Research Topics

Rhythm across the arts and sciences: A synergy of research

Edited by
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Rhythm across the arts and sciences: A synergy of research

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Editorial: Rhythm across the arts and sciences: a synergy of research

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Editorial on the Research Topic
Rhythm across the arts and sciences: a synergy of research

Readily apparent in music and dance, the universality of rhythm and rhythmic processes also permeates art, architecture, sports, neuroscience, psychology, and medicine. This collection presents multiple perspectives from these diverse domains that challenge assumptions and offer new insights into the pervasiveness and trans-disciplinary nature of rhythm and its centrality to the human condition. Rhythm is an essential part of art and life, found in music, movement, circadian cycles, and learning. The predictable patterns of regularity that exist throughout the physical universe and in human activities enable us to understand the world, generate meaning, and engage in both quotidian as well as inspired creative activities.

Although one might expect the majority of articles in a collection about rhythm to revolve around music, four papers look at different art forms: dance, poetry and visual arts. First, Wilson and Henley investigate the thoughts of three generations of dance teachers about the experience of rhythm, from Margaret H'Doubler's teaching about rhythm as "measured energy" to Wilson and Henley's research work on movement qualities, and further to Henley's educational approaches for dance students to explore and experience rhythm pre-reflectively.

Stupacher et al. aim to elucidate the neural mechanisms underlying groove, which was defined as the pleasurable urge to move to a rhythm. They look at the relationship between predictability and surprise in the experience of groove. Their study covers dance, music making, and music listening, in search of a better understanding of the interactions between temporal processing, movement, social behavior, and pleasure. The paper also discusses implications for future research that could encompass treatments for patients with motor impairment (e.g., Parkinson's).

In contrast to dance, poetry is at the center of the Beck and Konieczny study which investigates top-down and bottom-up processes while reciting poems out loud. The rhythmicity of the reading was modified when the syllable "tack" replaced randomly selected syllables. Participants were recorded reading both original and manipulated versions of the poem. Results of the analyses of syllable duration and intensity suggest that processes from both directions interact, and that the top-down processes supporting the metric structure seem stronger in participants with musical experience.

Hadavi et al., on the other hand, examine the positive effects of viewing visual artworks on visitors' mood and wellbeing. In a study conducted during the pandemic, participants visited a virtual exhibition of works, which had been created in response to specific musical compositions. The researchers did not find differences in mood when comparing those participants who viewed the artworks while simultaneously listening to the associated musical compositions and those who saw the art without sound. They demonstrate that a virtual art exhibit was able to increase positive affect and decrease negative affect in a widespread audience.

Other papers look at internal, biological and physiological phenomena. In their article, Kwak et al. describe a trio model of human biological rhythms—central rhythms, internal/external rhythms, and reflex/consequential rhythms—and their cycles. The authors view these three types of biological rhythm as members of a musical ensemble, which, in flexible mutual exchange and interconnection, lay the foundation for homeostasis as well as regeneration.

Through a single case study, Sebastiani et al. describe the influence of technical challenges, temporal, and emotional factors on heart rate variability in piano playing. When playing a classical piece, increased activation of the sympathetic nervous system was found, in contrast to when they played a jazz piece. This was presumably caused by challenges with regard to precision and correct playing technique. These challenges, in turn, appear to influence temporal features and emotional involvement.

Evidence exists that rhythm-based activities can be helpful for those who have experienced trauma by regulating arousal levels and supporting positive experiences. Building upon this, McFerran et al. use an action-based approach to investigate young people's responses to music therapy treatments after traumatic experiences. According to the data collected, participants preferred semi-structured activities that allowed for creativity, self-direction and individuality, and enjoyed moments of co-regulation and matching their own rhythms rather than entraining to an external rhythm.

Rhythm objects are defined by Godøy as "strongly coherent chunks of combined sound and body motion in music" in a literature review that looked at music psychology, music theory, philosophy and research in human movement science. In this article, the author considers rhythm beyond traditional and conventional definitions. He describes chunks of musical sound and the bodily motions associated with their production, that could be perceived holistically as quantal elements in musical experience.

Margulies et al. investigate the close temporal relationship between technical demands and compensatory movements of the left upper extremity while playing the violin. Minimizing compensatory movements could help violinists avoid playing-related health problems. Strategies discussed include individually optimizing the position of the instrument, frequently changing practice strategies when working on challenging passages, and taking breaks more often during practice sessions.

Honda and Fujii focus on the differences between amateur and professional darbuka players while learning rhythmically challenging finger tapping movements. Professionals showed better learning results both in terms of speed and precision of the movements, which the authors attribute to their greater wealth of experience with the instrument. Consistent with the efforts in music, dance, and sport, documented since 2008 in the framework of the *Art in Motion* symposia, these results suggest a need for optimization of instrument-related learning and practice strategies.

Taken together, this collection presents diverse and interdisciplinary research, all based on the common theme of "rhythm." These ten articles span a broad variety of topics, by looking at phenomena through studies of music-making, perceptual processing, as well as other aspects of human biology and behavior. The editors hope that these articles will serve to extend and challenge our conceptions of rhythm, and suggest questions for further research.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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CONCEPTUAL ANALYSIS
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Experiencing Rhythm in Dance

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In this article, two dance educators offer a definition of rhythm from both educational and performance perspectives and discuss pedagogical practices that waken students' awareness to rhythm as a lived-experience over which they have creative control. For the dancer, in the midst of the dance, rhythms are, in the words of Margaret H'Doubler, recurring patterns of measured energy. These patterns are nested in scales from the moment-to-moment shifts in muscular contraction and release to the rise and fall of dramatic tension in a performed dance. This approach to rhythm runs counter to many dance students' studio-based training in which rhythm is equated to synchronizing accents to a specific meter. The authors describe pedagogical practices in the studio that foster engagement with rhythm as lived-experience. Drawing attention to their kinesthetic experience while moving, students are encouraged to modulate levels of exertion embedded in the qualities of movement they are experiencing. As varying levels of exertion are attended to across temporal durations, students notice patterns as they emerge and recur. This attention to recurring patterns of measured exertion is, the authors claim, the lived-experience of rhythm in dance.

Keywords: dance, rhythm, experience, energy, H'Doubler

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INTRODUCTION

Rhythm is a familiar enough word; yet its meaning depends on the user or, more precisely, on how the user uses it. Rhythm means one thing to a farmer and another to a newspaper editor. Nonetheless, each user understands, in a general way, what the other user is referring to when they use the word. Rhythm is not a thing. Nor does it refer to a thing. Rhythm is a phenomenon like time and space. It extends well beyond the particulars of one's work. That makes it difficult to define. A popular answer to the question, "What is rhythm?" could be, "I can't define it, but I know it when I see, hear, or feel it." In short, rhythm is experiential, palpable to the senses though elusive to the analytical mind.

In the psychological literature, rhythm has primarily been considered in the domains of music and speech perception where it is generally defined as patterns of relative durations between notes, tones, or other acoustic events (Levitin et al., 2018). Cummins (2009) argues that these definitions inadequately account for the ecological role of rhythm. Whether in music or speech perception, rhythms are not mere acoustic waves available for passive perception, rather they serve as affordances for the coordination of stimulus and action. This coordination is referred to as entrainment, in which rhythm acts a coordinating force between dynamic systems.

Though entrainment between action and auditory stimuli serves an important role for ecological purposes of survival and social coordination, rhythm can also be perceived by sensory modalities other than audition including haptic, proprioceptive, visual, and vestibular systems (Levitin et al., 2018). Phillips-Silver et al. (2010) describe several forms of entrainment, one of which is self-entrainment, in which the stimulus to which an agent responds is their own rhythmic output. Rhythm is perceived not as a series of acoustic or visual events, but as the "energetic turning points in the [agent's] motion" (Waterhouse et al., 2014). Explicit awareness of the sense of self-movement, or kinesthesis, as a mode of self-coordination is central to the practice of dancing. Rhythmic awareness and practice sit at the center of many dances, wherein there is a mutual coordination between musician and dancer (Cruz Banks, 2021). In the historical traditions of modern and post-modern concert dance, which are the authors' areas of expertise, educators and choreographers sought to separate music as a source of the dancer's energetic coordination and prioritize the self as the source of rhythmic output. Thought of in this way, rhythmic awareness is a form of self-entrainment, in which the dancer attends to energetic turning points created by the dancing in which they are engaged.

In this article we describe how three generations of dance educators sought to understand and develop this approach to rhythm. The article begins with a brief history of Margaret H'Doubler's development of the definition: "rhythm is measured energy" (H'Doubler, 1921, 1932). We then describe how a student of H'Doubler's, and co-author of this article John Wilson, extended H'Doubler's definition through empirical research on primary and transitional movement qualities. In the final section, a student of Wilson's, and co-author of this article Henley, describes how these definitions have been informed, clarified, and extended in his own teaching practice by phenomenological and process philosophy. In **Supplementary Appendix**, we offer practical suggestions for readers to begin to develop their own awareness of rhythm as energy measured through the sense of self-movement.

THE SEARCH FOR MEANING IN DANCE EDUCATION

H'Doubler was neither a dancer nor a choreographer but she is celebrated in the dance world as the "pioneer" who created the first dance degree program in America at the University of Wisconsin in Madison. The year was 1926. This feat was followed by the creation of a master's degree program in 1928 leading to an M.S. or M.A. depending on the curriculum "track" the student pursued (Ross, 2000). H'Doubler (the H is silent) was the founder of an intellectual tradition that defines the facts and principles of the experience of dancing. Rhythm is but one of those principles (H'Doubler, 1940).

In 1916, H'Doubler,[1] an instructor in the Department of Women's Physical Education at University of Wisconsin, Madison was tapped by her director, Blanche Trilling, to take a leave of absence and go to New York City to "find out what this new dancing is all about. See if it has value for our young women" (Wilson et al., 2006). She departed for New York and Columbia University's Teachers College.[2] Teachers College was home to new ideas in experimental education that were gaining currency in the country. One of the experiments was a dance program designed and led by an adjunct faculty member, Gertrude K. Colby (1874–1960) and her associate, Bird Larson[3].

H'Doubler would have been aware of Colby's efforts but, for some reason, she recorded and spoke very little about that. Members of "Miss HuhDee's" (an affectionate appellation) graduate student seminars at UW-M after she retired in 1954 assumed that she felt Colby relied too much on familiar folk-dance rhythms for her students' "free expression."[4] H'Doubler had not yet figured out an alternative to teaching dance by "steps in time." Nonetheless, Colby's speculative ideas about the significance of rhythm in human movement very much coincided with H'Doubler's developing ruminations on the subject. As her experimentation developed over the years, Colby often expressed her belief that dance education should spring from each child's "natural" body rhythms—that each child is endowed at birth with her or his unique, personal rhythms and that those rhythms "should be the foundation of her [Colby's] educational program." Her guiding principle was: "By making ourselves free instruments of expression, rhythmically unified, we are enabled to express in bodily movement the ideas and emotions which come from within. 'We dance ideas, not steps'" (Colby, 1922, pp. 7–8)[5].

The identity of Colby's thoughts within H'Doubler's cannot be missed. Those thoughts become pronouncements in the latter's classic book, *Dance: A Creative Art Experience* (1940). The heading for Chapter 2, "The Province of Dance," states: "Art as creative expression has its source within man's physical, mental, and emotional structure; dance therefore is the heritage of all mankind." Subsequent chapters 3–7 lay out how this can be

[1] Margaret Newell H'Doubler (1889–1982) was born to Charles and Sarah H'Doubler in Beloit, Kansas. Margaret was a tomboy and the third of four children. They were raised in Warren, Illinois where the family moved for better financial prospects. Four years later they moved to Madison to be near the University of Wisconsin. Margaret entered the university in 1906 where she studied biology and philosophy. She was active in women's sports—particularly basketball in which she excelled. In 1910 she graduated with a B.A. with honors in biology. She was hired as a teaching assistant in the Department of Women's Physical Education to teach women's sports and to coach the women's varsity basketball team. Her position was elevated to instructor in 1911.

[2] Visiting the private studios, Maragaret found that most classes were rudimentary ballet that she did not approve of. They did not, to her mind, promote the students' awakening to their inner person. Ballet was too rigid. There was no play and no free exploration of movement. Occasionally she attended a modern dance (also known as "free dance" or "contemporary dance") concert in the city or classes given by the rising professionals of the time. These performers represented the "new dancing" that Miss Trilling referred to. Again, Margaret was not pleased. She saw only unabashed egos and their imitators on display—no values for college women to cultivate.

