it in dance, trance, military marches or lullabies [2] and, even when we stand still, how we hear it remains strongly influenced by our motor system [3]. Because both music and movement unfold in time, the idea that there should exist a temporal mapping between the two appears intuitive, and indeed a vast body of research has shown that walking [1] and running speed [4] spontaneously align with beat frequency (tempo). More generally, an extraordinarily rich literature has investigated people's ability to move in synchronization with external auditory stimulation [3, 5], be it with classical finger tapping studies [6], limb movement [7] or dancing [8]. Expressive timing in music performance, such as the final *ritardando* in the Baroque and Romantic period [9], also appear to share much of the temporal dynamics of motion [10].

Yet, music is more than a sophisticated metronome and, while we know a lot about how music maps to motion 'horizontally' (in the time domain), little is known about whether the other 'vertical' (i.e. spectral) dimensions of music such as pitches, harmony and timbre relate to movement.

Indeed, while theories of embodied music cognition [11, 12] have been quick to extend beyond temporal/rhythmic parameters to propose that spectral aspects of music such as musical tension [13], pitch contours [14] and consonance [15] also share cognitive representations with the physical features of body movement, empirical demonstrations of such links remain few and almost entirely limited to explicit judgements. For instance, in forced association tasks between music and dynamic visual stimuli, listeners tend to associate rising pitch contours with ascending motion [14]; random pitch intervals with jerky physical motion [10]; dissonant and unstable chords with motion having low physical stability [16, 17]; and alternations of consonant and harmonically-close chords with the imagined situation of someone walking (the "Sorcerer's Apprentice effect" [18]).

Such experiments demonstrate that music is able to evoke motion percepts or interpretations in listeners, which in itself is relatively uncontroversial [19, 16, 17, 20] and is also reminiscent of well-studied pitch-space associations [21]. It is however an entirely different question whether these associations are based on sensorimotor representations that are able to directly interact with the human motor system. For instance, if listeners in [18] reported less association to an imaginary walking situation for musical sequences including dissonant than consonant chords, does this mean that dissonant events would also disrupt their actual gait if they were to synchronize their steps to them?

In [22], musical dissonance was found to alter the finger-tapping performance of participants asked to synchronize to either two dissonant or two consonant chords: in tasks where stimuli were dissonant, participants were less accurate in tapping, and remained less steady and regular after the sequence had stopped. However, in such a paradigm with a limited number of stimuli presented in separate blocks, it is difficult to conclude that it was the spectral/tonal properties of each individual sound event that matched and interfered with the corresponding motor event, or whether dissonance induced a more general cognitive or attentional load which interfered with the task on a broader and non-specifically-motor way [23].

Here, we introduced a data-driven paradigm in which participants were asked to walk on a force-sensing treadmill while listening to a large variety of musical tones systematically varied in pitch. Such a paradigm has tremendous advantages for our research question. First, because each tone can be time-stamped to the X-Y-Z force time-series of the corresponding step, we were able to investigate how each individual sound event interferes with the corresponding motor event, similarly to the event-related methodology in neurophysiology. Second, because we can have participants step along with thousands of successive tones with randomly different pitch, the resulting data is amenable to analysis with psychophysical methods inspired by reverse-correlation and we are able to infer what exact part of a participant's steps is statistically influenced by pitch, in a purely data-driven manner.

Results

We let N=20 (female=9, male=11) young, Western, educated participants walk on a force-sensing treadmill while they listened to a 10min. sequence of musical tones (piano notes), whose pitch was randomly sampled within the two medium octaves of the western 12-tone chromatic scale (among 240 possible tones between C4/255.8Hz and B5/1045.8Hz, sampled at a frequency resolution of 10% of a semitone). Each successive tone in a sequence was repeated three consecutive times, at a rate of 75 events per minute (IOI=.8s). We then epoched the force time-series into individual steps and, in the manner of event-related analysis in electrophysiology, paired each step with its corresponding sound event. This resulted in an average M=668 trials per participant (see *Materials and Methods* for details). Six participants were removed because more than 20% of their steps were not synchronized with a musical event, leaving N=14 (female=6, male=8) for subsequent analysis.

Participants' step data displayed a saddle shape in the vertical and medio-lateral force dimensions and a progressive transition from anterior to posterior force, which is the expected shape for a stance including an initial, braking heel strike followed by a final propulsive 'toe off' (see e.g. [24]). Step duration was stable at M=105ms (SD=71ms). Consistent with similar synchronization tasks in the literature [3], we found that participants' steps steadily anticipated the onset of the notes, with a mean onset time occurring M=608ms (SD=83ms) after the start of support of the corresponding step, roughly at a local minimum of antero-posterior and latero-medial forces (Figure 1).

To analyze the relation between step force data and musical pitch, we used a data-driven technique inspired by the psychophysical method of "classification images" [25]. Classification images indicate the strength of the statistical association between force at each time point and the z-scored, log-transformed pitch of the corresponding note: at each time point, we tested whether the images differed from zero with one-sample t-tests (see *Materials and Methods* for details).

