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BODILY MOTION AS A PERCEPTUAL MODULATOR: HOW PASSIVE LINEAR MOVEMENT SHAPES MELODIC INTERVAL JUDGMENTS

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Abstract: Embodied music cognition research has long focused on voluntary bodily movement's role in music perception, yet passive motion's impact remains underexplored. This study examined how linear passive motion across three translational degrees of freedom (Z/X/Y axes) modulates melodic interval perception via a 6-DOF motion platform, with 39 normal-hearing participants completing perception tasks under static and motion conditions. Independent-samples t-tests and cent-based quantitative analysis revealed significant perceptual differences between the two conditions ($p<0.05$), with vertical (Z-axis) motion inducing more pronounced effects. Ascending intervals were perceived as expanded, descending ones contracted, and larger intervals showed greater perceptual changes; pitch register had no significant effect. Platform motion direction interacted systematically with interval direction, amplifying expansion-contraction contrasts in specific directions. These findings validate embodied cognition, proving passive bodily motion actively shapes melodic interval perception and enriching the theoretical framework of embodied music cognition.
Keywords: Embodied music cognition; Passive linear motion; Melodic interval perception

1 INTRODUCTION

Since the introduction of the concept of embodied music cognition, there has been growing scholarly interest in the bodily aspects of musical engagement. However, it is only in recent years—thanks to advances in technology that allow for precise recording and analysis of human movement—that embodiment has emerged as a central paradigm in musicological research [1]. Central to this perspective is the idea that the human motor system, gestures and bodily movements, plays an active and integral role in how music is perceived and experienced [2].

Leman et al. suggest two pathways for advancing our understanding of embodiment in music cognition: (1) demonstrating that embodiment constitutes a core part of a larger cognitive-emotive network involved in affect processing, conceptualization, tool use and the entire array of functions needed to make sense of music. For example, the common coding theory proposed by Maes and colleagues suggests that the motor system plays a functional role in shaping auditory experiences. Their findings indicate that simply observing or engaging in bodily movement while listening to music can alter the listener's perceptual experience in real-time [3]. And (2) approach emphasizes that embodiment is not merely a consequence of music influencing action, but that the influence of action on music perception plays a crucial role in making sense of music [4]. These perspectives, while distinct in methodological emphasis, are not mutually exclusive and together offer a more comprehensive view of embodied music cognition [2].

A number of studies have gained attention in recent years that have been biased toward exploring specific issues about the role of actions in perception. For instance, experimental evidence has shown that spectators' auditory perception of note durations can be influenced by the concurrent visual observation of a percussionist's movements [5]. Similarly, studies by Jessica Phillips-Silver demonstrated that incorporating bouncing movements while infants experience musical beats significantly impacts their perception of rhythm, providing strong evidence for the critical role of bodily movement in rhythm perception [6]. Furthermore, bodily movement has been shown to interact with various aspects of music perception, such as pitch, rhythm, and musical preference, with expressive body gestures influencing children's perception of musical expressivity [7]. These studies collectively establish empirical links between bodily movement and music perception, offering foundational support for embodied music cognition research [2].

Research has also begun to explore the body movements of musical experiences in social and ecological contexts. Dotov et al. tracked bodily movements during collective listening to music varying in rhythm and tempo, while also collecting participants' ratings of grooviness, emotional valence, emotional intensity, and familiarity. Notably, participants exhibited greater movement energy when listening to high-groove music with their eyes open, suggesting an enhanced embodied response under conditions of increased social awareness [8]. In a large-scale study conducted in 2023, researchers investigated physiological and motor synchrony among 132 concertgoers during classical music performances. Findings revealed high levels of synchrony in heart rate, respiration, and skin conductance, as well as coordinated bodily movements across participants, though breathing patterns were not synchronized [9]. These results provide strong evidence for the resonance and shared embodied experience among audience members in live musical settings.

Some scholars have found that music and spatial cognition may be strongly linked, there are similarities in metaphors between music perception and spatial cognition, and this result may have significant implications for embodied cognition society [10]. Experiments have shown that the musical notes may be represented vertically, and that there is a similarity between the high or low pitch and the high or low spatially for music experts [11]. Yi Wooyong building upon prior research exploring the metaphorical association between pitch and spatial perception, designed an experiment to investigate how musical pitch influences visuospatial behavior. This study used pitch, one of the fundamental elements of music, as the independent variable, and employed a drawing task as the behavioral measure. The experiment tested two primary hypotheses: first, that participants would draw images larger when exposed to repetitive melodies with wider pitch intervals; second, that ascending melody would similarly lead to larger drawings compared to descending ones. The findings indicated that melody had a measurable influence on participants' behavior, suggesting an involuntary, metaphorically grounded response to auditory stimuli. This study provides evidence that musical pitch can influence spatial representation, thereby supporting embodied and metaphorical frameworks of music perception [12].