[3] But that program, just 3 years old, was evaluated by the overseers and found not to meet the criteria set for the Speyer School (originally a Settlement House built in 1906 for children) where the program was carried out (Spiesman, 1960). Those criteria were: "To design and develop a [dance] program that would be natural and free for [all] children; to permit self-expression; to harmonize (. . .) with the total school program." The program was ended in 1916. However, Colby was hired by the Teachers College to continue experimenting with and developing a new progressive dance program not in the style of commercial studios.

[4] From H'Doubler interview with Wilson (1966, Book 1, p. 23).

[5] Though improvisation was a new element in the discipline of dance training, and it revealed to the experienced dance teacher's eye what the individual students' personal rhythms might be, no one had figured out how to "rhythmatize" them—to make them *rhythmically unified*. Even progressive teachers resorted to known folk dances and their rhythms which might not capture or stem from the student's personal rhythms. This surmise was made by the graduate students in Miss HuhDee's seminars.

realized in education. And, by implication, that was not only in dance education but general education.[6]

Trilling also suggested H'Doubler attend a class taught by Alys Bentley (1869–1951), a children's music teacher in New York City who was regarded as an innovator in her teaching methods. First, the children were instructed to lie on the floor as music played. The children were to react to what they felt, emotionally, by moving their bodies. H'Doubler joined in this exercise and suddenly realized the key to what would be basic to her dance classes:

> "(. . .) she got us down on the floor and had us do some rotations and work with some flexions and extensions (. . .) but not talking to us or telling us why or anything about it. But then it came just like a flash: 'Of course! Get on the floor where we're away from the pull of gravity then work out what really are the structural changes of position of the body when it can move freely!' And then I commenced to get really excited."[7]

THE PROGRESSIVE DANCE CLASS

The necessary parts of H'Doubler's thinking at last coalesced. From childhood her temperament was that of a scientist. Her father, whom she followed like his shadow, was an inventor with a dozen or more patents in his name. Her academic major was biology. She understood human movement as a kinesiologist does. She also understood motor perception and kinesthesis and its linkage with emotions. From her required undergraduate P.E. classes she knew how to perform folk dance and eurhythmics (Findlay, 1971). She was committed to progressive education, and she preferred teaching in the Socratic method with interactive dialogue.

A full sized, manufactured human skeleton hung on a rolling pole in every class she taught in her long career. To begin the physical activity of a class, following a short anatomical lecture for the day, the recumbent students spontaneously explored joint movements with their eyes closed. Continuing the improvisation she instructed them to give their attention to the kinesthetic feedback they experienced from muscle contraction and release. The classes ended with short, student-taught dance pieces followed by class discussion on the day's learning experiences.

Transferring to standing posture, the students were instructed to continue the joint and muscle explorations that had begun on the floor. Shortly after that part of the activity the students, individually, created their own rhythms to support the movements they had experienced kinesthetically and emotionally. Eventually H'Doubler had each student demonstrate what she or he had created. After a brief response from the witnessing class, the student's creation was repeated. The accompanist joined in spontaneously with piano, percussion, or wordless song (Ross, 2000).

All elements of a progressive "new dance" experience were in logical sequence for teaching and artmaking. H'Doubler's definition for rhythm served her classes, but posed an important question: how is energy measured? In the next section, we describe how Wilson addressed that question.

THE MOVEMENT QUALITIES

H'Doubler retired from the Department of Physical Education at the University of Wisconsin-Madison as Professor Emerita in 1954. She was often invited by the department faculty to return to the campus to teach classes and lead open discussions. Seminars for graduate students were conducted in the studio where they experienced her unique movement classes, followed by in-depth discussions on topics that the students brought up. Questions about rhythm and the teaching thereof were frequent. H'Doubler's succinct definition, "measured energy," was particularly provocative, both on the practical and the theoretical level. How can energy *be* measured? Energy within the body is constantly in flux so is not *exertion* what we are concerned with, not energy? We are concerned with *how* exertion is used—how it is manifested in our movements. This question deserved exploration. It deserved empirical evidence. With H'Doubler's encouragement, a team of graduate classmates set out to find that evidence.

The first subset of questions was to find what the phrase *movement qualities* referred to. Every dance teacher and choreographer uses the term "quality" and its plural form. But there is no set or universal vocabulary to describe all the qualities. The most often named as qualities are "swinging," "percussive," "sharp," "soft," "smooth," "heavy," "light." These and dozens more can be useful—even essential—instructions to dancers depending on the circumstances. Rudolf von Laban (1879–1958), Hungarian choreographer and dance theorist, developed a vocabulary for movement *efforts*. Many books by Laban and his followers are in publication or rare books collections. Most of these are organized as manuals for teaching and several are theoretical (Laban and Lawrence, 1947; Newlove and Dalby, 2004).

In his system for teaching Laban uses the term "effort" rather than energy. But his "Eight Efforts" refer to biomechanical actions rather than to root neurological qualities. The Eight Efforts are: punch, slash, dab, flick, press, wring, glide, and float. These "efforts" imply but do not specifically refer to "raw" exertion. A member of the research team added the word raw to exertion to differentiate what they were searching for from efforts by which Laban identified actions, a critical distinction in the pursuit of movement qualities.

A second question arose: are there a limited number of basic movement qualities on which all variations are based? How those were to be found was the challenge. The team began by using very thin electrodes inserted in specific muscles, such as rectus femoris that extends the knee and its antagonist, biceps femoris, that assists in flexing the knee. The electrodes were to record

[6] American philosopher and scholar, John Dewey (1859–1952), was an influential faculty member at Columbia and a frequent lecturer at Teachers College. Margaret, who had been exposed to progressive education thinking at UW-M, and by Trilling in particular, was drawn to Dewey's theories on democracy and experiential education. Her own thinking and values were growing, becoming loftier, during her two difficult years in New York. Eventually, her standard lead-in to her classes and speeches became: "In all of time there is but one of you. To find the quickening spirit that is you is your life's work".

[7] H'Doubler interview with Wilson (1966, Book 1, p. 22).

electrical charges from the paired muscles on oscillograph paper as one, then the other, was contracted and the knee articulated.

The hope was that a distinctive "profile" of the charges would appear on the paper as the paired muscles contracted and released in different degrees in different trials. Would the amplitudes of the two contractions appear synchronously or asynchronously? Would frequencies coincide, overlap, or not coincide? The answer was null. The markings on the paper were almost black. No profiles appeared. In 1966, when the test trials were performed, electronic equipment was primitive; also, the electrode-to-oscillograph means to determine the profiles of movement qualities was, frankly, ridiculous. Not to be discouraged, however, the team conceived of another approach to answer the question: direct observation—empiricism, pure and simple.

Attempts were made to record moving dancers on film. Videotaping had yet to be invented. A few film strips were successfully made that revealed interesting images. However, the process was expensive and slow. The project was revised again, this time to direct observation of improvised movement with subsequent discussions among select panel members on qualities and how they defined them. The dancers, too, joined the discussions. Four of these sessions were staged, each session with a new set of five dancers at three levels of expertise, beginning to advanced.

At each session the observers—always the same four, including the advanced technique teacher, Louise Kloepper—came close to consensus on what recurring, primary movement qualities they saw and what to name them. A swinging quality was the most frequently performed by the dancers. Second in frequency was a smooth, gradual quality. Third was a percussive quality. One of the instructions to the dancers from time to time was to increase the degree of exertion they "put into" their movements. Almost always, that created moments of percussion; but the more advanced dancers began to experiment with the slow, smooth movement quality increasing to a shaking or vibratory quality as they increased exertion. This was a major discovery for the observers and the dancers alike. Greater or lesser exertion seemed to be the key to identifying different qualities.

After the four sessions were done the team and observers decided to have another two sessions with only advanced dancers participating. Coached now and again to speed up or slow down, or to increase or decrease exertion and yet maintain the quality they were working in at the time, the dancers had many discoveries that the observers witnessed as well. It was a "eureka!" moment. Speed and degree of exertion appeared to be independent factors in the performance of movement qualities. Smooth, for example, could be performed quickly, depending on the skill of the performer. Smooth did not have to be slow to be smooth. Swinging could be performed relatively slowly with high or low exertion. Percussive movement could be performed with a low level of exertion, etc.

These discoveries greatly increased the aesthetic value of the performances according to the observers and in the emotional responses of the dancers. This discovery—that speed of execution and degree of exertion—are independent factors in the performance of movement qualities was remarkable. It supported H'Doubler's thesis that dance is a creative art experience. A dancer not only can perform a form but interpret it. The heightened kinesthetic experience of the dancers and the heightened aesthetic experience of the observers gave powerful credence to her proclamation. Moreover, it concurred with one of her favorite mottos: "Science cannot make art, but it can contribute to a more truthful art."

The observing panel came to two conclusions. First, there are four primary movement qualities: sustained, pendulous, abrupt, and vibratory. These four are basic to all qualities of movement and are essential to ordinary living. This was obvious for sustained, pendulous, and abrupt; but vibratory seemed outside normal living experiences—until someone stated, "but when I'm cold or very angry I vibrate; and what about Katharine Hepburn's chin when she is getting ready to cry?" Vibratory quality did indeed belong in the four basic movement qualities.

The second, conclusive observation by the panel was that all four of these neurologically basic qualities could be *maintained* for several seconds or longer, depending on the energy (yes, *energy* in this usage) available to the performer, without slipping into a different quality. And yet, according to the dancers, there seemed to be (felt to be) other qualities that "tied together" the basic ones. A favorite, kinesthetically and emotionally, was a transition between sustained and pendulous, going either way. They called it "suspended." The difference between these qualities and the primary ones was that they could not be maintained; they were self-extinguishing—transitional.

The consensus of the panel and the dancers was that there are four primary (basic) qualities. Transitional qualities occur in the six zones between the four primary qualities: sustained-pendulous, pendulous-abrupt, abrupt-vibratory, vibratory-sustained, sustained-abrupt, and pendulous-vibratory (see **Figure 1**, the Autosphere and **Supplementary Appendix** for suggestions on use of the Autosphere). The characteristics of the primary qualities were also agreed upon:

a. Sustained: continuous movement with no acceleration or deceleration.
b. Pendulous: oscillating movement continuously accelerating and decelerating.
c. Abrupt: movement continuously starting and stopping.
d. Vibratory: continuous rapid quaking as antagonistic muscles contend against each other.

THE MEASURE OF MOVEMENT QUALITIES THROUGH TIME IS RHYTHM

The Autosphere (**Figure 1**) is an aid to exploring and experiencing the full range of the movement qualities. The two-dimensional circular image represents a sphere in which the primary and transitional movement qualities are depicted in a theoretical relationship. Each of the four primary (i.e., basic) qualities occupies one quarter of the two-dimensional image. At the center of the circle is a non-dimensional point that represents the collapse of all body energy. The qualities extend outward from that "dead center." The two-legged arrows indicate increasing

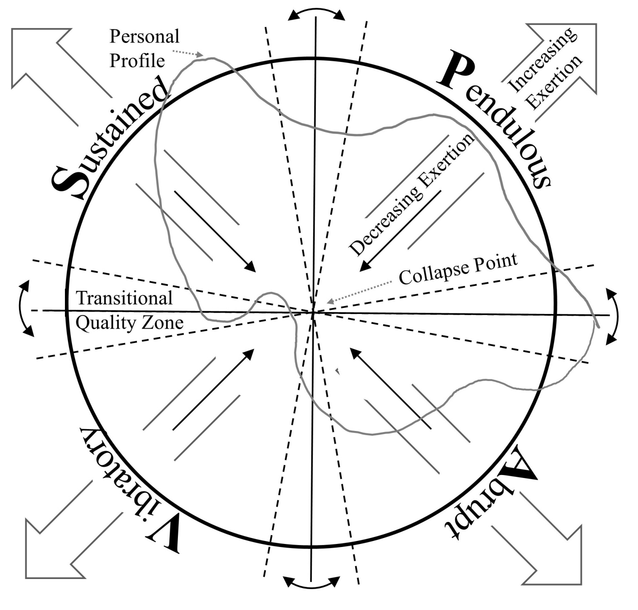

FIGURE 1 | The Autosphere: a graphic depiction of the primary qualities (pendulous, sustained, abrupt, and vibratory) and their transitional zones (e.g., sustained-pendulous). Perceived exertion is indicated by distance from the center or collapse point. Personal profile is an example of a hypothetical student's reflection on their own movement style.

exertion, even to and beyond the circle depending on the exertion of which the performer is capable. The single legged arrow indicates diminishing exertion toward the collapse point.

At the borders of conjunction between the primary qualities are zones in which the transitional qualities occur. Between sustained and pendulous, for example, is the zone of suspension, going either way from sustained to pendulous or from pendulous to sustained. Between abrupt and vibratory is the zone commonly called percussive; from vibratory to abrupt is typically called explosive, from abrupt to vibratory implosive. Vibratory to sustained is commonly referred to as a releasing quality, from sustained to vibratory a containing quality. Note that in a sphere pendulous and vibratory have a common border as do sustained and abrupt, adding up to six borders in all.

