Human Movement Science 66 (2019) 53–62

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Emotional states influence forward gait during music listening based on familiarity with music selections

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ARTICLE INFO

Keywords:
Affect
Emotion
Gait velocity
Motivation
Movement
Walking

ABSTRACT

Music elicits a wide range of human emotions, which influence human movement. We sought to determine how emotional states impact forward gait during music listening, and whether the emotional effects of music on gait differ as a function of familiarity with music. Twenty-four healthy young adults completed walking trials while listening to four types of music selections: experimenter-selected music (unfamiliar-pleasant), its dissonant counterpart (unfamiliar-unpleasant), each participant's self-selected favorite music (familiar-pleasant), and its dissonant counterpart (familiar-unpleasant). Faster gait velocity, cadence, and stride time, as well as longer stride length were identified during pleasant versus unpleasant music conditions. Increased gait velocity, stride length, and cadence as well as reduced stride time were positively correlated with subjective ratings of emotional arousal and pleasure as well as musical emotions such as happiness-elation, nostalgia-longing, interest-expectancy, pride-confidence, and chills, and they were negatively related to anger-irritation and disgust-contempt. Moreover, familiarity with music interacted with emotional responses to influence gait kinematics. Gait velocity was faster in the familiar-pleasant music condition relative to the familiar-unpleasant condition, primarily due to longer stride length. In contrast, no differences in any gait parameters were found between unfamiliar-pleasant and unfamiliar-unpleasant music conditions. These results suggest emotional states influence gait behavior during music listening and that such effects are altered by familiarity with music. Our findings provide fundamental evidence of the impact of musical emotion on human gait, with implications for using music to enhance motor performance in clinical and performance settings.

1. Introduction

From ancient to modern times, music has received a great deal of scholarly attention for its wide range of influences on human society. People of all cultures and ages enjoy moving along with music for exercise, entertainment, or ceremonial purposes. Greek philosopher, Plato, emphasized the role of musical rhythm and harmony in nurturing the human body and mind (Plato, 1991). A myriad of theorists and practitioners have explored and exploited physical and mental reactions to music respectively. With the advancement of science and technology, recent studies have found a variety of neuropsychological and behavioral correlates of

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https://doi.org/10.1016/j.humov.2019.03.004
Received 18 September 2018; Received in revised form 25 February 2019; Accepted 5 March 2019
Available online 23 March 2019
0167-9457/

music, implicating on cognitive, affective and motor functions in a wide range of healthy and clinical populations (Sacks, 2007).

Motor reactions to music have been largely attributed to the rhythmic features of music. For instance, hearing a groove laid by a drummer often engenders foot-stomping, head-bobbing, hand-tapping, and other observable behaviors. The periodicity of rhythmic sound makes the subsequent beat predictable, so listeners spontaneously or deliberately synchronize their movements to the beat without much effort (Merker, Madison, & Eckerdal, 2009). Rhythmic engagement of movement has justifiably received extensive scientific attention. However, other attributes of music, particularly the powerful influence of emotional reactions (Cochrane, Fantini, & Scherer, 2013), may further modulate motoric interactions with music.

The urge to move with music is accompanied by pleasant emotions (Janata, Tomic, & Haberman, 2012; Trost & Vuilleumier, 2013; Vuilleumier & Trost, 2015). A small but growing corpus of behavioral findings have implied emotional associations with music-motor coupling across the lifespan. For example, the duration of rhythmic movement in response to music and beat stimuli is associated with the duration of smiles in preverbal infants (Zentner & Eerola, 2010). A series of investigations have indicated that music-induced spontaneous body movements reflect emotional features of music (Burger, Saarikallio, Luck, Thompson, & Toiviainen, 2013; Burger, Thompson, Saarikallio, Luck, & Toiviainen, 2013; van Dyck, Burger, & Orlandoatou, 2017; Van Dyck, Maes, Hargreaves, Lesaffre, & Leman, 2013; Van Dyck, Vansteenkiste, Lenoir, Lesaffre, & Leman, 2014). Emotional and motivational responses to music potentially underlie the greater effects of music on gait compared with non-emotional isochronous rhythmic sounds (Leman et al., 2013; Wittwer, Webster, & Hill, 2013).

Neuroscientific evidence indicates that musical pleasure activates mesolimbic reward circuits (Zatorre, 2015), and that the activation of mesolimbic circuits is accompanied by activation of motor circuitry (Holstege, 1991; Mogenson, Jones, & Yim, 1980; Nieuwenhuys, Voogd, & van Huijzen, 2008; Pijnenburg, Honig, Van der Heyden, & Van Rossum, 1976). Healthy adults have shown notable increases in gait velocity and stride length by walking with rhythmic music, but not with isochronous rhythm via a metronome beat (Styns, van Noorden, Moelants, & Leman, 2007; Wittwer et al., 2013). Such effects are likely the result of the rhythmic and melodic features of music which are livelier and richer than a simple isochronous beat. Emotional aspects of music may also drive consequential increases in gait magnitude (Styns et al., 2007; Wittwer et al., 2013). Music listening indeed induces strong emotional responses (Cochrane et al., 2013) and most people listen to music to experience different emotions (Juslin & Laukka, 2004; Juslin, Liljeström, Västfjäll, Barradas, & Silva, 2008). Given that motor behavior is a typical means by which to express affective states (Aviezer, Trope, & Todorov, 2012), it is evident that music-induced movement is modulated by emotional elements of music. We sought to fill a notable gap in the music-gait literature by determining whether emotional states impact forward gait during music listening, and more specifically, to determine to what degree distinctive emotions induced by music are associated with gait changes.