Participants' classification images showed a cluster of statistically-significant negative associations between musical pitch and vertical force from t=800 to 1000ms ($t(13) \in [-2.20,-3.58]$, all $ps < .046$; Figure 1), showing that steps that occurred on lower notes exhibited more positive vertical force in their later, propulsive phase. This cluster co-occurred with a similarly negative association in the latero-medial dimension (from t=780 to 880ms; $t(13) \in [-2.24,-3.71]$, all $ps < .043$), indicating a medial direction consistent with the final toe off. There was no association between musical pitch and participants' steps in the antero-posterior dimension.

We then grouped each participant's trials and computed separated classification images for steps that occurred on the first, second and third repetition of each note. This revealed that the above effect was driven by negative associations that occurred specifically the second and third consecutive time any given note was heard and stepped onto. In the vertical force dimension, step 2 had a significant negative cluster from t=710 to 810ms ($t(13) \in [-2.23,-2.99]$, all $ps < .044$) and step 3 from 810 to 1060ms ($t(13) \in [-2.18, -4.01]$, all $ps < .049$), but none in step 1 (Figure 2-top).

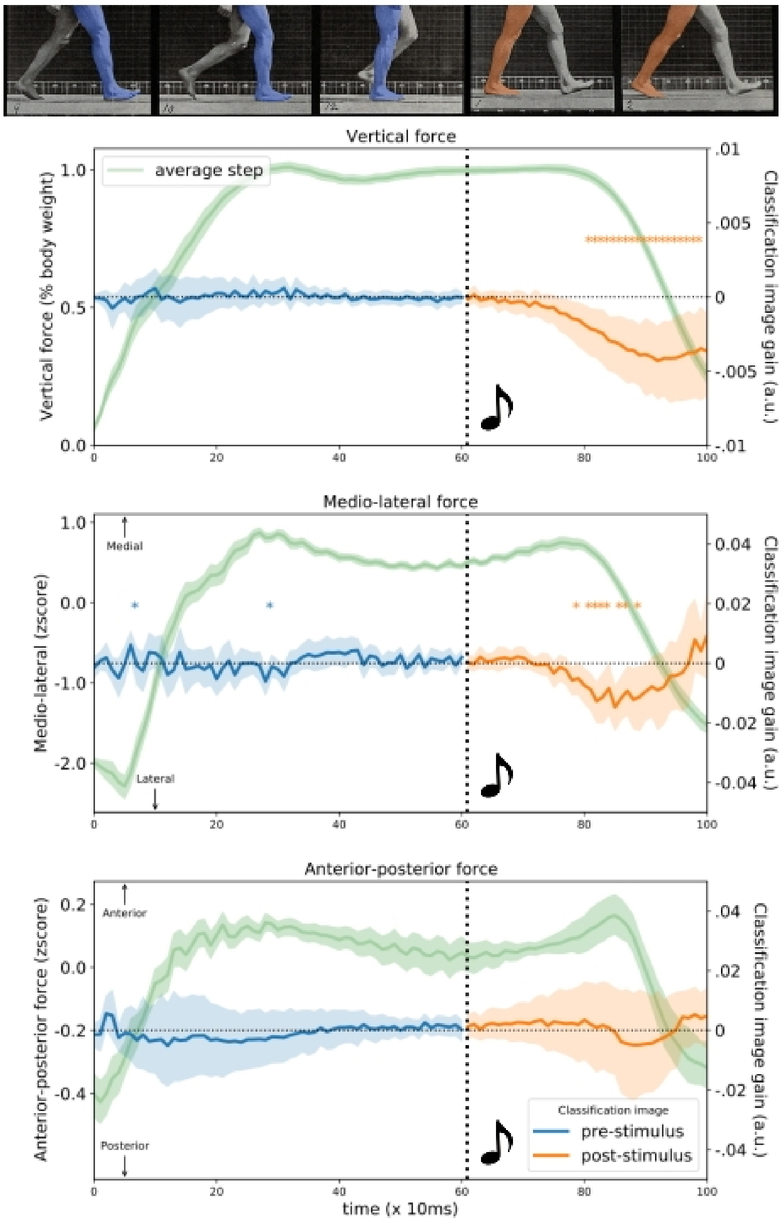

Figure 1: **Steps that occurred on lower-pitch notes exhibited more positive vertical force in their later, propulsive phase. Green:** Average vertical (top), medio-lateral (middle) and anteroposterior (bottom) force data for all participant steps (M=668 steps per participant). Participants' step data displayed the expected saddle shape in the vertical and medio-lateral force dimensions. **Blue/orange:** Classification images indicating the direction of the statistical association between force at each time point and the z-scored, log-transformed pitch of the corresponding note, before (blue) and after (orange) note onset (marked by dashed line and note icon). Classification images showed a cluster of statistically-significant negative associations between pitch and vertical and medio-lateral force, post-onset, in the toe-off phase of the step.