In the classroom or studio setting, the transitional names are left to the students to choose depending to how they experience those qualities kinesthetically and with different degrees of exertion or speed of transition. Pedagogically, these are major physical and cognitive learning experiences. The students themselves "own" the emotions generated by the physical experiences. This is the source of H'Doubler's conception of art-making in movement.

PATTERNS OF RHYTHMIC MOVEMENT

Over a period of 40 years' teaching dance, and choreographing some 90 works for professional and college ensembles, Wilson developed many exercises, including the one described in the preceding paragraph, based on the premise that, *in the art of the dance,*[8] *rhythm is experientially elastic and is fixed to a meter only in closed pattern form.*

It is generally assumed that dance is anchored to the meters by which the passage of time is marked in music; steps match meters. A waltz is anchored to 3/4 time. A march is anchored to a duple meter—2/2 or 2/4 time. A jig's meter can be marked in 2/4 or 6/8 time; but no matter how it may be counted, a jig is a jig is a jig.

But it is in the movement qualities that dancers make any beat elastic. Waiting in the wings of a stage, the dancer prepares to enter with an uplifting hop (in ballet called *temps levé)* and appears on stage already running, leaping, skipping, or hopping. The dancer's qualitative exertion—elegantly performed—extends her or his off-stage experience into an entire phrase of movement that may or may not step to the music's meter. Experience is elastic by virtue of its quality—sustained, pendulous, abrupt, maybe even vibratory, but most likely transitional between primary qualities.

Formed or choreographed works, whether of the fine art or exhibition variety, are rhythmically organized in one of four general structures. In larger works, different general structures are created and presented as 'movements' within a piece.

a. Open rhythm is common to sports, games, acting, and miming. Dance improvisation is by nature open rhythmed. Each dancer, as a soloist or as a member of an ensemble, moves freely in her or his personal rhythm. This is the ideal of expressing one's "natural rhythms" advocated by Colby and H'Doubler. In concert dances such rhythms can be incorporated in the choreography and either "set" or remain spontaneous for performance.

b. Closed rhythm is set from start to finish. Closed rhythm is standard for classical ballets, for dance hall and ballroom dancing, for movie dance numbers (think "Singin' in the Rain"), and for such popular dancing as swing, jitterbug, the twist, etc. Accompanying music or sound match the movements. Most Western meters are two, three, four, six, or eight beats to the measure. Slavic and East European folk dances are often in five, seven, nine, or more beats to the measure; Flamenco and Kathak in 12-beat measures, etc. Tempos might vary within measures; but the rhythms maintain their temporal characteristics.

c. Cumulative rhythm is an aggregate progression of disparate rhythms—often personal. They move toward an űber rhythm that no single rhythm can fully express. Stage plays are examples of this. Each character brings her or his personal rhythm to the story. Psychological tensions rise toward a climax as its many rhythms come toward each other in a complex crescendo. Think of the final scene of "Hamlet" or "Some Like it Hot." It makes no difference whether a play is a tragedy, a comedy, a history, a melodrama, or a farce. The over-all pattern of cumulative rhythms is the same though the stories and characters are different. Each character is unique to begin with, but as the action progresses the characters interact and begin to create a larger rhythm in which they play a part cumulatively.

[8]The first known use of the definite article with an art form was in *The Iliad* (Homer, 1865, ca. 950 B.C.E., Bk I, l. 729). It remains the only art form so honored. H'Doubler never knew where the reference to "the dance" had come from - it is a common aesthetic expression; but she always saluted "the dance!" when a libation was raised at a picnic or high social gathering.

As for concert modern dance, choreographers, following the lead of Merce Cunningham, sometimes use aleatoric, better known as "chance," methods for their works. From mid to late twentieth century and still in our day this method is increasingly used to achieve highly abstract works in a new aesthetic appropriate for our time. What appears to be chaotic or random is part of a larger order that peaks in an expanded consciousness.

Choreographer George Balanchine broke with ballet's classical tradition with his use of cumulative rhythm in his modern works like "Agon" and "Apollo." The steps and body positions performed by the dancers are clearly from the classical tradition—except for some idiosyncratic "Balanchinesque" embellishments like hyperextended wrists and heel bumps on the floor. The dancers keep to their closed rhythms while the music keeps to its closed rhythm—but they are not the *same* rhythm.

d. Phrased rhythm is most often used for concert modern dance, but also in music composed in the 20th and 21st centuries. American composer Charles Ives makes extensive use of phrased rhythms in his Symphony #4. Many modern choreographers deliberately do not "dance to the music"—which is an old aesthetic known as "music visualization" (considered *passé* and mildly degrading to *the Art of the Dance*). The dancers move in rhythmic phrases—but not metered phrases like Balanchine's—simultaneously or coincidentally with the music or in silence. Rhythm and tempo might not be considered at all during certain phrases of the dance. How does one dance with the music of, say, Anton Webern or Karlheinz Stockhausen? It is the dancer's movement qualities that create the dance, sometimes with, sometimes without meter. Sometimes the dance and music phrases cross or crisscross by choreographic design or by chance. Those times are like nodes in a temporal tapestry, a "partnership of temperaments" as Dalcroze instructor, John Colman, has said[9]. Such nodes are not necessarily metric. Frequently they are emotional.

The use of movement qualities can be seen and, certainly, heard in music. One should watch a string quarter or quintet by Schubert or Brahms and witness the vibrations of the left hand fingers, the sustained drawing of the bow sounding a harmonic, or watch the rapid changes of motion at the elbow. Often the entire torso sways in pendulous oscillations. The primary movement qualities provide the base for the emotional expressions of the transitional qualities.

All the performing arts employ the movement qualities to achieve emotional expression.

MEASURED ENERGY AS PHENOMENON

As a student of Wilson's, Henley recognizes in the description above an approach to rhythm that he experienced as a student but did not fully comprehend at the time. Wilson's class would often begin with creative modern improvisation in, as Wilson names it, an "open rhythmic" structure. The purpose was to attune, first to the awareness of our own energy, then begin to measure that energy in conversation with the musician and fellow dancers. Students would learn complex multi-metered "closed rhythms" that were impossible to count. If counted, you were already behind. You had to feel the rhythm, you had to be the rhythm. In one exercise, dancers would slowly walk across the floor, moving the arms in a single arc from the sides of the body, to the front of the body at sternum height, then opening to the side and floating back down to the starting place. This task is deceptively simple as the movement itself is not complicated, but attention to phrasing one's energy across the full space of the studio is quite challenging. Each of these experiences offered students an opportunity to attend to how we were, as H'Doubler would put it, measuring our energy.

Henley also has vivid memories of learning movement material and then having a fellow student, ask for clarification of the counts; to know which movements happen on which counts. Often, Wilson would offer a response similar to, "Let's do it a couple times and we will find it together." This was frustrating because part of the definition of being a good dancer, for Henley and his peers, involved doing the right move at the right time. This qualification for being a good dancer implied that a good teacher should, in turn, know the counts. These moments stand out because they were disequilibrating. Wilson either did not know or did not want to tell the dancers the counts for the movement phrase. He was urging the students away from superimposing counts on the movement and to discover and experience the energetic topography of the dance before tying it to an externally derived temporal structure. This is not to say that counting is bad, and certainly students did a lot of it in his class, but by removing the counts we were able to explore the rhythm of the dance as measured energy, or exertion, rather than than as alignment with meter.

Henley's experience as a student rippled into his professional career as a teacher, where he perceived that many students believed that dance was something to be accomplished from the outside, rather than experienced from the inside; something to be watched and judged rather than experienced and explored. Henley's practices in Wilson's classes deeply informed how he approached this dynamic in his own classes, as he incorporated improvisation as a form of awareness building and opportunity to "find the counts" in some of the phrase work throughout the class.

He also began to draw on Maxine Sheets-Johnstone's *Phenomenology of Dance* [2015 (1966, 1979, 1980)] as she made explicit experiences that had been implicit in his own work and his work with Wilson[10]. In her seminal dance philosophy text, Sheets-Johnstone argues that the phenomenological experience of dancing is of the creation of a dynamic line. Rather than dancing through space and time, the dancer creates a spatiality and temporality that has an inherent qualitative dynamic. In the experience of performance, the dance does not exist separately from the dancer. The dance and dancer are a form-in-the-making, an ongoing spatial and temporal revelation, and what the dancer creates and sustains is an illusion of force. In this definition, Sheets-Johnstone adopts

[9]Colman interview with Wilson (1966, Book 1, pp. 53-54).

[10]Sheets-Johnstone studied with H'Doubler in the 1950s and 1960s and received her Ph.D. from UW-Madision with a major in philosophy and a minor in dance.

Langer's (1953) position that, in art, we encounter not the real world, but an illusion or semblance of the real world. In dance, in particular, the illusion is of the symbolic form of human feeling as revealed through force in movement. If we translate Sheet's Johnstone's force to H'Doubler's energy or Wilson's movement qualities, then we begin to see the congruence. The phenomenological experience of dancing is not one of making shapes through space and time, but of creating a spatial unity and temporal continuity through energy realized as a dynamic line.

Within this broader definition, Sheets-Johnstone (2015) argues that rhythm is an inseparable component of the dynamic line, an "interplay of forces which rise and fall, recoil and expand, which have sudden shifts in direction, which are now vigorous, now flaccid, and so on" (p. 84). Further, "each successive movement creates a qualitative change, and this, in turn, creates an accentual pattern, changing intensities, within the dynamic line" (p. 85). Reading this description of rhythm evoked, in Henley, kinesthetic memories of experiencing Wilson's primary and transitional movement qualities. This rhythmic nature of the dynamic line is experienced pre-reflectively, or intuitively. It is part of the unity of the form-in-the-making. To count the meter, measure durations, or mark accents are reflective practices. They account for the temporal structure of movement, but "the dance does not come alive until the dancer passes beyond a mastery of the structure, and comes to realize the dynamic flow inherent in the total piece" (p. 88).

Sheets-Johnstone's argument made explicit the trends Henley described earlier for dancers to want to layer rhythm onto the movement from the outside, reflectively, by aligning movements with counts, rather than experiencing it pre-reflectively, as already integrated into and inseparable from the dancing. To be clear, we all have experience of measuring our energy in patterned ways, and certainly, students in all dance classes have had experience creating a dynamic line in which rhythm was not measured but experienced. If they danced salsa with their mother around the kitchen, if they joined a hip-hop cypher, if they went to the dance club with their friends, they know what it is like to experience rhythm pre-reflectively. There is an aura, though, in the formal modern/postmodern academic dance classroom, both in pedagogical culture and aesthetics, that leads some students to believe that they need to reflectively know the counts rather than experience the dynamic line in order to "get it right." In **Supplementary Appendix**, Henley offers Experiences 1–3 which facilitate students' prereflective awareness of measured energy, the reader is encouraged to try these as a solo or group practice.

MEASURED ENERGY AS PROCESS

The description above, inspired by a phenomenological approach to dance, prioritizes the individual's lived experience of rhythm. Henley has also become interested in approaches to rhythm that decenter the individual and consider how the experience of rhythm is influenced by or even constructed by sociomaterial contexts. For instance, if a dancer is asked to improvise and thereby generate an energetic topography, we might wonder how the construction of the physical space prefigures the energetic choices of the individual, architectural rhythms. We might also wonder about what types of movements have historically been done by this group, cultural rhythms, and how gender or age might affect expectations for how energy is measured, ontological rhythms.

In each of these scenarios, the intentions of the individual are reprioritized and considered within a situated and dynamic sociomaterial context. This approach aligns with process philosophy, an intellectual tradition that "opposes 'substance metaphysics'" or descriptions of reality as "collections of static individuals" (Seibt, 2017). Rather it seeks to define reality as dynamic, changing, and in the process of becoming. In her text *Relationscapes,* Erin Manning (2012) explores the nature of rhythm through reference to the sculpture of Umberto Boccioni. She describes that he does not sculpt the body moving, but rather movement itself, which happens to include a body. The body is described as a collection of potentials. Process is metaphysically prioritized over matter. In this construction, force or energy prefigures action, the environment is alive with potential and in the experience of dancing, the dancer and the sociomaterial environment combine in a machinic interface to produce the event of the dance.

Manning uses Boccioni's phrase "pure plastic rhythm" (15) to suggest that we exist in a world of malleable energy. Rhythm is an inflection of potential between body and environment such that the space both affects the dancer and the dancer affects the space. The dancer creates the space and the space creates the dancer. Before the dancer even enters the room there is already a rhythm (e.g., patterns of light on the wall, the wood grain of the floor, the clicking noise of the heater, and the flows of conversation between other dancers). No matter what the dancer's individual intentions are in generating a rhythm they are in a sociomaterial context in which patterns of energy are structured and being structured around them. In **Supplementary Appendix**, Henley offers Experience 4, which facilitates the reprioritization of the phenomenological self in the emergence of bodily rhythms.