A 2022 study examined how specific auditory features affect bodily movement, body representation, and emotional states, even when the actual movement performed remains constant. Across three controlled experiments, participants were instructed to execute a simple arm raise while synchronizing their motion with different types of auditory stimuli. Experiment 1 involved pure tones with ascending or descending pitch; Experiment 2 introduced harmonically rich musical stimuli; and Experiment 3 manipulated the absolute frequency range of the tones. Results showed that changes in pitch influenced people's general emotional state as well as the various bodily dimensions investigated—movement, proprioceptive awareness and feelings about one's body and movement. Adding harmonic content amplified the differences between ascending and descending sounds, while shifting the absolute frequency range had a general effect on movement amplitude, bodily feelings and emotional state [13].

Based on the aforementioned studies, it is evident that as research on embodied music cognition continues to advance, the theory has not only been supported at both individual and collective levels through evidence of mutual influence between certain voluntary bodily movements and music perception, but have also evolved to address more specific associations—such as the links between melodic direction, spatial metaphors, and bodily movement. These findings have sparked deeper reflections on the embodied nature of musical perception, including the presence of psychological metaphors and physical expressions. While some experimental results may provide new insights into the role of auditory and musical features in dance and exercise, our interest lies in the reverse question: if pitches or melody can influence certain voluntary movement and action, can different forms of passive movement or motion, in turn, affect the perception of pitches or melody?

It is well known that passive bodily movements can be achieved using multi-degree-of-freedom motion platforms, which have been widely applied in settings such as cinemas and amusement parks as part of 4D film experiences [14]. However, fundamental research on the relationship between passive bodily movement and music perception appears to have been largely overlooked. To explore the specific regular relationship between body movement and music perception, this paper analyzes the influence of the body on the perception of musical elements under passive multiple degrees of freedom linear motion through a listening experiment, innovatively utilizes a multi-degree-of-freedom motion platform as an experimental tool, to provide a new theoretical basis for the interactive music experience.

2 MATERIALS AND METHODS

2.1 Participants

This study investigated the auditory perception of melodic intervals under conditions of passive movement along three translational degrees of freedom (vertical, lateral, and anterior-posterior) using a motion simulator platform. A total of 39 participants (19 males, 20 females) participated in the experiment. The equal gender distribution helped control for potential gender-related influences on the experimental data. The participants were between 20 and 35 years of age, and all had normal bilateral hearing. The participants perform a melodic interval perception task while the platform is either stationary or in motion. The primary objective is to examine whether passive linear movement in three degrees of freedom influences the perceived direction and pitch distance of melodic intervals by comparing the effects between static and dynamic conditions.

2.2 Materials and Stimulus Selection

From the perspective of selecting musical parameters for the study, melodic intervals serve as a fundamental element of musical expression. The directional nature of melodic intervals conceptually aligns with the multidirectional movement capabilities of the motion simulator platform. Notably, the sense of motion induced by the platform bears a conceptual resemblance to the contour of melodic motion shaped by intervallic progressions. While traditional research on interval perception has focused primarily on auditory processing, music perception, in reality, is an open and multisensory process. Therefore, melodic intervals are chosen as the fundamental musical perceptual element for examining the potential influence of the motion simulator platform on auditory perception. Considering the possible influence of melodic intervals in different registers on the experimental results and the limitation of the number of experimental materials, unisons, major thirds, perfect fifths, and perfect octaves composed of different pitches were selected for each of the three registers of the bass, middle, and treble regions in the full range (C2–c5).

The experiment involved 12 sets of melodic intervals. In a single degree of freedom, with the exception that the unison has only two variables of the relative motion direction of the platform, each type of interval of the major third, perfect fifth, and perfect octave has a total of four variables according to the ascending melodic interval, descending melodic interval, and relative motion direction of the platform in one degree of freedom, for a total of 42 groups of melodic intervals. To minimize potential memory effects on the experimental materials, the 42 melodic intervals in each of the three translational degrees of freedom were presented in a fully randomized order. All auditory stimuli were pure tones (sine waves) with uniform loudness. Each melodic interval had a fixed duration of 2.15 seconds. The participants listened to the stimuli through monitoring headphones.