This pattern of data is consistent with the interpretation that participants' steps performed on tones with lower pitch were heavier (showing more vertical force), but also that these steps were longer: because classification images were computed by aggregating steps of varied duration, it is possible that steps that had (positive) vertical force for longer amounts of time occurred more often for lower pitch, and that shorter steps, whose vertical force reached zero earlier, were conversely associated with higher pitch. For a confirmatory analysis, we therefore computed separate repeated-measure correlations [26] between the (log-transformed) pitch in each participant's trials and the weight (computed as the mean vertical force between 800 and 1000ms) and duration of the corresponding steps: both correlations were significant at step 3 (weight: $r(2291)=-0.043$ [-0.08, -0.0], $p=.03$; duration: $r(2291)=-0.066$ [-0.11, -0.03], $p=.001$; Figure 3). In addition, to verify that musical pitch had an influence on step weight beyond the effect on step duration, we repeated the classification image analysis by normalizing all steps to 100% duration (figure 2-bottom). Classification images in the vertical dimension continued to exhibit a significant negative cluster at step 2 (from t=670 to 740ms, $t(13)\in[-2.23,-3.72]$, all $ps < .044$), and repeated-measure correlations between log pitch and weight in the same range (700-750ms) remained consistent, albeit non significant: $r(2286)=-0.034$ [-0.08, 0.01], $p=.09$.

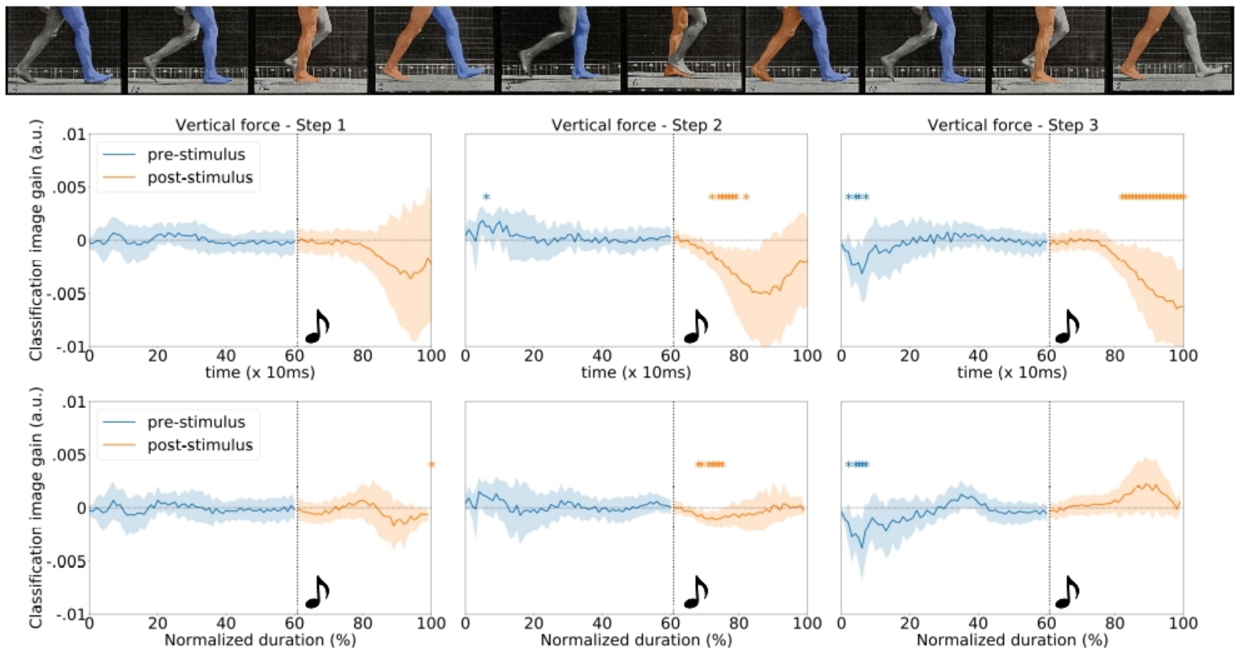

Figure 2: **Negative associations between vertical force and pitch that occurred specifically the second and third consecutive time any given note was heard and stepped onto, and remained even when the effect of step duration was normalized**. **Top:** Classification images between vertical force at each time point (actual duration, in ms) and the z-scored, log-transformed pitch of the corresponding note, before (blue) and after (orange) note onset; computed separately for the first, second and third consecutive repeat of each note. **Bottom:** Classification images in the same conditions, computed by normalizing all steps to 100% duration.

All in one, we therefore found converging evidence that participants' steps were *both* longer and heavier when they stepped on musical notes with lower pitch. The effect on vertical force when lowering pitch from B5 to C4 was M=+3.6% [3.05%,4.19%], and the effect on duration was M=+1.4ms [1.19ms,1.61ms].

Finally, to test whether the influence of pitch was an effect of musical expertise, we tested for possible differences between the classification images of musically- and non-musically trained participants, using paired t-tests at each time point. There was no difference between both types of participants at any time point, for any of the effects we tested, regardless of whether we used participants' reported years of training or a standard test of musicianship (Gold-MSI) as a cutoff measure (e.g. vertical force, all ps > .55 from t=80 to 100ms).

Discussion

To investigate whether musical pitch influences the gait parameters of simultaneous motion, we used a data-driven paradigm in which participants were asked to walk on a treadmill while listening to a large variety of musical tones systematically varied in pitch. Using analysis techniques inspired by psychophysical reverse correlation, we show that participants' gait patterns while walking to music spontaneously encode pitch height: despite being instructed to simply synchronize in time, participants steps were both longer and heavier on tones with lower pitches. This effect was demonstrated vertically and latero-medially in the toe-off stage of the steps (Figure 1); it occurred specifically the second and third consecutive times any given note was heard (Figure 2); and it was present similarly in musically- and non musically-trained participants.