In these phenomenological and process philosophy informed approaches to rhythm, Henley aims to disrupt students' prioritization of "knowing the counts" as a reflective activity and offer them the opportunity to experience temporality as flows of energy. Though these experiences are offered as improvisational exercises, it is possible to then transfer this awareness to set choreography, in which, yes, the dancer must "do the right move at the right time." With this new awareness, however, that accomplishment is a side effect of attending to and following the energetic flow, or dynamic line of the dance.

CONCLUSION

In this article, the authors have put forth a definition that originated with Margaret H'Doubler, that rhythm is measured energy. Wilson expanded on the relationship between measured energy and kinesthesis through the study of muscular activity and observation of dancers dancing. He identified four primary movement qualities that, when performed, evoke empathetic response in the performer and viewer. In this way, measured energy both scientifically and experientially describes rhythm. Henley extended Wilson's approach by describing how the principle of measured energy was further developed through Sheets-Johnstone's phenomenological description of rhythm as flows of force experienced through pre-reflective temporality, and Manning's description of the ways in which we construct, and are constructed by, rhythms already embedded in the material and social world.

We developed the premise that action is not exclusively a response to rhythmic stimulus, but can itself be a rhythmic output which is developed through kinesthetic awareness to be used for aesthetic purposes. The periodicity or relative duration of movement qualities, perceived through kinesthetic awareness, are a schema around which a dancer can perceive and enact the energetic topography of a dance, or, put another way, the dance's rhythm. Though we have put forth approaches to rhythm here, rooted in more deeply understanding qualities of movement and particular perceptions of the passage of time, we recognize that across time and geography, patterns will shift and change. Fundamental to our argument is that this phenomenon is experiential. We therefore invited the reader to engage in the movement exercises provided in **Supplementary Appendix**. We hope, that in the study of rhythm, researchers will seek a bridge between the scientific and the experiential.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.866805/full#supplementary-material

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What Young People Think About Music, Rhythm and Trauma: An Action Research Study

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A number of popular theories about trauma have suggested rhythm has potential as a mechanism for regulating arousal levels. However, there is very little literature examining this proposal from the perspective of the young people who might benefit. This action research project addresses this gap by collaborating with four groups of children in the out-of-home-care system to discover what they wanted from music therapists who brought a strong focus on rhythm-based activities. The four music therapy groups took place over a 12 month period and each cycle of action and reflection led to adjustments in what activities were offered, as well as exploring different levels of structure and ways of building relationships in the groups. The initial group incorporated a strong emphasis on highly structured rhythm-based activities, but young people found the format difficult to engage with. The second cycle included more opportunities for creativity and self-direction within semi-structured activities which children reported enjoying, but too much freedom also became overwhelming at times. The two groups in the third cycle seemed to balance structure and responsiveness successfully but were also influenced by the introduction of individual sessions prior to group commencement, which was designed to contribute to safety and trust building. Final reflections on the role of rhythm in supporting young people who have had adverse experiences were centred around the ideas of co-regulation. This was qualitatively different to our expectations that practicing rhythm-based activities would lead to an expanded window of tolerance that resulted in less time being spent in either hypo-arousal or hyper-arousal. Instead of entraining to an external rhythm, young people felt safe when their rhythms were matched, even if they were irregular, out of time and unpredictable. The small moments of co-regulation resulted in pleasure, comfort, satisfaction and peace and these moments were highly valued by the young people, who described just wanting to be relaxed and happy. Although not as rhythm-specific as the literature might suggest, music making with trusted adults helped the young people in this study feel more content.

Keywords: rhythm, trauma, music therapy, action research, co-regulation, arousal

INTRODUCTION

The discourse on trauma recovery is currently dominated by neurological models. Two of the most popular theorists quoted in this discourse have suggested that rhythm has potential as a mechanism for regulating arousal levels. This includes Porges's (2011) emphasis on regulating a hyper-vigilant amygdala and van der Kolk's (2015) focus on stimulating positive and reparative experiences through repetitive neural brainstem activity. The emphasis in both these theories is on engaging primitive neurological functions and both theorists adopt a medicalised view of trauma that can be resolved by repairing damaged areas of the brain.

This contrasts starkly with older, psychoanalytic models that focussed on processing experiences through the resolution of discord between conscious and unconscious awareness (Brunner, 2018). This approach to the resolution of trauma became prominent after the recognition of a link between behaviour labelled as "hysteria" and repressed memories of adverse experiences. These ideas were developed by French theorists around the turn of the century, firstly by Jean Martin-Charcot and then Pierre Janet through understanding the mechanism of dissociation (Walusinski and Bogousslavsky, 2020). Sigmund Freud is also recognised for his contributions in the Austrian context, although interpreted differently through the case study of Dora (Freud, 1953). Music (but not specifically rhythm) has been utilised in psychoanalytic approaches because of the affordances of improvised music as a "blank page" onto which unconscious meaning can be externalised and made apparent (Priestley, 1994). The recent interest in rhythm might be seen to have renewed interest in the role of music in therapy with people who have had adverse life experiences (Hillman et al., 2021).

It is noteworthy that both the older and the new perspective have been established by privileged white men in developed societies primarily for the purpose of treating the problems of abused women and children. This requires critical understandings be considered, particularly examining whose voices are being ignored while others are privileged. The most outstanding exception to the privileged standpoints to date has been Judith Herman's (1997/2015) work on trauma and recovery, in which she introduced a systems lens to conceptualisations of trauma in the United States in the 1990s. Herman emphasises more contextualised and idiosyncratic understandings of people's unique responses to a range of adverse experiences and does not propose solutions, but rather ways of understanding. Music therapists frequently reference Herman's work (McFerran et al., 2020), as do educators (Stokes and Turnbull, 2016), and the emphasis in programs that align with her model are usually on building trusting relationships and the importance of safety, in education.

In considering whose voice is missing then, one significant group is the young people who have been traumatised by adverse experiences and whose perspectives have been sparsely represented in the psychiatric literature, although are more often included in education discourse (Stokes et al., 2019; Stokes and Aaltonen, 2021). Their absence is noteworthy in the music therapy literature (Lai et al., 2020) and although many authors emphasise the importance of trusting relationships and experiences of safe attachment, this has traditionally been presented from the perspectives of the adult practitioners. There are ethical reasons for this. Knowing young people have often been at the disposal of adult needs and expectations through their adverse experiences, many of us have strong urges to protect them from further demands. The ethical research systems are also designed to protect children in this way, and the national ethics guidelines specifically identify challenges for children's understanding of what they are agreeing to and vulnerability to coercion (NHMRC, 2018 Updated 2018). However, this can also lead to a lack of representation. The Australian guidelines acknowledge this, and further state that "there are particular tensions between not placing children at risk in studies of new interventions and the need for knowledge about how such interventions are best used for children." (p. 65). If we assume that young people are too vulnerable to risk engaging in the intellectual field that shapes the support they are surrounded by, then we also disenfranchise their perspectives.

Even if we overcome the ethical barriers of gathering the perspectives of young people who have had adverse experiences, we also face some cognitive challenges. Young people who have experienced neglect often do not have the vocabulary to articulate the complexity of their experience, sometimes described as alexithymia (Terock et al., 2020). According to cognitive developmental theories based on Jean Piaget's work (now critiqued, Babakr et al., 2019), young people also do not have the cognitive ability to give more than an egocentric response, when research questions are seeking a more meta-perspective. When using music, this challenge of articulation is intensified, since even professional adults struggle to find words to describe the embodied experience of shared music making for therapeutic benefit. This is seen by the emphasis in the literature on case studies and investigations of professional experiences where rich descriptions of practice are elaborated. The use of case studies seems to be the closest researchers feel able to come to describing the phenomenon. Again, the lack of representation is partly explained by the challenge of collecting the alternate perspectives from young people.

Our intention in this research study was to critically examine the ideas in the trauma literature that suggested rhythm might have unique affordances for processing and resolving trauma. We acknowledge how attractive theories on rhythm are in the field because they can be used to justify existing music-based practices and provide a scientific explanation for mechanisms that are otherwise difficult to articulate. However, the assumption that playing in rhythm is helpful was not a good match with our practice-based experiences of working with youth with experiences of trauma who may not have musical training and who find steady rhythms both challenging and disheartening. We also questioned the move away from responsive and relational program planning and toward highly structured and pre-determined activities that were congruent with a brain-based approach where rhythm had a healing influence (Colegrove et al., 2018), and is more similar to models such as EDMR (Oren and Solomon, 2012). We wanted to understand when rhythm was experienced as helpful by young people and to explore if there were identifiable conditions associated with those moments. We decided to focus on young people's actions, and to explore different rhythm-based activities with different groups of young people in iterative cycles that enabled co-construction of knowledge. We aimed to adjust and adapt to what young people seemed to want, both within each session and structurally between sessions and between programs, and listen to what was expressed by the young people through their engagement, their artistic expression and their words. We endeavoured to answer the question:

How satisfied are young people in the out-of-home-care system who participated in various rhythm-based music therapy activities, as communicated by their verbal and written feedback as well as their observed responses and actions?

METHODOLOGY

Despite the dominance of highly intellectualised neurological theories in research in the trauma field, we chose to privilege experiential knowing as potentially leading to novel discoveries that have greater relevance for practice. Given the effectiveness of play-based methods with marginalised young people (Post et al., 2019), we selected research methods that enabled multiple ways of communicating how satisfied the young people were with the programs. By integrating non-verbal feedback, we were able to draw on our practice experiences as music therapists who grapple regularly with the challenges of interpreting arts-based and behavioural responses as an equally interesting way of understanding phenomena (Chamberlain et al., 2018). This interpretation is the basis of creative arts therapies generally and the reason it is often posed as an alternative to talk-based therapies when people have experienced adversity (e.g., Fairchild and McFerran, 2019). Arts-based research has recently gained prominence in the field, with theorists arguing that the sensitivity of the arts enables understandings that embrace emotional aspects as well as ambiguity and paradox, which may be relevant in this kind of research (Leavy, 2020). Aesthetic theories (Juslin, 2013) and musical theorising (Ferrara, 1991) already exist that can be used for analytic meaning-making purposes and have been in understanding existential crises such as grief and loss (McFerran and Wigram, 2005).

Action research design supports this approach, with an emphasis on both situated processes of collaboration and extended notions of knowledge (Greenwood and Levin, 2006). Polanyi's (1958/1998) valuing of personal knowledge and moving beyond propositional theorising has influenced many action researchers who have instead emphasised presentational and relational ways of knowing (Smith et al., 1997). In the field of music therapy, action research has often been used for examining community-based programs with people who are marginalised (Stige and McFerran, 2016), and the combination of arts-based approaches and action research values have been emphasised in some approaches where the arts might be either a methodology, or a radical event (Ledger and McCaffrey, 2015). Action research is also commonly used for the purpose of planned change and improvement (Cohen et al., 2007; Kemmis et al., 2014). The reflective and cyclic nature of action research provides researchers with opportunities to ascertain the degree to which the intervention is a success and to analyse the data for why this might be the case. Following this they can then proceed or make necessary changes to the intervention.

ACTIONS AND REFLECTIONS WITHIN THE PROGRAM

Approval and Collaboration

We were granted ethics approval from the university ethics committee (ID#1852103.1) to undertake an action research project in partnership with a not-for-profit community provider who work with children, young people and families to prevent harm and empower families including home-based care (foster care), parenting support, and family violence programs. The provider was responsible for recruitment, using materials that we generated, and which advertised "a fun, music-making group for young people (from their service) aged 8–12." They also made rooms available, liaised with other community providers and were supportive of our desires to understand whether music therapy was useful for children in their care. They benefitted from the provision of fee-free programs they could promote to their clientele without monetary investment. An internal research institute at the university provided the funds for the investigation, with the requirement that community collaboration be centralised in the research and that youth voice be prominent in as many aspects of the design as possible.

Exploring Structure for the Program

There were three cycles of action and reflection across a 12-month period involving a total of 16 young people (see **Table 1**). Two qualified music therapists co-facilitated groups of 3–5 members, lasting between 8 and 13 weeks, supported by a community facilitator who was also one of the researchers. Group size was intended to include a maximum of 6 young people, but the number of cycles was not pre-determined, except by the 2-year time frame of research funding.