Familiarity with music (i.e., whether the music is known or unknown to the listener) is another crucial factor to consider when studying the influence of emotional and motor reactions to music. Enhanced familiarity with music via repeated listening has been previously shown to promote increased stride velocity, decreased stride variability, and better performance of step-beat synchronization (Leow, Rinchon, & Grahn, 2015). Walking with familiar music may reduce attentional resources necessary for perceiving the music, thereby resulting in comparatively greater autonomy of walking during music listening. Familiarity with music may also increase the capacity for elicitation of emotional responses. Repeated exposure to novel music enhances self-reported pleasure and arousal levels (van den Bosch, Salimpoor, & Zatorre, 2013), and emotion-related limbic regions and reward circuits are activated to a greater extent when listening to familiar music compared with unfamiliar music (Pereira et al., 2011). Enjoyment from familiar music stimulates dopaminergic activity in the reward circuits (Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011), which can invigorate motor actions (Mazzoni, Hristova, & Krakauer, 2007). In sum, existing literature suggests that the impact of music-evoked emotional responses on motor behavior generally, and gait more specifically, may be altered by familiarity with music.

The purpose of this investigation was twofold: (1) to determine whether emotional states impact forward gait during music listening; and (2) to examine whether the emotional attributes of music alter gait behavior as a function of familiarity with the music. Participants were asked to complete forward gait trials while listening to pleasant-familiar and -unfamiliar as well as unpleasant-familiar and -unfamiliar music selections. Gait parameters measured during pleasant music listening conditions were compared to those observed while listening to unpleasant music selections in which pitch-distorted, dissonant counterparts of the pleasant music were used to manipulate emotional features while preserving rhythmic and temporal attributes. We hypothesized that pleasant music would evoke faster and longer strides compared to unpleasant music, and that increased gait velocity and stride length would be positively correlated with pleasant emotions and negatively correlated with unpleasant emotions. We also predicted that differences in gait parameters would be found between pleasant-familiar to unpleasant-familiar music conditions, but not between pleasant-unfamiliar to unpleasant-unfamiliar music conditions.

2. Materials and methods

2.1. Participants

A convenience sample of 24 graduate and undergraduate students from the University population participated in the study. The age of participants ranged between 19 and 33 (20 females: M age = 21.5, SD = 3.67; 4 males: M age = 23.75, SD = 5.54). Participants were healthy individuals without any history of brain surgery, orthopedic injuries in the past 6 months that could affect their walking, hearing problems that could impact their listening, or cognitive impairment or affective disturbances that could impact their understanding of experimental instructions and ability to perceive music stimuli. Participants' depression, anxiety, overall affective states, and music anhedonia were evaluated based on normative values of Beck Depression Inventory (BDI-II; Beck, Steer, & Brown, 1996), State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, Vagg & Jacobs, 1983), Positive and Negative

Table 1
Demographic and psychometric traits of participants (n = 24).

Variables	$M \pm SD$	Normative values
Age	21.88 ± 4.22	–
Education (years)	14.71 ± 1.97	–
Trait Anxiety (STAI-T)	34.83 ± 9.00	35.74 ± 9.68
State Anxiety (STAI-S)	29.79 ± 5.60	36.42 ± 10.45
Depression (BDI-II)	4.08 ± 3.35	Lower than 13
Positive Emotion (PANAS)	33.58 ± 7.42	31.31 ± 7.65
Negative Emotion (PANAS)	12.67 ± 4.29	16 ± 5.90
Music Reward (BMRQ)	52.12 ± 8.21	Greater than 35

Affect Schedule (PANAS; Crawford & Henry, 2010; Watson, Clark, & Tellegen, 1988), and Barcelona Music Reward Questionnaire (BMRQ; Mas-Herrero, Marco-Pallares, Lorenzo-Seva, Zatorre, & Rodriguez-Fornells, 2013). Participants' demographic and psychometric characteristics with normative values are provided in Table 1.

2.2. Procedure

Upon arriving at the laboratory, each participant reviewed and signed an informed consent form, which was approved by the Institutional Review Board of the University of Florida. Participants then completed a battery of questionnaires in which they self-reported affective states and psychological disposition as detailed above (i.e., BDI, STAI, PANAS, BMRQ). Thereafter, retro-reflective markers were attached to participants' feet and arms in preparation for kinematic data collection. Baseline gait trials (i.e., walking without music) were captured at the beginning and the end of the musical gait trials to check any experimental impacts such as fatigue on participants' gait behavior. Participants completed a total of eight 1-min trials of walking 8–10 m back and forth in a laboratory room while listening to two music selections in four conditions, which were presented in a randomized order. After each trial, participants reported their emotional state using a self-report questionnaire and took a short break during which they completed a backward-counting task to neutralize emotional experiences from the previous trial.