Despite our analysis being entirely data-driven, the temporal extent of the effects found here (from 700 to 1000ms within step) was consistent with the constraints holding on the sensory-motor system. First, none of the effects occurred before the onset of the corresponding sound event, which was on average around 600ms within step. Second, the fact that the effect of a new note did not occur in the first time this pitch was heard is consistent with the sensory latency of processing musical pitch [27] and the motor latency of initiating walking motor commands [28], which would collectively leave little time for the central nervous system to initiate any modulation of walking gait within the

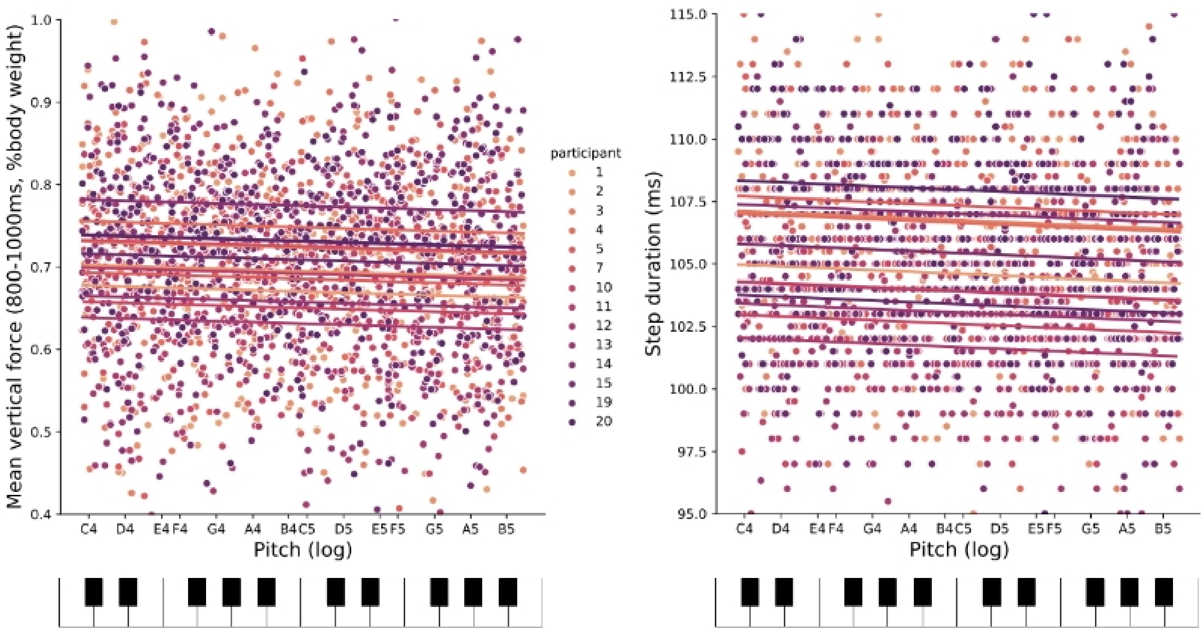

Figure 3: **Confirmatory analysis that participants' steps performed on tones with lower pitch were heavier but also longer. Left:** Negative repeated-measure correlation between the (log-transformed) pitch in each participant's trials and the toe-off weight (computed as the mean vertical force between 800 and 1000ms) of the corresponding step. **Right:** Negative repeated-measure correlation between the log-transformed pitch in each participant's trials and the duration of the corresponding step.

100-400ms after the sound is first heard. In a comparable psychoacoustic study [29], motor reaction times (button press) measured in response to pitch deviations of the range used here (2 to 13 semitones) were in the range of 750-1100ms post-onset. At a rate of 75bpm (IOI=800ms), such latencies would correspond to the range [-50ms, + 300ms] around the onset of the *next* consecutive note event, which is very similar to what we see here.

Our finding that our participants associate low pitch with longer and heavier motion is interesting to discuss in the context of the larger theoretical debate whether music can be said to have meaning [30] and a semantics [16, 17]. Indeed, our results are reminiscent of a number of other studies reporting cognitive associations between musical pitch and other spatial concepts, such as elevation - the SMARC effect [21] - or speed [31]; between falling pitch contours and descending motion [14]; between the repetition of low-pitched sound and quantity of motion in dance music [32]; between consonant and stable chords and motion stability [16, 17]; and between alternations of consonant and harmonically-close chords and the imagined situation of someone walking [18]. That musical pitch can be interpreted as *representing* weight or stability therefore reinforces an emerging view that music is not only iconically referential, e.g. in the mapping between melodies and animal characters in Prokofiev's Peter and the Wolf [33], but can support a rich typology of semantic inferences about the properties and actions of non-auditory objects [17], in the same sense as language, gestures or visual animations [34].

Even though the emergence of such representations is often studied in a musical context, one may question whether they are specifically musical, or of a more generic cognitive nature. Many existing cognitive mappings between, e.g., pitch and speed [31] are thought to result from the associative learning of events co-occurring in the natural environment (e.g. doppler effects [35]). For the behavior demonstrated here, it appears plausible that participants have developed sensory associations between heavy objects that hit the ground forcefully, and the resulting low or deep impact sounds, and that there is nothing intrinsically musical to this mapping. This suggests, as others have also proposed, that some of the semantics of music is "continuous" with generic auditory cognition [16], in the same way that musical emotions are thought to be partly evoked by mimicking the acoustic properties of non-musical emotionally significant events, such as thunder [36], or emotional vocalizations [37]. In the present study, the fact that musically and non-musically trained participants showed similar effects shows that musical expertise is in any case not necessary for the association between pitch and stepping weight/duration to exist.