As summarised in **Table 1**, the content of the program evolved in response to the feedback from young people. Their feedback was shared *via* their behaviour, levels of engagement, comments made during sessions and at closure of the sessions, as well as from comments made by carers. Our understanding of their feedback directly influenced what activities were prominent in sessions and what evaluation measures we used to try to capture any benefits experiences using objective measures. The details of this process will now be described.

Measuring Responses

During Cycle 1, we discovered that the young people were not able to complete the measures we had identified as being most suitable to capture any changes in self-regulation that might be experienced because of participation [Social Emotional Competence Questionnaire (Zhou and Ee, 2012) and the DERS-16 (Bjureberg et al., 2016)]. When presented with the forms

TABLE 1 | Overview of research process.

	Cycle 1	Cycle 2	Cycle 3	
Program	**1**	**2**	**3**	**4**
Length	13 weeks	8 weeks	8 weeks	8 weeks
Youth	5 young people	3 young people	4 young people (1 withdrawal/child relocated after week 3)	4 young people
Referral	Experienced trauma and displaying aggression at school, observations of being withdrawn/emotional, needing extensive support with regulation, complex parent mental illness and parent death (witnessed).	Experienced trauma with reports of experiences of ableism/restrictive practice at mainstream school (resulting in home schooling), witnessing domestic violence and removal from home at a young age. Two young people lived with immediate family and one had experienced many care placements.	Difficulty regulating emotions, swings in mood, barriers in accessing school. One young person lived with immediate family, two were in kinship care and one was in permanent care.	Lived experience of homelessness, needing extensive support with regulation, complex parent mental illness. Two young people were living with immediate family and two were in permanent care.
Session structure	Group sessions only. Pre-set session plan delivered with no (or very limited) choice for participants	Individual sessions provided before group commencement. Pre-set session plan with options for choice of one or two activity.	Individual sessions provided before group. Session plans negotiated from set options with young people.	
Rhythm-based activities	Tune in sheet Ti Rakau Obwisana Rock Games Beanbag Toss Rapping/Songwriting Dance off Djembe Drumming	Tune in sheet Ti Rakau Obwisana Rock Games Beanbag Toss Rapping/Songwriting Dance off Djembe Drumming	Tune in sheet Ti Rakau Beanbag Toss Rapping/Songwriting Dance off Djembe Drumming Chair drumming	
Evaluation strategies	SERQ and DERS measures Semi structured interviews Parent/carer feedback	6 item self-designed scale Semi structured interviews Parent/carer feedback	Prioritised incidental feedback. Arts-based feedback activities Semi structured interviews Parent/carer feedback	

they expressed disappointment in having to do what felt like "work," fell into patterns of ticking consecutive boxes rather than contemplating authentic responses, and engaged in critical rumination about behaviours they believed to be negative or bad. Varied literacy levels caused embarrassment and defensive responses from some and it was clear that the ideas being assessed were too complex.

Therefore, in Cycle 2 we moved to session evaluation strategies that used a shorter six-item self-composed measure designed to capture the differences between the young people's baseline state at the commencement of the program (reflecting on life in the 2 weeks prior) and how they felt as each session ended. This tick box measure was created with specific reference to factors stated in interviews with participants in Cycle 1 as being experienced within sessions including safety, belonging, freedom, pride and self-control (See **Appendix 1**). A mid program "check-in" was also introduced to enable participants to offer feedback on what was helpful and preferred in sessions, aimed at determining session content for the remainder of the program.

By Cycle 3, we understood through verbal and behavioural feedback from the young people that written evaluations and measures were generally not well accepted or effective in capturing or understanding participant experience. Even the short, simple questions elicited defensive, disengaged behaviours as seen by crumpling the paper into a ball or using it for drawing unrelated sketches by memory or leaving the table to attend to other things in the room or even just to wander. We therefore placed greater value on reflections captured in semi-structured interviews, provided arts-based feedback opportunities involving drawing, colour choice and movement, and tuned in more to the incidental feedback regularly offered by the young people within sessions. Such evaluation methods, however, were not objective and relied on a level of interpretation from facilitators. These interpretations were made through a growing understanding of the language and behaviours these young people were using to highlight their sense of enjoyment, safety, belonging and pride in the moment.

Choosing Activities

The incidental feedback communicated by the young people in sessions also influenced decisions about session planning and the choice of activities offered. Group leaders were transparent about the purpose of the sessions with participants, who understood that all group members had experienced trauma. They suggested that music and rhythm activities might help to improve their mood and offer a sense of self-control or a feeling of being regulated. We asked explicitly for their feedback on this, and the young people were frequently reminded that they were co-researchers in this project, that their thoughts and ideas about the music or program as a whole was valued and key to the program's development and success. Rather than being seen through an objective lens as biasing the young people or having a placebo effect, this transparency was essential to the participatory action research approach being adopted (Kemmis et al., 2014).

In addition, believing that the group might be helpful is seen as critical to success in group psychotherapy (Yalom and Leszcz, 2005) and individual therapy (Duncan et al., 2007). That being said, the group leaders' verbal explanations may not have been very useful, given the complexity of articulating the topic, as described in the rationale. Most importantly, the exploratory and experimental nature of the group enabled these ideas to be examined in an embodied, playful and responsive way throughout the four groups.

To explore the notions of rhythm and regulation, rhythm underpinned each activity implemented in Cycle 1. Chants, props and recordings were used to support structured activities such as the singing of greeting songs, Ti Rakau (a Māori stick game) and beanbag toss, with the sole purpose of deeply embedding rhythm in multi-relational ways (sight, sound, touch). Within hour long sessions, the emphasis on highly structured activities required an intense amount of focus and the young people reported feeling tired and bored. Activities such as songwriting (which might usually offer freedom in style and form) and dance-offs were then included to raise interest and engagement but even so, were limited to modern pop styles with dance beats, which are dependent on strong, steady rhythms. The young people engaged with the creative parts of the songwriting process but displayed some frustration trying to perform their piece within the tight restraints of a rigid rhythm.

Before Cycle 2, the research team reflected on the fatigue this rigidity seemed to cause and incorporated opportunities for more creativity and self-direction within semi-structured activities. Chair drumming for example, allowed the young people to individually explore rhythms along to the beat of a recorded song. It also led to organic opportunities for turn-taking, following and leadership amongst group members, celebrating individual creativity and performance. Noting this enjoyment of less structured activity, and a request for more from the young people, facilitators introduced individual song writing where they could each begin a song from scratch using iPad/GarageBand generated beats and sounds. On reflection, the leap to sessions with far less structure, requiring almost complete self-direction, overwhelmed participants in a different way and none completed a composition, while some reacted with varied levels and displays of frustration, withdrawal and distraction.

By Cycle 3, the young people had led us to understand the need for a balance between both structured and semi-structured activities with a continued emphasis on rhythm. We utilised the benefits of embedding choice and control within a structured "base," both within whole sessions (choice of order of activities or choice between two activities) and individual activities (tempo, addition of complexity). We also determined that some basic routines (greeting and farewell songs), and strict, shared-rhythm activities (structured drumming) could contribute to greater engagement and success in the more free and creative activities that followed. Drumming to a consistent beat, with the added challenge of "pausing" on a specific count and beanbag toss with physical challenges and an increase in the number of beanbags in play, were activities that were accepted and tolerated by the young people, even with a degree of excitement and enthusiasm. The transition into free dance or group improvisation on a range of instruments with no set beat or rhythm was managed with little to no resistance, and ongoing enthusiasm.

Building Relationships

During Cycle 1, we noticed that group members regularly spoke over one another and positioned themselves physically in front of each other, in what at first appeared social disregard for those around them. After careful observation across the 10 weeks, we were able to see how this subsided as everyone's relationship and comfort with the facilitators increased. The facilitators became more aware of each young person's story, personality, preferences and talents, and were able to acknowledge them in ways that demonstrated how valuable they were in the group. Subsequently, the need to seek attention in more overbearing physical and noisy ways decreased. After reflecting on this change with the research team, individual meetings were instituted from the beginning of Cycle 2. These occurred prior to the commencement of the group itself and incorporated music making activities to prepare the young people for the nature of groups and to better understand their regulatory needs. These meetings supported the facilitators understanding of the young people from the outset and allowed the young people to develop insight into the program they were joining. It also built comfort and rapport and enabled better communication with carers who also had access to the facilitator in the visits, likely contributing to the young people's trust in facilitators. The impact of this change was so significant that group program duration could confidently be reduced from thirteen weeks to eight weeks and competitive and attention seeking behaviours substantially decreased.

DISCUSSION AND META-REFLECTIONS

In addition to the learnings that were adopted throughout the cycles of action and reflection that are described above, the research team also reflected on the actions of the group participants (participant, leaders, carers and organisers) at a more propositional level (to draw on Polanyi's distinctions). Our focus for the meta-reflections was on regulation/dysregulation, because of its prominence as a topic within trauma studies and being the facet of experience that is most often linked to rhythm, as noted in the introduction. Our considerations drew on Siegel's (1999) conceptualisation of traumatised people having a narrower "window of tolerance" caused by nervous system dysregulation. Research has already shown that a small suite of activities, including rhythm, physical exercise, and mindfulness have seemed to assist some people to return to a state of psychological and physiological arousal (Ogden et al., 2006). By extension of the same theoretical conceptualisation, practicing these kinds of activities should lead to an expanded window of tolerance resulting in less time being spent in either hypoarousal (where the parasympathetic nervous system produces a freeze response) or hyperarousal (where the sympathetic nervous system produces a fight or flight response).

The flaw in this logic, as noted in the introduction, is that many young people are not able to settle into a rhythm, which can therefore lead to further anxiety or withdrawal if encouraged to participate in something that might be beyond their current capability. For example, a child in Cycle 2 was observed to become very frustrated when he could not match the rhythm of the group, and left the group to practice the activity solo, before re-joining the group once he had mastered the rhythm. The same child described how the thundering of the drumsticks on chairs during a rhythm activity was an unpleasant sensory experience and again, removed himself from the group briefly while the facilitators adjusted the activity. He was often observed to be hyperaroused, and therefore the arousing quality of rhythm could easily push him further away from his window of tolerance, rather than closer to it. However, other children in the same group described the same experiences as helpful. One girl who was often observed to be hyperaroused said that she loved chair drumming because "you didn't have to think." Another girl in Cycle 1, who also tended toward hypoarousal, similarly commented that "a steady beat helps steady my mind."

The degree of challenge experienced by each child as they joined in rhythmic activities varied markedly. Sometimes activities that were too easy were experienced as boring and unsuccessful in engaging the young people. For example, in Cycle 1, two young people who often presented with high energy levels reported enjoying a game that involved tossing a small bag of beans in time with a beat, using chanting and name calling to supplement the movement. However, others in the group who had lower energy levels described the beanbag toss as boring. The second group in Cycle 3 struggled most with activities that were too simple and began to explore ways to extend the physical challenge of tasks such as standing in "tree pose" or on a chair whilst tossing the beanbag. This resulted in some group members feeling "happy and settled."

Change in energy levels were also extremely varied between children whilst engaging in the rhythm activities, again, not always in the same direction. For example, one child in the first group in Cycle 3 would often arrive in a highly energised state and focus hard to participate and then report feeling tired afterward. Another child in the same group often described feeling tired upon arrival and then feeling energised after the rhythm activities and "ready" for creative activities such as song writing. She was also observed to have low arousal levels when feeling anxious, such as when a new carer was watching the program.

Examining the relationship between regulation, rhythm and trauma was further complicated in our research project by the neurodiversity that was apparent in many young people in our groups (6 of the 16 had diagnoses of Autism or ADHD). Although there is no relationship between Autism and trauma, there is debate about whether adverse experiences contribute to or exaggerate ADHD symptomatology (Szymanski et al., 2011). Relatedly, research has shown that the core symptoms of ADHD are part of an Autism diagnosis and that children with Autism might initially be diagnosed as having ADHD (Mayes et al., 2012). These overlaps were useful in reflecting on the diversity apparent in our research groups and led us to reflect on the different language that might be used regarding regulation depending on the diagnostic labels common in each field. For example, discussion of arousal in the autism literature often uses more psychotherapeutically informed terms such as co-regulation and self-regulation (Ting and Weiss, 2017), rather than the constructs of hyper and hypo-arousal that are more common in ADHD and trauma literature.

FIGURE 1 | A tree with a dark trunk and expansive branches, its leaves consist of a burst of colourful music notes, clefs, sharps. and flats.

There were several children in our groups whose ways of connecting through rhythm seemed better understood using the terminology of co-regulation, along with more relational notions such as attachment (Kinniburgh et al., 2017). For example, one child in Cycle 2 seemed to be co-regulating with the facilitator during a particularly difficult day after discovering she would not be able to see her mother in the usual access time. After playing together with the music therapist, her mood seemed to brighten and she said, "Music is good for your brain, like an exercise... but you don't have to move, you can listen or think." In the same group, another child seemed to self-regulate by communicating that he needed to take some time out when the group got loud and boisterous. A child from Cycle 3 took this a step further and started using drumming actions at school when he was feeling angry, taking himself outside to a tree he could play on until he felt better. The school went on to purchase a drum pad after liaising with the program facilitators so this could be supported.