2.3. Apparatus and task

2.3.1. Music stimuli

Four music conditions were created. The *unfamiliar-pleasant* condition consisted of experimenter-selected, instrumental dance-tunes, J. S. Bach's Bourrée (Overture No. 1, BWV 1066) and Rejouissance (BWV 1069), which have been used to evoke pleasant emotional states in prior studies (Fritz et al., 2009; Koelsch, Fritz, Cramon, von Muller, & Friederici, 2006; Sammler, Grigutsch, Fritz, & Koelsch, 2007). Experimenter-selected unfamiliar music selections were unknown to participants before participation. All participants reported that they did not know the titles, rhythm, or melody of unfamiliar music selections. The *familiar-pleasant* condition consisted of participants' individual selections of their favorite songs. Two songs of pop rock or pop dance were selected for each participant. Rhythm-preserved, dissonant counterparts of unfamiliar and familiar music were then created using a sound-editing software (Audacity 2.1.0; Audacity Team Inc.). First, each of the original familiar and unfamiliar excerpts was simultaneously recorded together with two pitch-shifted versions of the same excerpt; one with whole tone above and the other with tritone below the original pitch. This method has been used to elicit unpleasant emotional states, while keeping the rhythmic features and temporal outline in identical condition with the original music (Fritz et al., 2009; Koelsch et al., 2006; Sammler et al., 2007). These conditions were labeled *unfamiliar-unpleasant* and *familiar-unpleasant,* respectively. We also quantified the tempo of each music selection by rating beats per minute (bpm) using an audio-mixing software (Virtual DJ 8.2; Atomix Productions Inc.).

Analyses of the musical selections were completed to determine: (1) whether pitch distortion for emotion manipulation resulted in any changes of musical tempo, and (2) differences in music tempo between unfamiliar and familiar selections. Paired sample t-tests showed no difference in music tempo (bpm) between the original familiar music [M (95% CI) = 114.33 (107.46, 121.20)] and dissonant familiar music [M (95% CI) = 114.77 (107.08, 122.46)] (t = 0.09, df = 45, p = .929). The t-tests were followed by equivalency tests (Rogers, Howard, & Vessey, 1993). Differences in tempo between original and distorted familiar music [M (95% CI) = −0.44 (−10.47, 9.60)] fell within a 10% margin of original familiar music tempo (11.43 bpm), which substantiated the equality of tempo between two music conditions. In contrast, however, one sample t-test showed that the tempo of familiar-pleasant (and by default, familiar-unpleasant) music was higher than that of unfamiliar-pleasant (and by default, unfamiliar-unpleasant) music (M = 105.5) (t = 2.59, df = 45, $p < .05$). Therefore, the difference in music tempo between familiar and unfamiliar stimuli (percentage change score of music tempo = [(familiar music − unfamiliar music)/unfamiliar × 100] was considered as a covariate when analyzing the impacts of familiarity on gait behavior.

2.3.2. Musical gait trials

Participants were given the instruction, "feel the music first, and then walk with the feeling," on each trial. More specifically, participants were asked to listen to each musical excerpt while standing in a comfortable posture with their eyes closed. Once participants determined they had experienced emotion elicitation or mood changes in response to the music, they opened their eyes

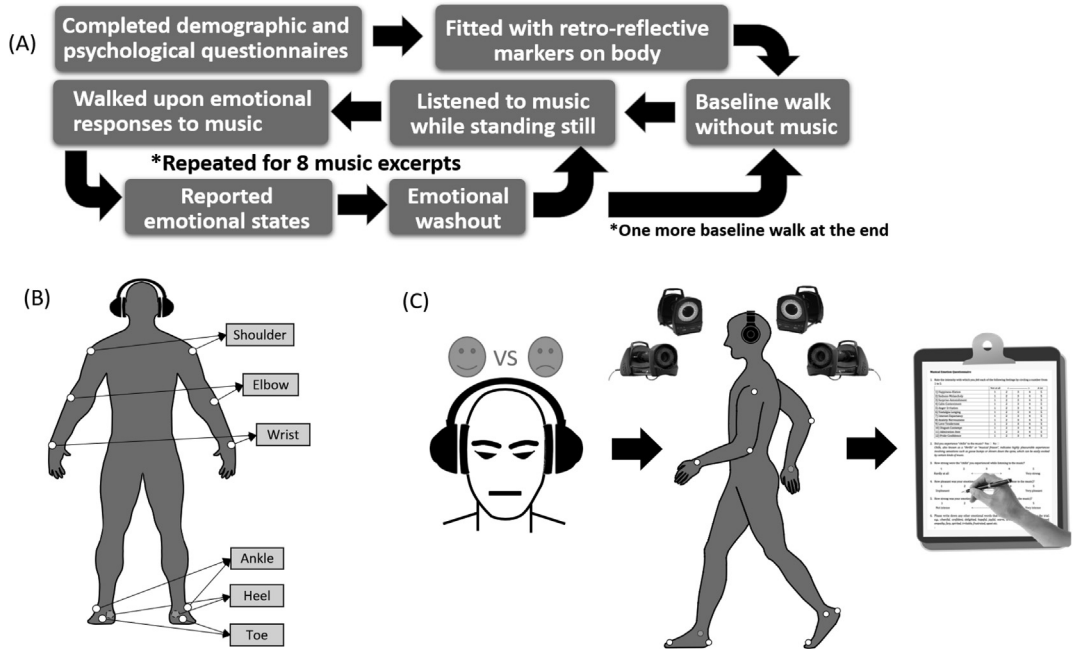

Fig. 1. Experimental procedure. (A) Overall course of participant's action. Baseline gait trials (no musical stimulus) before and after music trials showed no differences with each other, indicating minimal fatigue or other confounding effects. (B) Experimental setup for a participant with a Bluetooth headset and retroreflective markers on right and left arms and feet. Markers attached on arms were used as a reference point to observe participants' normal gait behaviors in coordination with foot markers. Foot markers were used to obtain spatiotemporal stepping parameters. (C) Gait trials with music listening. Participants were asked to "feel the music first and walk with the feeling until the music stops". They reported their emotional responses to music after each trial.