The experiment utilized a 6-DOF motion simulator platform (capable of uniform movement along six spatial degrees of freedom) with participants seated on it. Motion ranges were Z-axis 0–80 mm, Y-axis -109–100 mm, X-axis -97–99 mm; to standardize distance, a fixed displacement of 40 mm (Z-axis half-range, within safe limits) was selected. Platform velocity was maintained at 10 mm/s for uniform motion, with each movement lasting ~4 seconds. Auditory stimuli synchronized with motion ensured each melodic interval was fully presented during movement.

This study employs the scaling estimation method, which is based on the comparison of the subjective perceptual magnitude of a standard stimulus with that of a comparison stimulus—to generate psychometric scales (Figure 1). The psychometric scale ranged from 0.5 to 2, with the perceived interval distance in the stationary condition normalized to a reference value of 1. The participants were instructed to compare the subjective perceptual magnitude of melodic intervals heard in the motion condition against those heard in the stationary condition and record their perceived interval distances on the scale. A score greater than 1 indicated an expansion of the perceived interval distance, whereas a score less than 1 indicated a contraction. The participants are required to evaluate the perceptual magnitude of the comparison stimulus relative to the standard stimulus and indicate their perceived magnitude on a psychometric scale.

Figure 1 Psychological Scales Used in the Experiment

2.3 Procedure

Participants were not informed of platform motion direction. Starting with the Z-axis (vertical), a melodic interval was first presented (platform stationary), then replayed as the platform moved along Z-axis; participants completed a psychometric scale, repeating this for all intervals. After Z-axis trials, booklets were collected/labeled, and the same was done for X-axis (lateral) and Y-axis (anterior–posterior) trials, with final booklet collection/labeling. Trials could be repeated if participants were unready or unclear of stimuli. Total duration was ~45 min (15 min per degree of freedom), with short breaks allowed between conditions.

2.4 Analysis of Data

A total of 4,914 sample data points were collected. Given the large dataset, an initial data preprocessing step was conducted to identify and remove outliers. Data analysis revealed that the sample data for each melodic interval in each translational degree of freedom followed a normal distribution. Therefore, the three-sigma limit was applied to exclude outliers. After the three-sigma limit was applied, the number of outliers removed per sample group was ≤2, indicating high data reliability.

To examine whether there was a significant difference in melodic interval perception between the stationary and motion conditions across all three translational degrees of freedom, an independent-samples t test was conducted. The results revealed a statistically significant difference. Further independent-samples t tests were performed separately for the Z-axis, X-axis, and Y-axis conditions. Significant differences were observed in the auditory perception of melodic intervals between the stationary and motion conditions along three degrees of freedom ($p < 0.05$).

To quantify the perceived change in interval distance, the interval variations were digitized into cents. After computing the cents change values across the three translational degrees of freedom, the data were further categorized on the basis of register, interval quantity, interval direction, and platform movement direction. The corresponding values for each variable were averaged and are summarized in Table 1.

Table 1 Mean Values of Auditory Changes in Cents for Different Categories of Distinctions in 3-DOF

Z-axis			**Y-axis**			**X-axis**		
categories		**cent change**	**categories**		**cent change**	**categories**		**cent change**
register	bass	15	register	bass	7	register	bass	24
	middle	24		middle	11		middle	11
	treble	23		treble	26		treble	18
interval quantity	unison	8	interval quantity	unison	-5	interval quantity	unison	4
	major third	6		major third	-4		major third	0
	perfect fifth	28		perfect fifth	18		perfect fifth	19
	perfect octave	34		perfect octave	40		perfect octave	40
interval direction	parallel	8	interval direction	parallel	-5	interval direction	parallel	4
	ascending	60		ascending	45		ascending	44
	descending	-14		descending	-9		descending	-4
platform motion	up	27	platform motion	forward	11	platform motion	left	14
	down	14		back	18		right	21

Table 1 shows that the overall trends of the cents across the Z, X, and Y axes are similar. However, the absolute values of cents variation in the Z-axis condition, particularly concerning interval quantity and direction, were greater than those observed in the X- and Y-axis conditions. This suggests that the change in the auditory perception of the quantity and direction of melodic intervals was more pronounced overall for the Z-axis direction than for the X- and Y-axis directions, as illustrated in Figure 2.