In comparison with previous work, we find remarkable that the present results did not emerge from self-report tasks asking participants to explicitly compare stimuli, but from physiological data in an implicit walking task where participants were not instructed to pay attention to the pitch quality of the musical events. This suggests that part of these associations do not only derive from 'disembodied' mental representations, but are able to recruit sensorimotor representations that directly interact with the human motor system, in our case modulate the force characteristics of participants' gait. From the point of view of music semantics, the fact that musical pitch sequences should modulate overt walking behavior suggests that music might not only able to refer to or denote external objects or events [38], but also internal events (i.e. happening in the listener's body): if music has meaning, then maybe part of this meaning is about the listeners themselves. This is reminiscent of the question whether the smile-like spectral features of certain musical instruments can induce positive emotions and the imitation of a smile in listeners [37].

A related question concerns the cognitive 'chronometry' of the emergence of music-semantic representations relative to physiological responses: it is possible that pitch is first processed semantically as denoting heavier and longer steps, and that this representation then interacts with the (incidental) execution of the walking motor program; alternatively, pitch may first trigger an actual (or simulated) physical reaction, from which a mental representation is then lifted. Further experimental work, for instance with paradigms which examine stimulus evaluation while inhibiting or interfering with simultaneous motor behavior [39, 40], will be needed to clarify the interaction of cognitive-evaluative and sensorimotor processes in the behavior exhibited here. Conversely, it is also possible that motor actions such as stepping lightly or heavily can interfere with specific auditory perception tasks, in the same way that stepping on every second or third beat of a musical phrase can influence its perception as a march or a waltz [41] or, in the visual domain, that walking can modulate reaction time to the occurrence of far vs. near objects [42]. Finally, we believe our results may also motivate clinical applications where low-pitched sounds are used to stabilize gait in e.g. Parkinson's patients [43] or stroke survivors [44], possibly in conjunction with other well-described beneficial effects of tempo synchronization [3].

Finally, if musical pitch has an effect on gait, it appears possible that more complex spectral properties (rich harmonic structure, timbre, consonance) do too. The present data-driven paradigm (for which we provide all experimental software as open-source[1]) therefore opens up a vast domain of research to investigate the interaction of each of these dimensions with human motion, and elucidate the intricate sensorimotor mechanisms that subserve our perception of such elusive multimodal percepts as motor and musical stability [45], predictive uncertainty [46], tension [47] or smoothness/jerkiness [10].

Materials and Methods

Participants

N=20 young (M=25.5, SD=7), Western, educated participants (male: 11, female: 9) participated in the experiment. All participants gave their informed consent prior to the experiment and were debriefed about the purpose of the research immediately after. Each of them received a 15 euros lunch voucher as a compensation.

N=13 participants (65%) self-declared as musicians (M=8.6y of musical training). In addition, all participants completed a short self-report survey consisting of 15 items extracted from the Goldsmith Music Sophistication Index (MSI) measuring their active engagement with music, perceptual abilities, musical training and singing abilities [48]. Questionnaire scores significantly differed between musicians (M=51.4) and non-musicians (M=38.8; t(11.7)=2.66, p=.0209, [2.26, 22.79], Cohen's d=1.3).

Procedure

We tasked our participants to walk on a force-sensing treadmill while listening to generative music constituted by a large variety of musical tones systematically varied in pitch. Prior to each session, participants were asked to wear comfortable shoes, and stood still once on each side of the treadmill for calibration. Treadmill was then started, its speed set at a slow walking speed (M=2.5km/h) and participants practiced walking to the sound of a metronome (75 bpm, period=0.8s) until they were comfortable with the task. Participants were then instructed to walk on the treadmill and to synchronize their steps with a sequence of piano notes they heard through headphones, without the support of handrails and as naturally as possible. Each session used an uninterrupted sequence of 750 sound events, played at a constant rate of 75bpm (period=0.8s), amounting to a total of 10min. Participants were given the cover story that we were interested in how well people could adjust their timing to the period of the sounds, and that the pitch content of the notes was irrelevant and just introduced for variety. They were instructed to focus their attention on walking

[1] `https://github.com/neuro-team-femto/treadmill`

synchronously with the sequence. After the session, participants were explained the true purpose of the experiment, namely that it was to examine the effect of pitch height on their walking gait.

Apparatus

Step data was acquired using a legacy instrumented treadmill (Tecmachine ADAL3D), equipped with two force platforms measuring the time series of forces of each limb during walking, along the X (medio-lateral), Y (antero-posterior) and Z (vertical) dimensions. The treadmill was interfaced to our software using a generic USB I/O acquisition card (NI-6008, National Instrument). Data was acquired at a sample rate of 1000Hz, and recorded continuously for the duration of one experiment (10min). While they walked on the treadmill, participants were presented with sequences of musical notes using commercial wireless headphones (Beats Solo3). Using custom software written in Python (`https://github.com/neuro-team-femto/treadmill`), we synchronized step data acquisition with the triggering of each musical note, in order to be able to associate the time series of each step to the corresponding sound event.