The academic members of our research team undertook critical interpretive review of the literature (McFerran et al., 2020) and further delineated these ideas into uses of rhythm including stabilising (physiological regulation), entraining (co-regulation), exploration (emotion regulation) and performing (self-regulation). Both stabilising and entraining placed a stronger emphasis on the value of the structural components of music, including rhythm, that we were focussing on in the current research. However, we found that all four dimensions were relevant for the diverse young people in different groups in this project and trying to remain focussed only on one or two dimensions did not satisfy or engage the young people. Our meta-reflections on these findings led to the generation of a creative image that was inspired by comments made by some group members (see **Figure 1**). One child described the different program activities as elements of a tree, and two others bought images of trees into different activities (one drew a family tree, and another introduced a tree pose to bean bag throw). Bringing these together as a metaphor provided us with an arts-based representation of multiple levels of knowing.

The roots and trunk of the tree represented safety in relationships with the facilitators and with other group members which was the core emphasis in stabilising activities The roots of the tree represented each co-contributor, their individual histories, lineages, and experiences, spoken and unspoken. The trunk of the tree illustrated a meeting place between all group members; the young people and facilitators, where safety was the primary focus. In this focus was an acknowledgement by facilitators of shared experiences of trauma between the young people, an acceptance of how each young person presented and a core emphasis on stabilising activities.

The branches of the tree represent invitations and opportunities for making music together in individual or shared rhythms. Sharing music making in this way created potential conditions for co-regulation or self-regulation. As tree branches co-shape one another, so did group members and facilitators; shaping and adjusting activities to levels of individual comfort or challenge, and in group members showing great empathy and acceptance toward one another.

The leaves of the tree represented possibility, dreams, and play. Music/rhythm was an individual and collective compass in this space where young people could explore different ways of being and identities. One young person emerged as a rapper, freestyling with the group, another described playing the guitar as a huge achievement one of which his parent would be proud, and another contextualised their musical identity through family, in sharing songs they would play at home.

All trees change with the seasons, so too did each of the young people (and facilitators). There was always space among the branches, with safer conditions, the young people showed us how they used music and rhythm to share individual truths and experiences, and to feel happy and settled.

CONCLUSION

This research aimed to explore the question of how satisfied young people in the out-of-home-care system were with participating in various rhythm-based music therapy activities. We collected a range of data that included verbal and written feedback as well as observing and analysing their creative, playful and behavioural responses and actions. The use of an action research framework enabled a responsive approach where we could make adjustments throughout the process to allow for change and improvement in ways that would help us better answer the question, which was focussed on the satisfaction of the young people in the group. Our intention was to privilege the voices of young people and for them to influence the increasingly neurological approaches favoured in the literature. We wanted to know whether young people's experiences were congruent with the idea that rhythm-based activities would support them to be able to regulate their emotional reactions and expand their window of tolerance.

The focus of each action and reflection cycle in this study was on trying to understand when rhythm was experienced as helpful by young people by observing their personal, interpersonal and creative behaviours as well as listening to their feedback. In the reflection stages between each cycle we tried to identify whether there were any conditions that might explain when rhythm was helpful – potentially the young person's age, their unique background experiences, their current home conditions, their ability to regulate their own behaviour, the group membership, and other factors. It became apparent that all these things did converge to influence their experience of the helpfulness of rhythm and of the therapy group generally, but in idiosyncratic ways. This multidimensionality was consistent with statements made by other critical scholars in the field, who suggest avoiding the tendency to try and simplify responses to trauma.

"By de-linking from traditional ways of thinking about trauma, we can reconsider what trauma is in all of its manifestations: specific and murky, lived and remembered, physical and emotional, individual and communal, past and present, named and unnamed, spoken and silenced, fragmented and cohesive, destructive and healing, threatening and empowering." (p. 14, Gagnon and Novotny, 2020).

This was abundantly apparent when working with the young people in this research who each had their individual stories. As they shared their music with us, we felt privileged to witness a piece of who they were and how they were surviving a world that had been unfair to them. For the young people involved, in some ways what they needed was simple. Some described much-needed relief through moments of restoration and reprieve, such as when one young person said simply, "I could relax because I wasn't at home." But we also felt conscious that we should avoid the allure of simplification and saviourism, as Gagnon and Novotny (2020) note. We felt fortunate to be able to offer a group, funded by a university research grant, to children who otherwise might not have access to simple, creative, safe experiences with trusted others. Listening to children's voices resulted in important findings that represented the significance of groups in ways that quantitative research has failed to capture, likely because of the diversity of individuals and the need for to describe average benefits across all members (for example: Jee et al., 2015; Auslander et al., 2017).

The cycles of action and reflection have enabled us to bring young people's voices and preferences into the discourse by illustrating how they responded to rhythm-based activities and responding to what they shared of their needs in the context of their unique life stories. They told us that they liked sharing time in music, and that it helped to distract them, to have fun, and to feel safe. These simple experiences should be readily available to all children, but are not easily accessible for those who struggle in school and at home due to challenges in regulating themselves. Although rhythm may not be a panacea in itself, it is an inherent element in most music making experiences and when combined with tempo and form, was prominent in the types of music experiences that the young people responded to. For this reason, we suggest that making music with safe and responsive adults who are able to adjust activities creatively and tailor the structure of groups to meet the needs of the individuals in their particular groups might address the WHO's Convention on the Rights of the Child (Article 31, Children's Version) that states: "Every child has the right to rest, relax, play and to take part in cultural and creative activities" (UNICEF, 2020). Some children may need more support than others to be able to access the affordances of rhythm and music and this is where creative, responsive and trustworthy adults have a role to play, both in advocating for funding and providing these opportunities.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because of the small sample size, anonymity may be compromised if data is shared. Requests to access the datasets should be directed to k.mcferran@unimelb.edu.au.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The University of Melbourne, Human Research Ethics Committee (ID# 1852103). Developing and piloting a rhythm-based, group music therapy program for children who have experienced trauma. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

KM conceived and led the project, solicited the funding, and wrote the manuscript. KT and ZK co-facilitated the groups, collected the data, and contributed to the manuscript. HS and AC contributed to research design, analysis and the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

Appendix 1: Researcher-created measure of regulation used in Cycle 2.

Please tell us how often during today's session you felt:

	Not at all	Not much	Don't know	A little bit	A lot
Safe					
Like you belonged					
Free to express yourself					
Proud to have achieved something					
Happy with choices you made					
Regulated – in control of your thoughts & actions					

If you'd like to, let us know WHICH activities helped you to feel these ways and WHAT about the activities you liked?

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Tapping Performance of Professional and Amateur Darbuka Players

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Motor skills of professional musicians can be regarded as a model to investigate human skill acquisition after prolonged practice. Although rhythmic tapping skills of musicians such as drummers and pianists were investigated previously, the tapping performance of hand percussionists is still largely unknown. In this study, we investigated the tapping performance of professional and amateur darbuka players. Three tapping tasks were performed: single-, double-, and triple-finger tapping tasks. The participants were asked to tap as fast as possible for 12 s in the single-finger tapping task while they tapped as fast and alternate/even as possible in the double- and triple-finger tapping tasks. The tapping speed and variability of inter-tap interval (ITI) and tapping amplitude were assessed for each task. In the single-finger and triple-finger tapping tasks, there was no significant difference in the tapping speed between the professional and amateur darbuka players. In the double-finger tapping task, the tapping speed was significantly faster in the professional players than the amateur players. Interestingly, the professional players showed faster tapping speed in both familiar and unfamiliar patterns of finger coordination. The tapping speed of the double-finger tapping task was significantly correlated with the duration and the age of commencement of darbuka training. The professional players also showed less variability of ITI and tapping amplitude compared to the amateur players. These results suggest that prolonged practice of the hand percussion increases the performance stability and coordination speed of both familiar and unfamiliar patterns.

Keywords: darbuka players, motor skills, rhythm, tapping, coordination

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INTRODUCTION

After prolonged practice, musicians show rapid, rhythmic motor performance. For example, an expert pianist plays 1,800 notes per minute with the hands to play the 6th Paganini-Etude by Franz Liszt (Münte et al., 2002). The winner of a contest to find the world's fastest drummer plays about 1,200 beats per minute with the hands (Fujii et al., 2009; Fujii and Moritani, 2012a,b). Musicians are therefore considered an ideal population to investigate behavioral and brain changes in the hand-motor system after extensive practice (Münte et al., 2002; Schlaug, 2003). To assess the skilled manual performance, a fast rhythmic tapping task, which asks a participant to tap as fast as possible in dozens of seconds, has been used in many previous studies (Peters and Durding, 1978; Jäncke et al., 1997; Lutz et al., 2004; Aoki et al., 2005; Fujii and Oda, 2006; Rüber et al., 2015).

The previous studies have shown that the rhythmic tapping speed depends on at least three factors: First, the tapping speed depends on the digit to be used. Aoki et al. (2005) asked pianists and non-pianists to tap either with a thumb, an index, a middle, a ring, or a little finger as fast as possible by using the metacarpophalangeal joint movement. They showed that the tapping speed of an index or a middle finger was faster than that of a ring or a little finger in both pianists and non-pianists. Interestingly, there was no significant difference in the speeds of the index and middle fingers between the pianists and the non-pianists, while a difference was found in the speeds of the ring and little fingers between the groups. The results suggest that piano practice increases the tapping speed at the ring and little fingers but not at the index and middle fingers.

Second, the tapping speed depends on the degree of hand dominance. Many tapping studies have shown that the tapping speed of a preferred hand was faster than that of a non-preferred hand (Peters and Durding, 1978; Jäncke et al., 1997; Lutz et al., 2004; Fujii and Oda, 2006). Therefore, the degree of tapping-speed asymmetry has been used as a measure of hand dominance (Peters and Durding, 1978). Previous studies on musicians showed that the degree of tapping-speed asymmetry was reduced in drummers, keyboard, and string-instrument players compared with non-musicians (Amunts et al., 1997; Jäncke et al., 1997; Fujii and Oda, 2006). These studies suggest that musical practice reduces tapping-speed asymmetry between the hands.

Third, the tapping speed decreases when the finger and hand are coordinated. For example, when we tap at a maximum speed while coordinating two fingers alternatively, the tapping speed per finger is slower than that performed without finger coordination. The tapping speed in the double-finger tapping task is slower than that in the single-finger tapping task (Aoki et al., 2005). Another example is the difference between unimanual and bimanual tapping performances. When we coordinate two hands at maximum speed, the bimanual tapping speed is slower than the unimanual tapping speed (Fujii et al., 2010). Previous studies showed that musicians were faster and more stable than non-musicians when coordinating the movements of fingers and hands (Yamanishi et al., 1980; Verheul and Geuze, 2004; Aoki et al., 2005; Fujii et al., 2010).

Taken together, the tapping speed depends on the digit to be used, the hand dominance, and the way of manual coordination. Also, these factors are thought to interact with the degree of experience of musical practice. However, the instrument-specific effect on tapping performance remains unclear.

Recently, Matthews et al. (2016) compared the rhythmic tapping performance among drummers, pianists, singers, string players, and non-musicians. They found that the musicians clearly outperformed compared with non-musicians, yet the difference among the subgroups of musicians was unclear. Their finding suggests that there may be little or no instrument-specific effect on the finger tapping performance. On the contrary, the other studies suggest that the tapping performance may be different among subgroups of musicians. For example, Jäncke et al. (1997) showed the difference between keyboard- and string-instrument players: The keyboard-instrument players showed less tapping-speed asymmetry than the string-instrument players (Jäncke et al., 1997). This could be due to the fact that a keyboard-instrument player uses both left- and right-hand fingers to play a keyboard, while a string-instrument player uses left fingers more than the right to hold down the strings (Bangert and Schlaug, 2006). Nevertheless, the tapping skills of the other musical instrument players are still largely unknown.

In this study, we focused on the tapping skills of hand percussionists who play the percussion called "darbuka," a single-headed drum widely used throughout the Middle East (**Figure 1A**). Darbuka players are considered to be an interesting population to investigate the rhythmic manual skills because the players practice the finger and hand movements in a unique way (Karaol and Doğrusöz, 2014). To play the darbuka, the players mainly make three sounds named as (1) "Doum" (a low-pitch sound), (2) "Pa" (a slapping sound), and (3) "Tek" (a high-pitch sound). The Doum and Pa sounds are made by striking the center of a drum head with a preferred hand (Karaol and Doğrusöz, 2014). The Doum sound is made by keeping the palm and fingers straight with all fingers firmly closed to each other, while the Pa sound is made by keeping the hand shape like scooping water. The Tek sound is made by striking the edge of a drumhead with a ring finger of a preferred hand (**Figure 1B**) or an index or a ring finger of a non-preferred hand (**Figures 1C,D**).