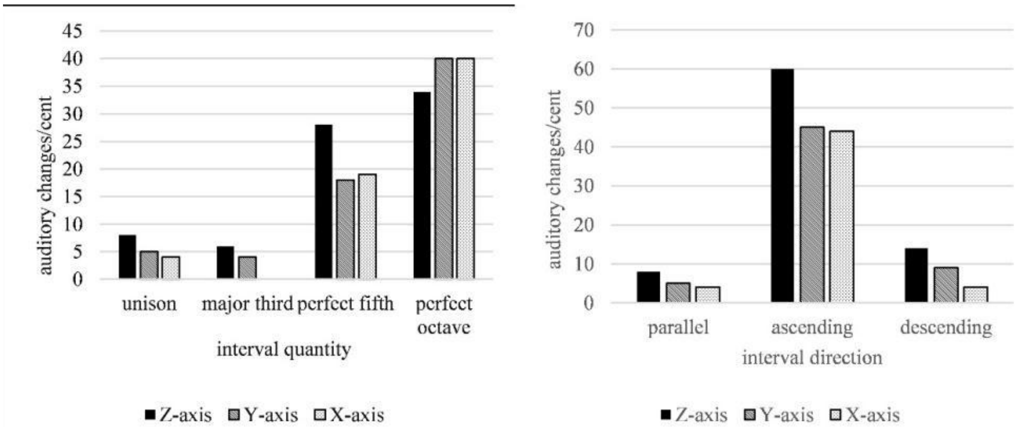

Figure 2 Auditory Changes in the Cents' Fractions of the Interval Quantity and Interval Direction under Linear Motion in 3-DOF

From the changes in the cents in the different registers of the three degrees of freedom movements in Table 1, the changes in the cents of the auditory perception after the three degrees of freedom movements are not corelated to the registers; this result has been subjected to an independent samples t test, and the result showed no significant difference. From the data in Table 1, a pattern emerges regarding the interaction between platform motion and the melodic interval direction. The direction of the melodic interval influences the perceived interval distance during platform motion. As illustrated in Figure 3, parallel melodic intervals exhibit the smallest cents variation across all three degrees of freedom, followed by descending melodic intervals, which show moderate variation. In contrast, ascending melodic intervals demonstrate the most pronounced change in perceived interval distance. Furthermore, the cents variation for ascending melodic intervals is consistently positive across all three degrees of freedom, indicating an expansion in perceived interval distance. Conversely, the cents variation for descending melodic intervals is consistently negative across all motion directions, suggesting a contraction in perceived interval distance.

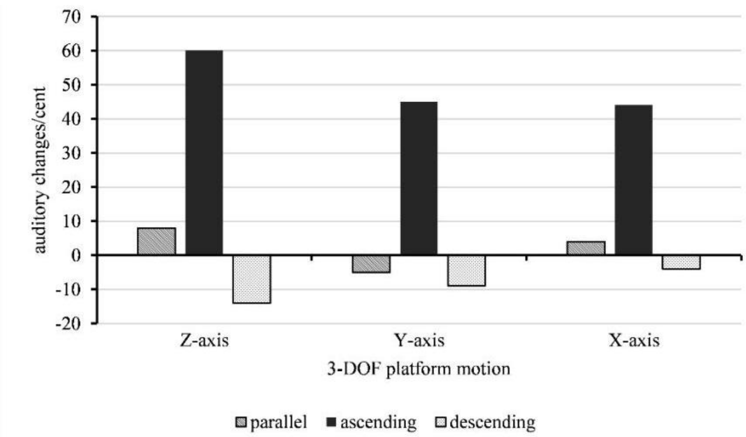

Figure 3 Changes in the Perceived Cents of Different Melodic Interval Directions under 3-DOF of Linear Motion

Additionally, Table 1 reveals the relationship between platform motion and the number of melodic intervals. As depicted in Figure 4, the cents variation for the unison and major third intervals is relatively small, whereas the cents variation for the perfect fifth and perfect octave intervals is more pronounced. Moreover, the trend is consistent across all three degrees of freedom—larger interval sizes correspond to greater perceptual changes in cents under platform linear motion.