and walked on a 10-m straight line back and forth in the laboratory room for 1 min until the music stopped. We maintained the room as dark as possible to minimize environmental distractions so that participants could focus on the music and the ensuing walking task. A total of eight excerpts in four music conditions (2 excerpts in each condition) were played in a randomized order via iTunes 12.5.3 on a portable computer (MacBook Pro, Mid 2010, Apple Inc.). Participants listened to the music via a Motorola S305 Bluetooth Headset linked to the portable computer, through which music was played and outside noise was blocked. An 8-camera Optical Motion Capture system (120 Hz, Vicon Peak, Oxford, UK) was used to record three-dimensional movement trajectories from the retro-reflective markers. A custom-developed questionnaire was used to obtain participants' discrete and dimensional aspects of musical emotions. Originally developed from a previous study (Juslin, Harmat, & Eerola, 2014), the questionnaire asked how intensely participants felt a set of discrete and dimensional emotions (i.e., happiness-elation, nostalgia-longing, love-tenderness, admiration-awe, interest-expectancy, pride-confidence, sadness-melancholy, anger-irritation, anxiety-nervousness, disgust-contempt, chills, overall pleasure, and arousal) based on a 5-point Likert scale. For the dimensional emotions, we measured emotional valence and arousal levels after each trial. This multi-dimensional measurement allowed us to have comprehensive understanding of various emotional responses to music and their associations with forward gait behaviors. See Fig. 1 for an overview of musical gait trials.

2.4. Data reduction and analysis

The movement trajectories of reflective markers attached on toe, ankle, and heel were identified and processed via the Nexus 2.5 software (Vicon Motion Systems Ltd.). Reflective markers attached on the arms were used for a reference point of typical gait behaviors so as to determine whether the arms were moving in coordination with the feet. We analyzed stepping data only from foot markers given our focus on spatiotemporal stepping parameters. We reduced and analyzed reflective markers on the feet to extract spatiotemporal stepping parameters. Each 1-min of a gait trial was separated into 3 sub-trials, in which 4–5 strides were included. All sub-trials were reduced to two gait cycles (i.e., two strides) in the middle of each walking trial on a straight line to focus analyses on steady state gait movements and eliminate acceleration and deceleration effects of walking into and after turning. In other words, initiating and terminating steps at the beginning and end of a straight walking path were excluded from analyses. Temporal gait events were determined using toe off from the ground and heel strike on the ground for right and left steps. Nine events in the two gait cycles (i.e., right heel strike – left toe off and heel strike – right toe off and heel strike – left toe off and heel strike – right toe off and heel strike) were exported. Using a custom-developed computer program (LabVIEW 12.0; National Instruments, Austin, TX), we calculated spatiotemporal gait measures, stride length (m), gait velocity (m/second), stride time (second), and cadence (steps/min). As a spatial gait measure, stride length is the absolute distance between the initiation and the termination of two steps (i.e., from heel stride by one foot to heel strike by the same foot). As another spatial gait measure, gait velocity is the relative distance of walking

completed during a one second time period (i.e., total distance traveled divided by total duration). As a temporal gait measure, stride time is the absolute duration between the initiation and the termination of two steps (i.e., from heel stride by one foot to heel strike by the same foot). As another temporal gait measure, cadence was operationalized as relative tempo of gait, calculated by dividing total number of steps by total duration of walking. We further computed gait change scores (%), which are the difference in gait measures between experimental condition and baseline [gait change score = (music trial – baseline)/baseline × 100] (Fawver, Hass, Park, & Janelle, 2014; Fox, 2002) This index indicates the net difference of movement in each condition relative to the baseline, and thus eliminated the effect of within-subject baseline differences or spurious effects of task execution (Fox & Spector, 2002).

Using SPSS Statistics 22.0 (IBM Corp, Chicago, IL), emotional responses to music conditions were analyzed via a one-way repeated multivariate analysis of variance (MANOVA), with one within-subject independent variable (i.e., music condition) and multiple dependent variables of emotional states (self-ratings of *happiness-elation, calm-contentment, nostalgia-longing, love-tenderness, admiration-awe, interest-expectancy, pride-confidence, sadness-melancholy, surprise-astonishment, anger-irritation, anxiety-nervousness, disgust-contempt, chills, overall pleasure,* and *arousal*). Separate ANOVAs and post-hoc tests with Bonferroni correction were used to compare emotional states between each music condition. One-way repeated MANOVAs and follow-up ANOVAs were further conducted to analyze the main effects of emotion (*pleasant, unpleasant*) on spatiotemporal gait parameters (*gait velocity, cadence, stride time,* and *stride length*) during music listening. Correlation coefficients were calculated to examine the relationship between distinct emotions and gait change scores. Additionally, a 2 (Familiarity: familiar, unfamiliar) × 2 (Emotion: pleasant, unpleasant) multivariate analysis of covariance (MANCOVA) was used to determine whether the impact of emotion on multiple dependent measures of forward gait differed as a function of familiarity with music. The music tempo difference between familiar and unfamiliar music conditions was used as a covariate in the MANCOVA. Significant main effects and interactions emerging from each MANCOVA were further decomposed using separate ANCOVAs. Equivalency tests were employed to compare the temporal features between music conditions.