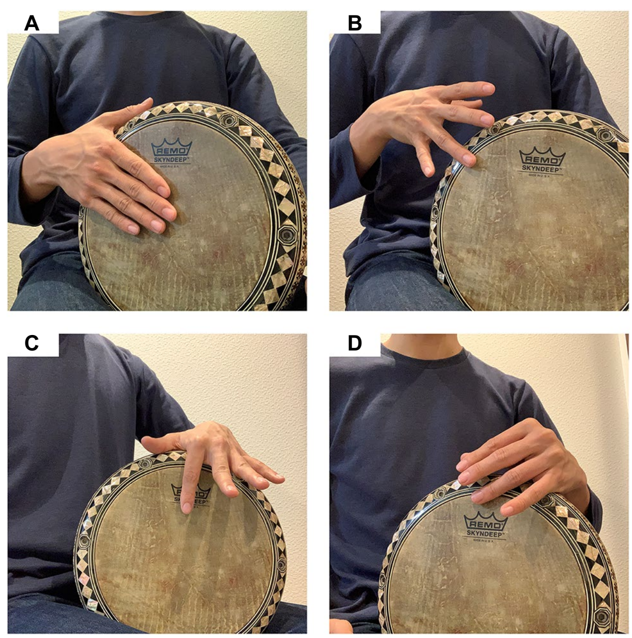

FIGURE 1 | An example of playing a percussion "darbuka" by a right-handed musician. To play the darbuka, the players mainly make three sounds named "Doum" (a low-pitch sound), "Pa" (a slapping sound), and "Tek" (a high-pitch sound). The Doum and Pa sounds are made by striking the center of a drum head by a preferred hand **(A)**. The Tek sound is made by striking the edge of a drum head with a ring finger of a preferred hand **(B)**, or an index or a ring finger of a non-preferred hand **(C,D)**.

The skills to play darbuka is unique in terms of which fingers to be used, coordination of fingers, and asymmetry of hands. First, darbuka players mainly use three fingers. For instance, the "split-finger" technique invented by Misirli Ahmet in the 1980s is well-known as a skill to perform the Tek sounds very quickly. The technique involves the sequential tapping movements of a ring finger of a preferred hand, the index and ring fingers of a non-preferred hand. Thus, not all fingers but specific fingers are contacted the drum surface during the practice of playing darbuka. Second, darbuka players show asymmetrical manual movements when they play the instrument. That is, darbuka players use the movements of the preferred hand more than that of the non-preferred hand because low-pitch sounds play an important role in the rhythm pattern of Middle Eastern music. Specifically, the players use the preferred hand more than the non-preferred hand to make the Doum and Pa sounds for playing rhythm patterns in Middle Eastern music.

We consider that darbuka players form a unique population for investigating the effect of musical practice on tapping skills. While keyboard players contact the keys with all their fingers to play the instrument, the darbuka players contact the drum surface with the specific fingers (i.e., a ring finger of a preferred hand and an index and ring fingers of a non-preferred hand). Drum-kit players mainly use a drumstick to hit the drum surface while the darbuka players contact with the fingers (Fujii and Oda, 2009; Eriksen et al., 2018). Therefore, we consider that darbuka players shed unique light on the instrument-specific effect on tapping performance after extensive practice. However, as far as we know, there has been no study investigating the tapping skills of darbuka players.

The purpose of this study was therefore to investigate the tapping skills of darbuka players. Specifically, we aimed to test the following hypotheses considering the previous tapping studies: First, we hypothesized that right-handed professional darbuka players would show faster tapping speed than amateur players when they tapped with the familiar fingers to play darbuka (i.e., left-index, left-ring, and right-ring fingers). Second, we hypothesized that professional and amateur darbuka players would show similar tapping-speed asymmetry because both professional and amateur darbuka players practice preferred hand more to play the rhythm patterns in Middle Eastern music. Third, we hypothesized that professional darbuka players would show faster tapping performance than amateur players when they tapped alternately/sequentially with the familiar fingers to play darbuka (left-index, left-ring, and right-ring fingers). To test these hypotheses, we compared the tapping speed of professional darbuka players and amateur controls. Additionally, we investigated the variability of inter-tap interval (ITI) and tapping amplitude to compare the performance stability of the professional and amateur players.

MATERIALS AND METHODS

Participants

Japanese professional darbuka players (8 males, mean age = 37.25 years, standard deviation [SD] = 5.66, range = 30–50 years) and Japanese amateur darbuka players (8 males, mean age = 41.50 years, SD = 9.34, range = 28–55 years) participated in this study (see **Table 1**). The professional players had experiences of earning money from their musical performances and teaching students, whereas the amateur players did not have any of those experiences. The professional players started to play the darbuka earlier than the amateur players (professional players: mean age of commencement = 24.38 years, SD = 4.27, range = 21–34 years, amateur players: mean age of commencement = 35.63 years, SD = 10.80, range = 25–51 years; $t(14) = 2.74$, $p = 0.023$). The duration of darbuka training of professional players is longer than that of the amateur players (professional players: duration = 13.75 years, SD = 2.77, range = 8–17 years, amateur players: duration = 6.38 years, SD = 4.92, range = 4–18 years; $t(14) = -3.69$, $p = 0.02$). The handedness of participants was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were right-handed (professional players: mean laterality quotient [LQ] = 92.37, SD = 10.54, range = 80–100, amateur players: mean LQ = 92.37, SD = 15.01, range = 60–100). The two groups were matched for sex, age and handedness. The experimental procedure was approved by the Ethics Committee of Keio University Shonan Fujisawa Campus (No. 161) and informed consent was obtained from all participants.

Task

There were three tasks in this study: (1) single-finger, (2) double-finger, and (3) triple-finger tapping tasks. In the single-finger tapping task, there were four conditions: left-index (Li), left-ring (Lr), right-index (Ri), and right-ring (Rr) finger conditions. The Li, Lr, and Rr were familiar conditions and Ri was an unfamiliar condition. In the double-finger tapping task, there were six conditions denoted as Li–Lr, Ri–Rr, Li–Ri, Lr–Rr, Li–Rr and Lr–Ri. For example, the Li-Lr indicates the alternate coordination of the left-index and left-ring fingers. The Li–Lr, Lr–Rr and Li–Rr were familiar coordination for the right-handed darbuka players because they usually tap with right-ring, left-ring, and left-index fingers to play the instrument. On the other hand, the Ri–Rr, Li–Ri, and Lr–Ri were unfamiliar

TABLE 1 | Age, age of commencement, handedness score for both groups (SD and range in parentheses).

	Mean age (years)	Mean age of commencement (years)	Mean duration of darbuka training (years)	Mean laterality quotient
Professional darbuka players ($n = 8$)	37.25 (5.66, 30–50)	24.38 (4.27, 21–34)	13.75 (2.77, 8–17)	92.37 (10.54, 80–100)
Amateur darbuka players ($n = 8$)	41.50 (9.34, 28–55)	35.63 (10.80, 25–51)	6.38 (4.92, 4–18)	92.37 (15.01, 60–100)

All participants for both groups are male.

to the right-handed darbuka players. The participants were asked to coordinate the fingers as fast and alternate as possible and to start the tapping from the preferred right hand when they coordinated the left and right hands. They started from the index finger when they coordinated the index and ring fingers in a hand. In the triple-finger tapping task, there was only one condition denoted as Rr–Li–Lr (coordination of right-ring, left-index, and left-ring fingers), which is known as the split finger technique (Karaol and Doğrusöz, 2014). In this technique, the participants were asked to coordinate the right-ring, left-index, and left-ring fingers sequentially in this order. The participants were asked to tap as fast as possible in the single-finger tapping task while they were asked to tap as fast and alternate/even as possible in the double- and triple-finger tapping tasks for 12 s after a start call of an experimenter. Note that the participants in this study were asked to tap with the fingers but allowed to use upper-arm joints movements without any constraints as they usually play the instrument. This was because we aimed to investigate the natural performance seen in actual darbuka playing. For each of the conditions in each of the tasks, the participants performed three trials each. The participants were asked to have one-minute rest between the trials to prevent fatigue. The order of the task and conditions were randomized among the participants.

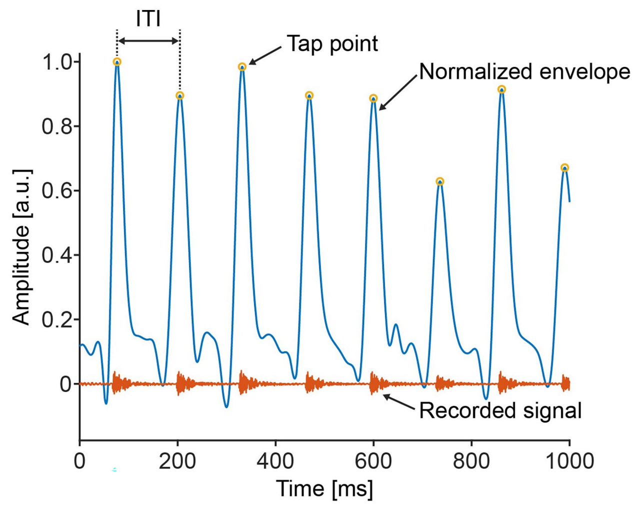

FIGURE 2 | A typical example of the recorded sound signal. The envelope of the recorded signal was calculated and the amplitude was normalized by the maximum value. The "tap points" were detected from the envelope signal. The inter-tap intervals (ITI) were calculated as the interval between the two sequential tap points.

Setup and Data Acquisition

The height and position of the drum chair were adjusted for each participant to be comfortable. The participants were asked to hold a darbuka (Aluminum die-cast model, Egygwhara) under the left upper arm. A microphone (M50, Earthworks) was located 50 cm apart from the center of the percussion head. The signals of the microphone were transformed from analog to digital at 192 kHz sampling frequency and 24-bit quantization by an audio interface (F8, ZOOM).

Data Analysis and Statistics

The tapping speed was assessed with the following steps. First, the audio data were rectified, and the envelope was calculated by using the Hilbert transform. The envelope signal was then normalized by the maximum value for each trial. From the normalized envelope signal, we detected a local maximum above 10% of the maximum value as the "tap points" (see **Figure 2**). The ITI in this study was defined as the interval between two sequential tap points.

We truncated the first and last parts of the 12-s tap-points data to eliminate the effects of start-up and final slowing and used the data during a middle 10-s period. We calculated ITIs from the 10-s tap-points data and removed outliers of ITI by using the median absolute deviation for each trial. We then pooled the ITI data from three trials for each condition and created linear mixed-effects models (LMMs) to test the hypotheses on tapping speed. We first entered Task (single/double/triple) and Group (professional/amateur) and their interaction as fixed effects in the LMM to test if the group and task differences affect the tapping speed. Participants and trials were entered as random effects in the LMMs to account for the inter-individual and inter-trial differences.

As for the ITI data from the single-finger tapping task, we used the LMM that had the fixed effects of Group (professional/amateur), Finger (ring/index), Hand (right/left) and their interactions. Specifically, we tested whether the professional players showed faster tapping speed with their familiar fingers by entering Group (professional/amateur) and Familiarity [familiar (Lr, Li, and Rr)/unfamiliar (Ri)] and their interaction as fixed effects in the LMM. Also, to test if the professional and amateur players showed similar tapping-speed asymmetry, we used the LMM that had Group and Hand and their interaction as the fixed effects.

As for the ITI data from the double-finger tapping task, we used the LMM that had the fixed effects of Group (professional/amateur) and Familiarity [familiar (Li-Lr, Lr-Rr and Li-Rr)/unfamiliar (Ri-Rr, Li-Ri, and Lr-Ri)] and their interaction to test if the professional players coordinated the familiar fingers faster than the amateur players.

To assess the variability of tapping performance, we calculated the coefficient of variance (CV) of ITI and CV of tapping amplitude. The CV of tapping amplitude was calculated from the 10-s tap-points data for each trial. The CV of ITI was calculated from the 10-s ITI data after the removal of outliers using the median absolute deviation for each trial. To test if the performance stability differed between the professional and amateur players, we used the LMMs that had Task (single/double/triple) and Group (professional/amateur) and their interaction as the fixed effects. In all the LMMs, participants and trials were entered as random effects to account for the inter-individual and inter-trial differences.