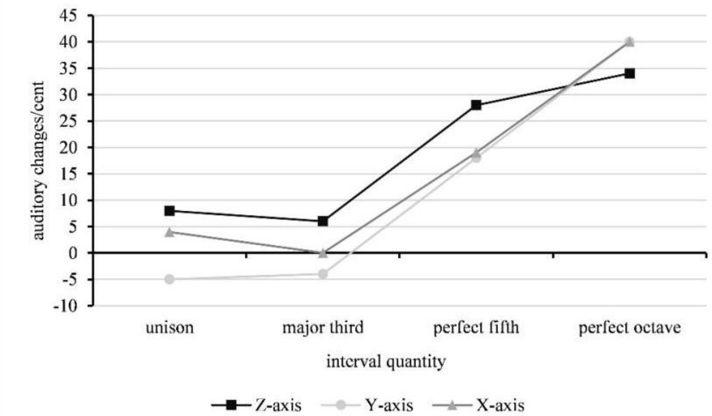

Figure 4 Changes in the Perceived Cents of Different Melodic Interval Quantities under 3-DOF of Linear Motion

To further explore the influence of motion direction on perceived interval changes, the data from Table 1 were subdivided by platform movement direction and melodic interval direction. Figure 5 illustrates the relationship between the six movement directions of the platform and the variation in melodic interval perception.

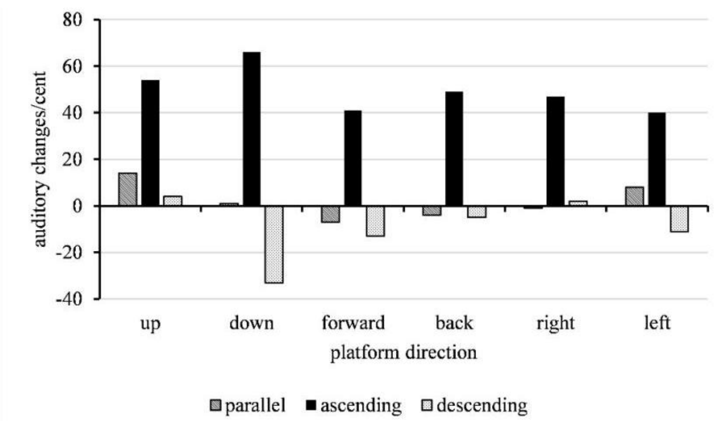

Figure 5 Relationships between Motion Direction and Changes in the Perceived Cents of Melodic Intervals

As shown in Figure 5, when the platform moves downward, forward, or leftward, there is a pronounced contrast in the cents variation between the ascending and descending melodic intervals. Specifically, in these three motion directions, ascending melodic intervals exhibit an expansion effect on the perceived interval distance, whereas descending melodic intervals exhibit a contraction effect.

When the platform moves upward, backward, or rightward, ascending melodic intervals continue to demonstrate an expansion effect. However, the influence of motion on the descending intervals is less pronounced, as indicated by the observed data. To verify the statistical significance of this pattern, an independent-samples t test was conducted. The corresponding p values are presented in Table 2.

Table 2 P Values for the Effects of Upward, Backward, and Rightward Platform Motion on the Perceived Changes in Different Melodic Interval Directions

melodic interval direction	**ascending**			**descending**		
platform motion	**up**	**back**	**right**	**up**	**back**	**right**
p value	0.001	0.001	0.001	0.752	0.558	0.814

Table 2 confirms the observed pattern, demonstrating a statistically significant difference ($p < 0.01$) in the perception of ascending melodic intervals under upward, backward, and rightward platform motion. This finding further supports the systematic relationship between platform motion direction and perceived interval expansion or contraction.

3 DISCUSSION

Based on the theoretical framework of embodied cognition, which posits that bodily movement influences music perception, in this study we designed an experiment to investigate the impact of platform motion on the auditory perception of melodic intervals. By comparing the perception of melodic intervals under stationary and motion conditions, we examined whether the perceived interval distance differed between these two states, thereby analyzing the effects of movement on melodic interval perception. The key finding was that linear motion along all three degrees of freedom (Z-axis, X-axis, and Y-axis) affects the auditory perception of melodic intervals. This finding is to provide specific empirical evidence for one of the directions of research on embodied music proposed by researchers such as M. Leman, P. J. Maes, and others- related research on the effects of movement on music perception. Previous research has largely focused on the influence of voluntary movement on music perception—demonstrating, for example, how bodily engagement such as bouncing or gesturing modulates rhythmic or expressive perception [5-7]. In contrast, the present study explores whether passive bodily movement, delivered via a motion simulator platform, can modulate auditory perception. The affirmative findings thus add a crucial dimension to the embodied music cognition framework, indicating that the body does not merely respond to musical stimuli, but that bodily movement—whether active or passive—actively shape perceptual outcomes.