Sound stimuli

Sound stimuli were extracted from the University of Iowa Musical Instrument Samples (MIS) dataset `https://theremin.music.uiowa.edu/MIS.html` and consisted in high-quality recordings of a Steinway & Sons model B piano, made in Nov. 2001 at the Voxman Auditorium, University of Iowa (Iowa City, USA) using a Neumann KM84 microphone. We selected one recording for each of the 24 notes spanning octaves 4 and 5, i.e. from C4 (263.3 Hertz, Hz) to B5 (1016.0 Hz), by steps of one semitone), played at medium dynamics (*mf*). To ensure that stimuli could be accurately synchronized to step data later in the experiment, we then normalized the loudness of the files, trimmed any initial silence (using a threshold at -30dB) and faded out each recording after 1.5sec so that all had the same duration.

We then produced a second derivative dataset by applying an algorithmic pitch transformation (pitch shifting) to each of the original files, in such a way that its fundamental frequency was reduced by 10, 20, 30, 40 or 50% of a semitone (or cents). Pitch shifting was done using a Python implementation of the phase vocoder algorithm [49]. Finally, we ran an automated pitch analysis algorithm (SWIPE, [50]) to document each musical note with its actual fundamental frequency, after pitch shifting. This resulted in a dataset of 240 musical notes, spanning the entire range of frequencies from a low-tuned C4 (255.8Hz) to a high-tuned B5 (1045.8Hz), by steps of 10% of a semitone (10 cents, corresponding to logarithmically increasing steps in Hz, from 1.5Hz at C4 to 5.9Hz at G5).

We then presented each participant with a random sequence of 750 sound events extracted from this dataset of 240 notes. Notes were played at the constant rate of 75bpm (period=0.8s), amounting to a total of 10min, and each note was repeated three consecutive times. In pilot studies, we experimented with several configurations, using only original recordings or using all pitch-shifted recordings, using notes from 2 octaves or 5 octaves, and using isolated or repeated notes. Because we found that, consistently with the literature [3], participants tended to anticipate the onset of the note to synchronize their steps (Figure 1), we decided to present each note three consecutive times so that steps 2 and 3 could be initiated and performed after one complete hearing of the corresponding note.

Step data signal processing

For each participant, we normalized the two time series of their left and right foot force data as percentage of the force corresponding to their standing weight, measured during calibration. We then resampled all time series at 100Hz and removed any linear trend across each session (due to treadmill electronics). Next, we segmented each participant's time series into individual steps using a simple threshold procedure: candidate start- and endpoints for each step were positioned where the vertical force time series crossed (resp. upwards or downwards) a threshold set at 5% of the amplitude range of the series, and we eliminated false positives that had a step duration shorter than 100ms. Finally, we associated each step with its corresponding sound event by selecting, for each step, the first sound whose time onset was between the step's start and end point. Steps for which no sound events were found (e.g. after the sequence ended) were deleted from the dataset, and steps for which more than one sound event were found were associated with the earliest of these events. The above procedure resulted in an average M=668 trials per participant (min=403, max=750, SD=114), each associating the time-series of a single step and the characteristics of the corresponding musical note. All analysis code (Python) is available on `https://github.com/neuro-team-femto/treadmill`.

Outlier selection

We selected as outliers participants who had more than 20% of their steps not associated with a musical event, on the rationale that this indicated a misunderstanding of the task, a low capacity to synchronize their walking gait to external sounds, or long attentional lapses. N=6 participants were removed from the dataset, leaving 14 participants for analysis (male: 8, female: 6).

Data-driven analysis

While previous work has focused on quantifying step data based on predefined characteristics (such as step and stride length, or heel and toe contact force [24]) and contrasting them along predefined stimulus properties (such as consonance, [22]), we use here a data-driven strategy in which we let regions showing significant associations with sound emerge from an *a posteriori* analysis of participant responses to many, systematically-varied sounds.

In more details, we use a method inspired by the psychophysical technique of "classification images" [25]. For each participant k, we compute a weighted time-series $\tilde{p}_k(t)$ by multiplying the time series of each the participant's n steps $p_i(t)$ (with $t \in [0, 100]$ for a 1-sec step sampled at 100Hz) by a weighting factor z_i corresponding to the z-score of the log-transformed pitch of the corresponding note. We then average these weighted time-series over all n steps: $\tilde{p}_k(t) = \Sigma_{i=1}^{n} p_i^k(t) z_i$. Doing so, we negatively weight the patterns of step data that are associated with sound events with lower-than-average pitch, and positively weight those associated with high pitch. The resulting "classification image" $\tilde{p}_k(t)$ is itself a time-series analog to a single step, which represents the strength of statistical association between step force and musical pitch, as a function of time.

Note that for this analysis, it is important that the distribution of stimuli is non-skewed, so that classification images that do not differ from zero indicate no statistical association. Because musical notes are spaced logarithmically in Hz (lower notes are closer to one another that higher notes) the theoretical distribution of random stimuli is skewed towards low Hz, while it is uniform in log-Hz (or cents). For this reason, time-series data is weighted with the logarithm of the pitch (log-Hz), rather than in linear Hz, in the above calculation.