3. Results

3.1. Emotional responses to music conditions

The one-way repeated MANOVA revealed a significant main effect of music condition on emotional state [*Wilks' lambda* = 0.021, F (45, 164.172) = 9.667, $p < .001$]. Followup one-way repeated ANOVAs revealed that manipulation of musical harmony affected multiple discrete emotions including happiness-elation [F (2.18, 50.22) = 143.53, $p < .01$, $\eta^2 = 0.862$], nostalgia-longing [F (1.97, 45.37) = 17.76, $p < .01$, $\eta^2 = 0.436$], love-tenderness [F (1, 23) = 4.471, $p < .05$, $\eta^2 = 0.163$], admiration-awe [F (3, 69) = 38.976, $p < .01$, $\eta^2 = 0.629$], interest-expectancy [F (3, 69) = 26.318, $p < .01$, $\eta^2 = 0.534$], pride-confidence [F (3, 69) = 71.794, $p < .01$, $\eta^2 = 0.757$], sadness-melancholy [F (1.99, 45.77) = 7.381, $p < .01$, $\eta^2 = 0.243$], anger-irritation [F (2.03, 46.66) = 39.394, $p < .01$, $\eta^2 = 0.631$], anxiety-nervousness [F (2.08, 47.76) = 38.206, $p < .01$, $\eta^2 = 0.624$], disgust-contempt [F (1.89, 43.54) = 57.27, $p < .01$, $\eta^2 = 0.713$], chills [F (1.86, 42.67) = 9.598, $p < .01$, $\eta^2 = 0.294$], overall pleasure [F (2.02, 46.45) = 115.939, $p < .01$, $\eta^2 = 0.834$], and arousal [F (3, 69) = 16.672, $p < .01$, $\eta^2 = 0.42$]. Post-hoc tests further clarified directional differences between each music category (all p's < 0.01). Overall pleasure ($M \pm CI = 4.52 \pm 0.23$), happiness-elation (4.44 ± 0.21), and pride-confidence (3.73 ± 0.36) were rated highest while listening to familiar-pleasant music, whereas disgust-contempt (3.73 ± 0.46), anger-irritation (3.21 ± 0.52), and anxiety-nervousness (3.13 ± 0.53) were the most notable responses to familiar-unpleasant music. Unfamiliar-pleasant music evoked modest levels of calm (3.54 ± 0.42) and pleasure (3.54 ± 0.31), while unfamiliar-unpleasant music elicited low to moderate levels of anxiety-nervousness (2.60 ± 0.46) and disgust-contempt (2.60 ± 0.56).

3.2. Emotional impacts on gait during music listening

Paired sample t-tests showed that pre- and post-experimental baseline walking were not significantly different for walking speed, stride length, stride time, and cadence (all p's > 0.05). Participants experienced minimal fatigue and/or no impact of extraneous valuables that might have influenced walking throughout the experiment.

The one-way repeated MANOVA revealed a significant main effect of emotion on gait measures during music listening [*Wilks' lambda* = 0.469, F (4, 20) = 5.671, $p < .01$]. Following ANOVAs specified the effects of emotion on gait parameters including cadence [F (1, 23) = 5.528, $p < .05$, $\eta^2 = 0.194$], stride time [F (1, 23) = 4.471, $p < .05$, $\eta^2 = 0.163$], gait velocity [F (1, 23) = 15, $p < .01$, $\eta^2 = 0.395$], and stride length [F (1, 21) = 20.381, $p < .01$, $\eta^2 = 0.470$]. Posthoc tests further revealed faster gait velocity (M = 3.14 cm/s, 95% CI = 0.38–5.90, $p < .05$), stride time ($M = -0.03$ s; 95% $CI = -0.07$ to -0.00, $p < .05$), and cadence (M = 3.14 steps/min, 95% CI = 0.37–5.90, $p < .05$) as well as longer stride length (M = 8.74 cm; 95% CI = 4.07–13.41, $p < .01$) in pleasant music conditions compared with unpleasant conditions (see Fig. 2).

3.3. Correlation between distinctive emotions and gait changes

Fifteen discrete musical emotions were correlated with change scores of four spatiotemporal gait measures based on bivariate correlation analyses. We applied the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995) to control the large number of correlations (60) based on the false discovery rate (p = .05). 34 correlations remain significant. Overall results are described in Table 2. Specifically, happiness-elation, nostalgia-longing, interest-expectancy, pride-confidence, and chills showed the strongest positive correlations with gait velocity (r = 0.24–0.36, all p's < 0.05, all df's = 90), cadence (r = 0.21–0.33, all p's < 0.05, all