Motion along the Z-axis results in greater perceptual variation in cents, particularly influenced by interval quantity and interval direction, than motion along the X- and Y-axes. A possible explanation is that the vertical axis holds a privileged status in the space–sound mapping [11]. This finding resonates with the observation that common musical metaphors almost universally use vertical terms: melodies “rise” and “fall,” pitch is “high” or “low”. The forward–back or left–right dimensions have far fewer conventional analogies in the domain of melody, which likely explains the null results along those axes. Therefore, changes along these directions are less pronounced than those along the vertical axis.

The findings of J. Ley-Flores demonstrated that changes in absolute frequency range have a general effect on movement amplitude [13]. Conversely, when examining whether the perception of pitch intervals is influenced by frequency range during observed bodily motion, our results revealed the opposite: the variation in cents perception due to linear motion is not significantly related to the pitch register.

The perceptual change in cents for ascending melodic intervals is significantly greater than that for descending and parallel intervals. Furthermore, ascending melodic intervals are perceived as expanded in distance, whereas descending melodic intervals are perceived as contracted, that corresponds with prior findings on pitch-movement interaction. For instance, Yi Wooyong’s study showed that ascending melodic contours can influence participants to produce larger drawings, evidencing a metaphorical linkage between pitch direction and spatial scale [12]. Our findings resonate with this idea and extend it to a novel context: when passive bodily movement is introduced, the same metaphorical mappings appear to guide or bias auditory perception of interval magnitude. This supports the assertion that sensorimotor mechanisms are integral to conceptual and perceptual musical processes.

An interesting finding is that the larger the interval size is, the greater the perceptual difference in cents induced by motion. This finding introduces a nuanced understanding of how linear motion affects pitch perception: the effect is not uniform across all interval sizes but scales with magnitude. From an embodied perspective, larger melodic intervals likely engage more extensive sensorimotor resources—both in terms of imagined motion (e.g., a "leap" versus a "step") and in their metaphorical association with spatial displacement. When bodily movement (even passively induced) interacts with these intervals, the perceptual system may become more sensitive to such spatial cues, leading to greater modulation effects.

While the results revealed certain effects of linear motion on interval perception, several limitations should be acknowledged. First, the study used a controlled laboratory setup with interval and motion profiles. It remains to be seen how these findings generalize to a wider range of musical materials. For instance, real music involves continuous melodic contours and music excerpt, not just intervals, so future studies should investigate whether the motion affects in complex melodies. It’s also found that the influence of motion direction on perceived interval distance is modulated by the direction of the melodic interval, with specific motion directions leading to systematic changes in perceived interval expansion or contraction, further studies with larger sample sizes are needed to verify this effect.

4 CONCLUSION

This study further validates the hypothesis of embodied cognition, demonstrating that multidimensional motion influences the auditory perception of melodic intervals. These findings reveal specific perceptual patterns, contributing to a deeper understanding of the relationship between motion and music perception. The significance of this important finding lies in clarifying that auditory perception is not an isolated sensory process but one deeply entangled with the sensorimotor system, even when bodily movement is passively induced and not volitional.

Future research can refine the experimental design by controlling extraneous variables to focus on the key motion-related factors affecting interval perception. Additionally, further investigations may extend to rotational degrees of freedom (pitch, roll, and yaw) to explore their impact on the perception of melodic intervals.

Finally, this study suggests a promising trajectory for future research in embodied music cognition: the investigation of how passively bodily movement—whether through motion simulation or other technological means—can systematically influence not only perceptual judgments but also affective and cognitive responses to music. Such research could deepen our understanding of how the body acts as a mediator of musical meaning and emotional experience, further bridging the contact between embodiment and music.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY STATEMENT

All relevant data supporting the findings of this study are available in 'figshare' (https://doi.org/10.6084/m9.figshare.28768913).

AUTHOR CONTRIBUTIONS

BingQing Xiao: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Writing – Original Draft, Writing – Review & Editing.

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