Ethics

The experiment was approved by the ethics evaluation committee of lnserm, the lnstitutional Review Board (IRB00003888, IORG0003254, FWA00005831) of the French lnstitute of medical research and Health, under the Opinion number 22-925.

Author contributions

LM, PG, JJA designed the experiment; QD and JJA developped the experimental apparatus and collected data; LM, QD, JJA analysed the data; LM and JJA wrote the manuscript, with contributions from PG.

Acknowledgments

This work was supported by ERC Grant StG 335536 CREAM (to JJA) and ERC Grant No 788077 Orisem (to P. Schlenker). Research was partly conducted at DEC, Ecole Normale Supérieure - PSL University. DEC is supported by grant FrontCog ANR-17-EURE-0017. Photographs of walking man featured in Figure 1 and 2 are adapted from public-domain photogravure by Eadweard Muybridge, 1887, Wellcome Collection gallery `https://wellcomecollection.org/works/v5t3b2ar`.

References

[1] Frederik Styns, Leon van Noorden, Dirk Moelants, and Marc Leman. Walking on music. *Human Movement Science*, 26(5):769–785, 2007.

[2] John Blacking. *How musical is man?* University of Washington Press, 1974.

[3] Bruno H. Repp and Yi-Huang Su. Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, 20(3):403–452, 2013.

[4] Edith Van Dyck, Bart Moens, Jeska Buhmann, Michiel Demey, Esther Coorevits, Simone Dalla Bella, and Marc Leman. Spontaneous entrainment of running cadence to music tempo. *Sports medicine-open*, 1(1):1–14, 2015.

[5] Michael H. Thaut and Mutsumi Abiru. Rhythmic auditory stimulation in rehabilitation of movement disorders: A review of current research. 27(4):263–269, 2010.

[6] Leon Van Noorden and Leen De Bruyn. The development of synchronization skills of children 3 to 11 years old. In *Proceedings of ESCOM—7th Triennial Conference of the European Society for the Cognitive Sciences of Music. Jyväskylä, Finland: University of Jyväskylä*, 2009.

[7] Kjerstin Torre and Didier Delignières. Distinct ways of timing movements in bimanual coordination tasks: Contribution of serial correlation analysis and implications for modeling. 129(2):284–296, 2008.

[8] Petri Toiviainen, Geoff Luck, and Marc R. Thompson. Embodied meter: Hierarchical eigenmodes in music-induced movement. 28(1):59–70, 2010.

[9] Peter Desain, Henkjan Honing, et al. Physical motion as a metaphor for timing in music: the final ritard. In *Proceedings of the International Computer Music Conference*, pages 458–460. INTERNATIONAL COMPUTER MUSIC ASSOCIATION, 1996.

[10] Beau Sievers, Larry Polansky, Michael Casey, and Thalia Wheatley. Music and movement share a dynamic structure that supports universal expressions of emotion. 110(1):70–75, 2013. Publisher: National Academy of Sciences Section: Social Sciences.

[11] Marc Leman. *Embodied music cognition and mediation technology*. MIT press, 2007.

[12] Musical gestures: sound, movement, and meaning, 2010. OCLC: ocn298781501.

[13] Marina Korsakova-Kreyn. Two-level model of embodied cognition in music. *Psychomusicology: Music, Mind, and Brain*, 28(4):240, 2018.

[14] Zohar Eitan and Roni Y. Granot. How music moves. 23(3):221–248, 2006.

[15] Bill Alves. Consonance and dissonance in visual music. *Organised Sound*, 17(2):114–119, 2012.

[16] Philippe Schlenker. Outline of music semantics. *Music Perception*, 35(1):3–37, 2017.

[17] Philippe Schlenker. Prolegomena to music semantics. *Review of Philosophy and Psychology*, 10(1):35–111, 2019.

[18] Léo Migotti and Léo Zaradzki. Walk–denoting music: refining music semantics. *Proceedings of the Amsterdam Colloquium 2019*, 2019.

[19] Siu-Lan Tan and Megan E. Kelly. Graphic representations of short musical compositions. 32(2):191–212, 2004.

[20] George Athanasopoulos and Nikki Moran. Cross-cultural representations of musical shape. 8(3):185, 2013.

[21] Elena Rusconi, Bonnie Kwan, Bruno L Giordano, Carlo Umilta, and Brian Butterworth. Spatial representation of pitch height: the smarc effect. *Cognition*, 99(2):113–129, 2006.

[22] Naeem Komeilipoor, Matthew W. M. Rodger, Cathy M. Craig, and Paola Cesari. (dis-)harmony in movement: effects of musical dissonance on movement timing and form. 233(5):1585–1595.

[23] Ehud Bodner, Avi Gilboa, and Dorit Amir. The unexpected side-effects of dissonance. *Psychology of Music*, 35(2):286–305, 2007.

[24] František Vaverka, Milan Elfmark, Zdeněk Svoboda, Miroslav Janura, et al. System of gait analysis based on ground reaction force assessment. *Acta Gymnica*, 45(4):187–193, 2015.

[25] Richard F Murray. Classification images: A review. *Journal of vision*, 11(5):2–2, 2011.