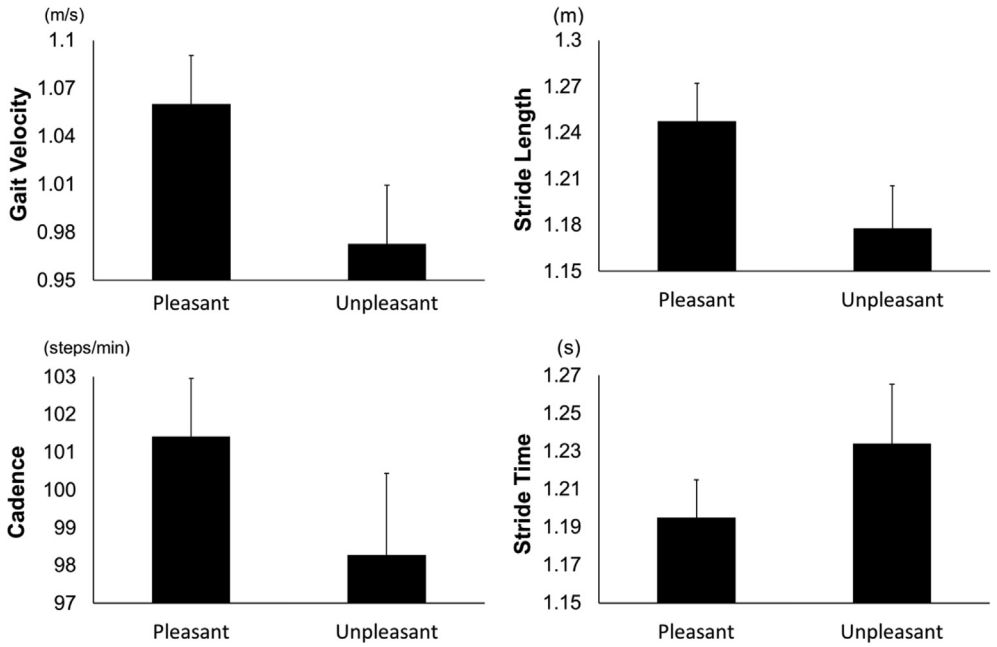

Fig. 2. Changes of gait parameters in emotional music conditions. Main effects of emotion (liked vs. disliked) on gait velocity ($p < .05$), stride length ($p < .01$), stride time ($p < .05$), and cadence ($p < .05$). Error bars represent +1 standard error.

Table 2
Correlations between discrete emotional states and gait change scores.

Variable	Happiness/ Elation	Nostalgia/ Longing	Interest/ Expectancy	Pride/ Confidence	Admiration/Awe	Anger/ Irritation	Disgust/ Contempt	Chills	Overall pleasure	Arousal
Gait velocity	0.30**	0.34**	0.36**	0.30**	0.21*	−0.21*	−0.36**	0.24	0.24*	0.27**
Cadence	0.24*	0.28**	0.33**	0.21*	0.15	−0.21*	−0.35**	0.21*	0.20	0.27**
Stride time	−0.24*	−0.25*	−0.35**	−0.21	−0.18	0.18	0.35**	−0.24*	−0.20	0.22*
Stride length	0.31**	0.30**	0.34**	0.33**	0.24*	−0.18	−0.32**	0.26*	0.25*	0.19

Note. Change scores of emotional states and gait measures were obtained by calculating differences between pleasant and unpleasant music conditions. Changes of musical emotions and gait measurers between all pleasant and unpleasant music trials were correlated ($n = 92$).
* $p < .05$.
** $p < .01$.

df's = 90), stride time ($r = -0.35$ to -0.21, all *p's* < 0.05, all *df*'s = 90), and stride length ($r = 0.30$–0.34, all *p's* < 0.01, all *df*'s = 90). While emotional valence (pleasure) was positively related to gait velocity ($r = -0.24$, $p < .05$, $df = 90$) and stride length ($r = 0.25$, $p < .05$, $df = 90$), arousal was related to gait velocity ($r = 0.27$, $p < .01$, $df = 90$), stride time ($r = -0.22$, $p < .05$, $df = 90$) and cadence ($r = 0.27$, $p < .01$, $df = 90$). Among unpleasant emotions, disgust-contempt had strong negative correlation with all gait measures including gait velocity, cadence, stride time, and stride length ($r = -0.32$ to -0.36, all *p's* < 0.01, all *df*'s = 90). Anger-irritation had modest negative correlation with gait velocity ($r = -0.21$, $p < .05$, $df = 90$) and cadence ($r = -0.21$, $p < .05$, $df = 90$).

3.4. Interaction effects between pleasure and familiarity of music

Results of the MANCOVA indicated no main effects of familiarity or pleasure on gait parameters (all *p*'s > 0.05). Critically, however, pleasure and familiarity significantly interacted to impact gait [*Wilks' lambda* = 0.59, $F(4, 18) = 3.133$, $p < .05$]. Follow up ANCOVA revealed a significant interaction of familiarity and pleasure on gait velocity [$F(1, 21) = 7.46$, $p < .05$, $\eta^2 = 0.262$] and stride length [$F(1, 21) = 11.575$, $p < .05$, $\eta^2 = 0.355$]. Familiarity-pleasure interaction effects on stride time ($p > .05$) and cadence ($p > .05$) were not significant. Collectively, these results provide evidence that gait velocity ($p < .01$, $\eta^2 = 0.337$) and stride length ($p < .01$, $\eta^2 = 0.468$) differed as a function of pleasant and unpleasant conditions when listening to familiar music. No impact of music-evoked emotion was identified for any gait parameters during the unfamiliar music listening conditions (all *p*'s > 0.10). These results are illustrated in Fig. 3.