[26] Jonathan Z Bakdash and Laura R Marusich. Repeated measures correlation. *Frontiers in psychology*, 8:456, 2017.

[27] B Godey, D Schwartz, JB De Graaf, P Chauvel, and C Liegeois-Chauvel. Neuromagnetic source localization of auditory evoked fields and intracerebral evoked potentials: a comparison of data in the same patients. *Clinical neurophysiology*, 112(10):1850–1859, 2001.

[28] Thomas Sinkjær, Jacob Buus Andersen, Michel Ladouceur, Lars OD Christensen, and JB2269822 Nielsen. Major role for sensory feedback in soleus emg activity in the stance phase of walking in man. *The Journal of physiology*, 523(Pt 3):817, 2000.

[29] Roi Cohen Kadosh, Warren Brodsky, Michal Levin, and Avishai Henik. Mental representation: What can pitch tell us about the distance effect? *Cortex*, 44(4):470–477, 2008.

[30] Meyer Leonard. Emotion and meaning in music. *Chicago: University of Chicago*, 1956.

[31] Yuri Broze and David Huron. Is higher music faster? pitch–speed relationships in western compositions. *Music Perception: An Interdisciplinary Journal*, 31(1):19–31, 2013.

[32] Edith Van Dyck, Dirk Moelants, Michiel Demey, Alexander Deweppe, Pieter Coussement, and Marc Leman. The impact of the bass drum on human dance movement. 30(4):349–359, 2013.

[33] Laurel J Trainor and Sandra E Trehub. The development of referential meaning in music. *Music Perception*, 9(4):455–470, 1992.

[34] Lyn Tieu, Philippe Schlenker, and Emmanuel Chemla. Linguistic inferences without words. *Proceedings of the National Academy of Sciences*, 116(20):9796–9801, 2019.

[35] Michael K Mcbeath and John G Neuhoff. The doppler effect is not what you think it is: Dramatic pitch change due to dynamic intensity change. *Psychonomic bulletin & review*, 9(2):306–313, 2002.

[36] Weiyi Ma and William Forde Thompson. Human emotions track changes in the acoustic environment. *Proceedings of the National Academy of Sciences*, 112(47):14563–14568, 2015.

[37] D Bedoya, P Arias, L Rachman, M Liuni, Clément Canonne, Louise Goupil, and J-J Aucouturier. Even violins can cry: specifically vocal emotional behaviours also drive the perception of emotions in non-vocal music. *Philosophical Transactions of the Royal Society B*, 376(1840):20200396, 2021.

[38] Daniel A Putman. Why instrumental music has no shame. *The British Journal of Aesthetics*, 27(1):55–61, 1987.

[39] Fritz Strack, Leonard L Martin, and Sabine Stepper. Inhibiting and facilitating conditions of the human smile: a nonobtrusive test of the facial feedback hypothesis. *Journal of personality and social psychology*, 54(5):768, 1988.

[40] E-J Wagenmakers, Titia Beek, Laura Dijkhoff, Quentin F Gronau, A Acosta, RB Adams Jr, DN Albohn, ES Allard, Stephen D Benning, E-M Blouin-Hudon, et al. Registered replication report: strack, martin, & stepper (1988). *Perspectives on Psychological Science*, 11(6):917–928, 2016.

[41] Jessica Phillips-Silver and Laurel J Trainor. Feeling the beat: movement influences infant rhythm perception. *Science*, 308(5727):1430–1430, 2005.

[42] Annalisa Tosoni, Emanuele Cosimo Altomare, Marcella Brunetti, Pierpaolo Croce, Filippo Zappasodi, and Giorgia Committeri. Sensory-motor modulations of eeg event-related potentials reflect walking-related macro-affordances. *Brain Sciences*, 11(11):1506, 2021.

[43] Jeffrey M. Hausdorff. Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. 26(4):555–589, 2007.

[44] Melvyn Roerdink, Claudine JC Lamoth, Gert Kwakkel, Piet CW van Wieringen, and Peter J Beek. Gait coordination after stroke: Benefits of acoustically paced treadmill walking. 87(8):1009–1022, 2007.

[45] Philippe Schlenker. Musical meaning within super semantics. *Linguistics and Philosophy*, 2021.

[46] Niels Chr Hansen, Haley E Kragness, Peter Vuust, Laurel Trainor, and Marcus T Pearce. Predictive uncertainty underlies auditory boundary perception. *Psychological science*, 32(9):1416–1425, 2021.

[47] Marco Costa and Mattia Nese. Perceived tension, movement, and pleasantness in harmonic musical intervals and noises. *Music Perception*, 37(4):298–322, 2020.

[48] Daniel Müllensiefen, Bruno Gingras, Jason Musil, and Lauren Stewart. The musicality of non-musicians: An index for assessing musical sophistication in the general population. *PloS one*, 9(2):e89642, 2014.

[49] Juan José Burred, Emmanuel Ponsot, Louise Goupil, Marco Liuni, and Jean-Julien Aucouturier. Cleese: An open-source audio-transformation toolbox for data-driven experiments in speech and music cognition. *PloS one*, 14(4):e0205943, 2019.

[50] Arturo Camacho and John G Harris. A sawtooth waveform inspired pitch estimator for speech and music. *The Journal of the Acoustical Society of America*, 124(3):1638–1652, 2008.