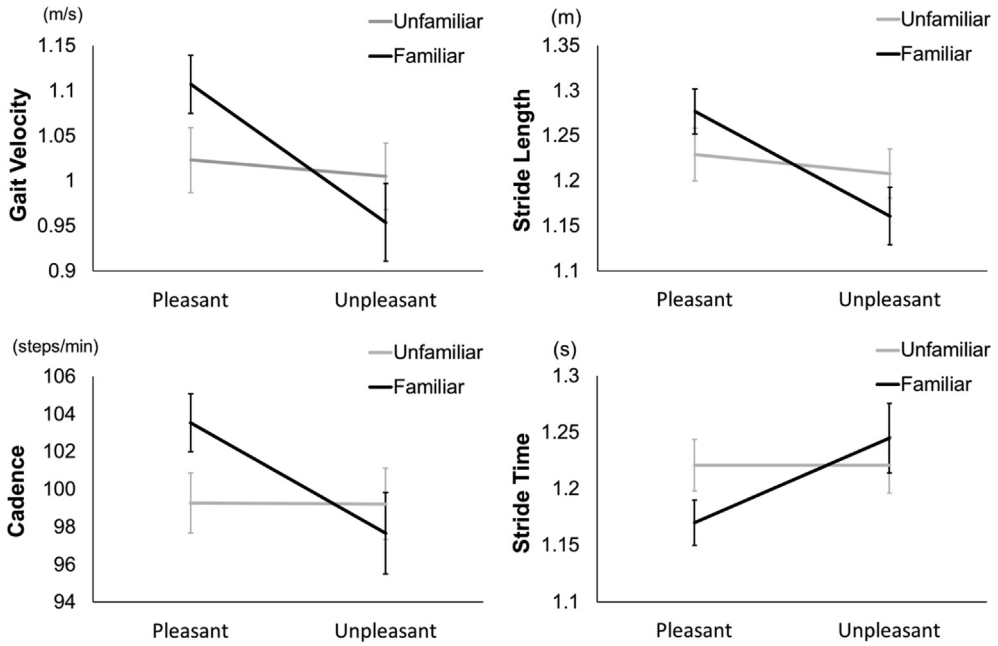

Fig. 3. Changes of gait parameters in emotional music conditions, mediated by familiarity. Familiarity (familiar vs. unfamiliar) and emotion (liked vs. disliked) made interaction effects on gait velocity, stride length, stride time, and cadence. Univariate tests further revealed differences between pleasant and unpleasant conditions in gait velocity ($p < .01$), stride length ($p < .01$), stride time ($p = .07$), and cadence ($p = .06$) during familiar music condition, whereas no difference was found in unfamiliar music conditions (all p's > 0.10). Error bars represent +1 standard error.

4. Discussion

Consonant and dissonant versions of participant-chosen familiar and experimenter-chosen unfamiliar music were used to investigate how emotional states impact the spatiotemporal characteristics of forward gait during music listening, and whether the emotional impacts of music on gait differ by music familiarity. Faster gait velocity, cadence, and stride time, as well as longer stride length were found during consonant (pleasant) versus dissonant (unpleasant) music conditions. Our study provides seminal evidence that emotions experienced when listening to music impact gait behaviors differently as a function of familiarity with musical pieces. As the rhythmic structures and melodic outline were identical between consonant and dissonant music selections, differences in gait parameters can be attributed to the distorted harmony and timbre, which induced discrete emotional states. Increases in gait amplitude were positively related to distinct musical emotions such as happiness-elation, nostalgia-longing, interest-expectancy, pride-confidence, chills, pleasure, and arousal, indicating that pleasant musical emotions were associated with fast and vigorous movement, arguably as a function of greater motivation to move. Anger-irritation and disgust-contempt were negatively related with gait changes, indicating unpleasant musical emotions were associated with slow and depressed movement, potentially due to diminished motivation to move. While faster and longer strides were found in the familiar-pleasant music condition relative to the familiar-unpleasant condition, no difference in any gait parameters were found between unfamiliar-pleasant and unfamiliar-unpleasant music conditions, indicating that familiarity with music modulates emotional effects of music on gait.

This is the first study to examine whether gait behaviors during music listening are altered by emotional responses to music. Previous findings have implied that the emotional/motivational aspects of music alter motor behaviors. Indeed, walking with rhythmic music led to faster gait velocity and longer stride length compared with walking with an emotion-void isochronous metronome beat (Styns et al., 2007; Wittwer et al., 2013). Yet, what components of music account for these changes has remained unclear. Isochronous rhythm mainly trains movement timing, while expressive features of music cues provide additive relaxing and activating influences on movements (Leman et al., 2013). The perspective that emotional states are tied to motor reactions when listening to music was directly evidenced in a prior study, in which preverbal infants' duration of motor reactions to music was strongly related with their duration of smiles (Zentner & Eerola, 2010). Neuroscientific evidence has also substantiated that the urge to move with music is accompanied by pleasant emotions, through the activation of mesolimbic reward circuits in connection with the motor system (Janata et al., 2012; Trost & Vuilleumier, 2013; Vuilleumier & Trost, 2015). Our findings are consistent with existing behavioral (Zentner & Eerola, 2010) and neuroscientific evidence (Janata et al., 2012; Trost & Vuilleumier, 2013; Vuilleumier & Trost, 2015), while extending the current knowledge base by providing the first direct evidence of the emotion-gait linkage in a musical context.

In non-musical contexts, empirical evidence has indicated that discrete emotional states are associated with approach or avoidance motivations and ensuing motor behaviors (Chen & Bargh, 1999; Coombes, Cauraugh, & Janelle, 2007a; 2007b; Harmon-Jones, 2004). Emotional states elicited by visual images or memory recall have brought about marked alterations of upper extremity

movements such as arm flexion and extension using lever pushing or pulling (Cacioppo, Priester, & Berntson, 1993; Centerbar & Clore, 2006; Chen & Bargh, 1999; Duckworth, Bargh, Garcia, & Chaiken, 2002; Solarz, 1960) and extension movements of the wrist and finger muscles (Coombes, Cauraugh, & Janelle, 2006; 2007b; Coombes, Gamble, Cauraugh, & Janelle, 2008). Emotional states have also been shown to alter whole body locomotor movements such as gait initiation and walking behavior in healthy adults (Fawver et al., 2014; Gélat, Coudrat, & Le Pellec, 2011; Kang & Gross, 2015; Naugle, Hass, Joyner, Coombes, & Janelle, 2011; Naugle, Joyner, Hass, & Janelle, 2010; Stins & Beek, 2011; Stins et al., 2011; Stins, van Gelder, Oudenhoven, & Beek, 2015).

Our data reveal that distinctive emotional responses to music are associated with gait amplitude changes. Specifically, happiness-elation, nostalgia-longing, interest-expectancy, and pride-confidence elicited by music were strongly coupled with increases in gait amplitude, whereas disgust-contempt were coupled with decreases in gait amplitude. The effects of pleasant musical emotions on gait amplitude could be associated with comparatviely greater motivation to move. This hypothesis is in line with prior evidence that pleasant emotional stimuli have been found to induce approach motivation and facilitate gait initiation and execution, while unpleasant emotional stimuli have been shown to evoke avoidance motivation and inhibit forward gait behaviors (Fawver et al., 2014; Gélat et al., 2011; Kang & Gross, 2015; Naugle et al., 2010; 2011; Stins et al., 2011; 2015; Stins & Beek, 2011). Although these studies have provided emotional stimuli not in auditory but in visual formats, these finding provide evidence that resultant emotional states can impact gait behaviors across different sensory modalities. While tentative assertions at this time, these postulates are ripe for future investigation of how emotional states are associated with motor behaviors in musical contexts.

Emotional impacts on gait velocity and stride length were occasioned when walking with familiar music, but this was not the case when walking with unfamiliar music. Familiarity with music is known to reduce the cognitive demands associated with music perception (Leow et al., 2015). When walking with familiar music, perceiving well-known rhythm and melody becomes cognitively less demanding than stepping with unknown music. The affective content of the music selections would arguably be more salient when there are fewer competing demands for attention and cognition. Under more familiar circumstances, therefore, gait parameters are more likely to be altered due to the emotional characteristics of the music. On the other hand, when walking with unfamiliar music, consonant and dissonant music selections yielded less magnitude of difference between pleasant and unpleasant emotional states compared with emotional changes in familiar music condition. Accordingly, emotional states did not predictably impact gait behaviors during the unfamiliar music condition compared with the familiar music condition. Only modest levels of unpleasant emotions were reported while walking and listening to dissonant unfamiliar music, yielding minimal deterioration of walking compared to consonant unfamiliar music. On the other hand, dissonant familiar music elicited high levels of unpleasant feelings, and markedly hampered walking compared with all other conditions. Collectively, these findings highlight the role of familiarity with music in evoking emotionally-induced changes of gait behavior.

Limitations of this project warrant acknowledgement and serve as the basis of suggestions for future work in this area. First, designs that focus on how the effects of music-induced emotional states and familiarity manifest over time and during comparatively unconfined environmental conditions could potentially enhance the external validity of work in this area. In this study, necessary constraints of the laboratory setting maximized the integrity of the motion analysis system, but movement was confined to the laboratory space. Future investigations should be conducted in a more spacious environment over a longer period of time to examine the maximum impact of music on locomotor behaviors. Second, we found only modest levels of unpleasant emotions by walking and listening to dissonant unfamiliar music, yielding minimal deterioration of walking compared to consonant unfamiliar music. Participants might have gotten irritated by the manipulation of familiar music and thus walked differently from the original consonant music. However, they might have tolerated walking with dissonant version of unfamiliar music less than familiar music since they did neither know the music very well nor choose it in the first place. Future research efforts would be helpful in delineating the degree to which musical preference and familiarity with music elicits different emotional and rhythmic motor reactions. Third, it should be noted that although changes were documented in the speed and length of stepping, these findings on movement amplitude do not comprehensively establish that participants in this study exhibited a better quality of movement or healthier gait. The variability and complexity of human movement time series such as walking are other crucial indicators of healthy movements in humans (Stergiou & Decker, 2011). Future research should consider the impacts of musical familiarity and emotion on linear and nonlinear indices of gait variability such as stride time variability or fractal scaling of gait dynamics. Measures of gait variability and dynamics would provide another crucial perspective in how temporal variability and complexity of music are associated with those of human movement, and how music-motor coupling can be affected by emotional responses to music.

5. Conclusions and implications

Results of the current investigation provide evidence that listening to music impacts emotional states and gait behavior. The emotional impacts of music on gait varied as a function of familiarity with music. Pleasant emotions in particular, appear to play a vital role in modulating musical impacts on motor behavior when listening to music with which people are familiar. Furthermore, evidence suggests that familiarity with specific music selections and associated emotional reactions may modulate musical effects on motor behaviors. These findings inform a growing body of literature focused on the clinical use of music for populations with affective or movement disorders. As we observed in this study, music is an effective channel for eliciting discrete emotional states and ensuing motor actions. Our data indicate that individuals experience pleasant emotional reactions and enhanced motor activity in response to familiar music. With further replication, targeted intervention strategies could be developed to integrate these and other music attributes into tailored clinical and training settings designed to optimize movement effectiveness and efficiency.

Declarations of interest

None.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.03.004.

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