In one professional player, we recorded the signals at a 48 kHz sampling frequency and missed a double-finger tapping

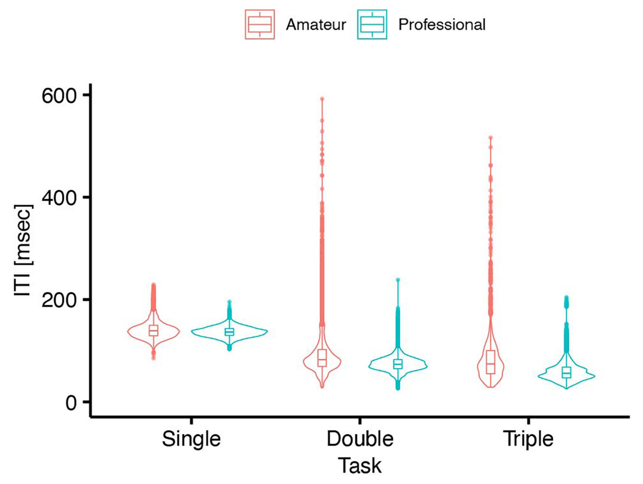

FIGURE 3 | Inter-tap interval of professional and amateur darbuka players in the single-, double- and triple-finger tapping tasks ($n = 8$ for the professional group and $n = 8$ for the amateur group).

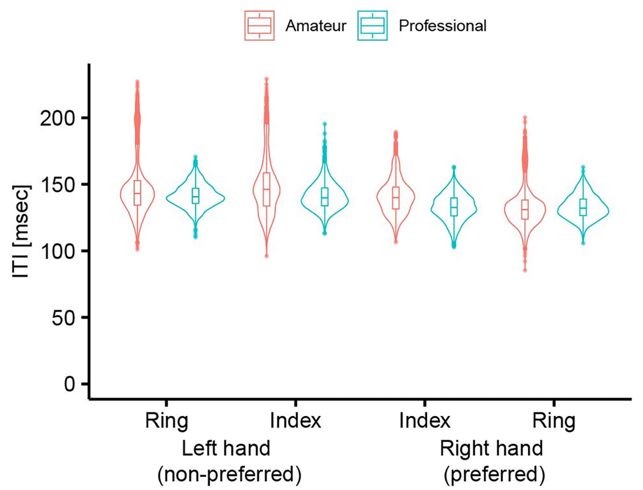

FIGURE 4 | Inter-tap interval of professional and amateur darbuka players in the single-finger tapping task ($n = 8$ for the professional group and $n = 8$ for the amateur group).

task (Rr–Li). We omitted the sound signals of an amateur player in a single-tapping task (Li) due to the too low signal-to-noise ratio to detect the taps. Because the tapping frequency is enough slower than the sampling frequency of the sound signal and the LMMs have the robustness for missing values, we conducted the LMMs including these participants.

To investigate if the tapping speed of an individual was related to the experience of musical training, we performed correlation analyses. We calculated the tapping frequency as the inverse of the median ITI for each trial. The tapping frequencies were then averaged using the data from the double-finger tapping task (see "Results" for the reason why the data from the double-finger tapping task were used). We tested if the age of commencement of darbuka training and the duration of darbuka training were correlated with the tapping frequency to investigate whether earlier commencement of training and longer duration of training lead to faster tapping performance (Jäncke et al., 1997; Bailey and Penhune, 2010; Kopiez et al., 2010; Rüber et al., 2015). We examined how linear and polynomial functions were able to explain the data variance in the correlations. We used Spearman's rho correlation coefficients to assess the relationships.

The data processing was performed with MATLAB software (R2021b, Mathworks), and the statistical analyses were performed by R software. The LMMs were performed by using the "lmer" function in the "lme4" package for R software (Bates et al., 2015). Wald Chi-Square tests were used to reveal significant main effects and interactions in the LMMs. The statistical results were deemed as significant at the level of $p < 0.05$ for each of the statistical analyses. We calculated the partial eta squared (η_p^2) values as the effect sizes. In the **Supplementary Material**, we described the details about all the LMMs we used for the analyses.

RESULTS

Effects of Task and Group on Tapping Speed

The LMM on ITI revealed a significant interaction between Task and Group ($\chi^2(2) = 913.40$, $p < 0.01$, $\eta_p^2 = 0.019$, **Figure 3**). The main effect of Task was significant ($\chi^2(2) = 13390.90$, $p < 0.01$, $\eta_p^2 = 0.46$) while the main effect of Group was not significant ($\chi^2(1) = 0.72$, $p = 0.40$). *Post hoc* LMM analyses entering Group as the fixed effect for each task showed the significant main effect of Group in the double-finger tapping task ($\chi^2(1) = 5.77$, $p = 0.016$, $\eta_p^2 = 0.29$). On the other hand, the main effect of Group was not significant in the single-finger tapping task ($\chi^2(1) = 1.21$, $p = 0.27$) nor in the triple-finger tapping task ($\chi^2(1) = 3.12$, $p = 0.077$). Thus, the professional players performed faster than the amateur players only in the double-tapping task ($\beta = -0.022$, $t = -2.40$, *95%* CI = −0.039– −0.0031). The detailed results on the LMMs were summarized in the **Supplementary Material**.

Tapping Speed in Single-Finger Tapping Task

The LMM on ITI revealed significant interaction among Group, Finger, and Hand in the single-finger tapping task [$\chi^2(1) = 55.12$, $p < 0.01$, $\eta_p^2 = 0.0047$, **Figure 4**]. The LMM also revealed a significant interaction between Group and Familiarity [$\chi^2(1) = 15.07$, $p < 0.01$, $\eta_p^2 = 0.0013$]. However, *post hoc* LMM analyses entering Group as the fixed effect for each familiarity showed no significant main effect of Group [familiar, $\chi^2(1) = 0.96$, $p = 0.33$; unfamiliar, $\chi^2(1) = 2.66$, $p = 0.10$, respectively].

We found a significant interaction between Group and Hand in the single-finger tapping task [$\chi^2(1) = 189.27$, $p < 0.01$, $\eta_p^2 = 0.02$]. *Post hoc* LMM analyses entering Hand as the fixed effect for each group showed that there was a significant main effect of Hand in both of the groups [professional, χ^2

(1) = 1598.16, $p < 0.01$, $\eta_p^2 = 0.20$; amateur, $\chi^2(1) = 1706.53$, $p < 0.01$, $\eta_p^2 = 0.24$, respectively]. Nevertheless, the significant interaction showed that the professional players had less degree of tapping-speed asymmetry between hands ($\beta = 0.0085$, $t = 39.98$, 95% CI = 0.0081–0.0089) compared to the amateur players ($\beta = 0.014$, $t = 41.31$, 95% CI = 0.013–0.014).

Tapping Speed in Double-Finger Tapping Task

The LMM revealed no significant interaction between Group and Familiarity in the double-finger tapping task [$\chi^2(1) = 0.00054$, $p = 0.98$, **Figure 5**]. The main effect of Familiarity was not significant [$\chi^2(1) = 0.71$, $p = 0.40$] while that of Group was significant [$\chi^2(1) = 5.76$, $p = 0.016$, $\eta_p^2 = 0.29$]. The model showed that the professional players performed the double-finger tapping faster than the amateur players ($\beta = -0.022$, $t = -2.4$, 95% CI = −0.040– −0.0036).

Variability of ITI and Tapping Amplitude

As for the CV of ITI, the LMM revealed a significant interaction between Task and Group [$\chi^2(2) = 32.30$, $p < 0.01$, $\eta_p^2 = 0.06$]. *Post hoc* LMM analyses entering Group as the fixed effect for each task showed the significant main effect of Group in all the tasks [single, $\chi^2(1) = 7.36$, $p < 0.01$, $\eta_p^2 = 0.34$; double, $\chi^2(1) = 7.17$, $p < 0.01$, $\eta_p^2 = 0.34$; triple, $\chi^2(1) = 6.12$, $p < 0.01$, $\eta_p^2 = 0.39$, respectively]. Namely, the professional players showed less variability of ITI than the amateur players in all the tasks [single, $\beta = -0.013$, $t = -2.71$, 95% CI = −0.023 – −0.0036; double, $\beta = -0.088$, $t = -2.71$, 95% CI = −0.16– −0.023; triple, $\beta = -0.11$, $t = -2.47$, 95% CI = −0.21– −0.016, **Figure 6A**].

As for the CV of tapping amplitude, the LMM revealed a significant interaction between Task and Group [$\chi^2(2) = 6.94$, $p < 0.031$, $\eta_p^2 = 0.014$]. *Post hoc* LMM analyses entering Group as the fixed effect for each task showed the significant main effect of Group in the single-finger and double-finger tapping tasks [single, $\chi^2(1) = 4.77$, $p = 0.029$, $\eta_p^2 = 0.25$; double, $\chi^2(1) = 25.53$, $p < 0.01$, $\eta_p^2 = 0.63$, respectively]. Namely, the professional players showed less variability of tapping amplitude than the amateur players in the single-finger and double-finger tapping tasks (single, $\beta = -0.047$, $t = -2.18$, 95% CI = −0.092 – −0.0053; double, $\beta = -0.086$, $t = -4.85$, 95% CI = −0.12 – −0.051, **Figure 6B**). The main effect of Group did not reach a significant level in the triple-finger tapping task but the professional players still showed the tendency of less variability of tapping amplitude [$\chi^2(1) = 3.50$, $p = 0.061$].

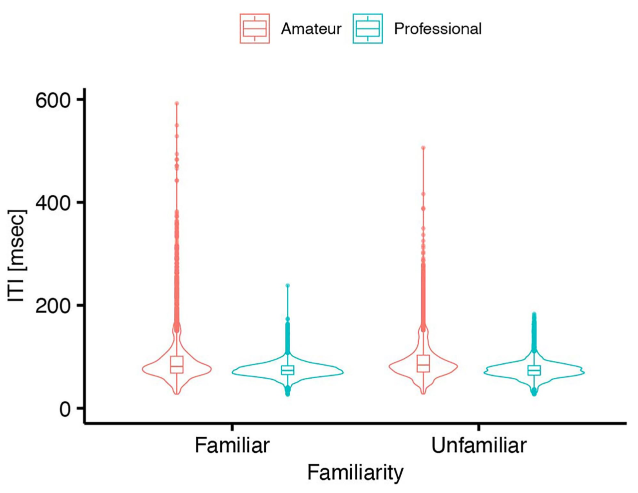

FIGURE 5 | Inter-tap interval of professional and amateur darbuka players under familiar (Li-Lr, Lr-Rr and Li-Rr) and unfamiliar (Ri-Rr, Li-Ri, and Lr-Ri) conditions in the double-finger tapping task ($n = 8$ for the professional group and $n = 8$ for the amateur group).

Correlation Between Tapping Frequency and Musical Experiences

Since the professional players tapped faster than the amateur players only in the double-finger tapping task, we calculated the average of tapping frequencies in this task for each participant and correlated it with the age of commencement and duration of darbuka training (**Figure 7**). The age of commencement of darbuka training was significantly correlated with the average of the tapping frequency in all the participants (Spearman's $\rho = -0.58$, $p = 0.020$, **Figure 7A**). The R-square value of the linear fitting model was 0.38 while that of the polynomial fitting model was 0.39. When we subdivided into each of the professional and amateur groups, the correlation did not reach at the significant level (professional, Spearman's $\rho = -0.34$, $p = 0.41$; amateur, Spearman's $\rho = -0.33$, $p = 0.43$, respectively).

The duration of darbuka training was significantly correlated with the average of the tapping frequency in all the participants (Spearman's $\rho = 0.52$, $p = 0.040$, **Figure 7B**). The R-square value of the linear fitting model was 0.30 while that of the polynomial fitting model was 0.70. When we subdivided into each group, the correlation did not reach a significant level (professional, Spearman's $\rho = -0.55$, $p = 0.16$; amateur, Spearman's $\rho = 0.51$, $p = 0.20$, respectively).

In addition, we investigated if the years of age at the time of the experiment related to the tapping frequency. However, there was no significant correlation between the years of age and the average of the tapping frequency (Spearman's $\rho = -0.33$, $p = 0.20$).

DISCUSSION

We compared the tapping performance between the professional darbuka players and the matched amateur controls to test the following three hypotheses: (1) Right-handed professional darbuka players would show faster tapping speed than amateur players when they tapped with the familiar fingers to play darbuka (i.e., left-index, left-ring, and right-ring fingers). (2) Professional and amateur darbuka players would show similar tapping-speed asymmetry because both professional and amateur darbuka players practice preferred hand more to play the rhythm patterns in Middle Eastern music. (3) Professional darbuka players would show faster tapping performance than amateur players when they tapped alternately/sequentially with the familiar fingers to play darbuka (left-index, left-ring, and right-ring fingers).

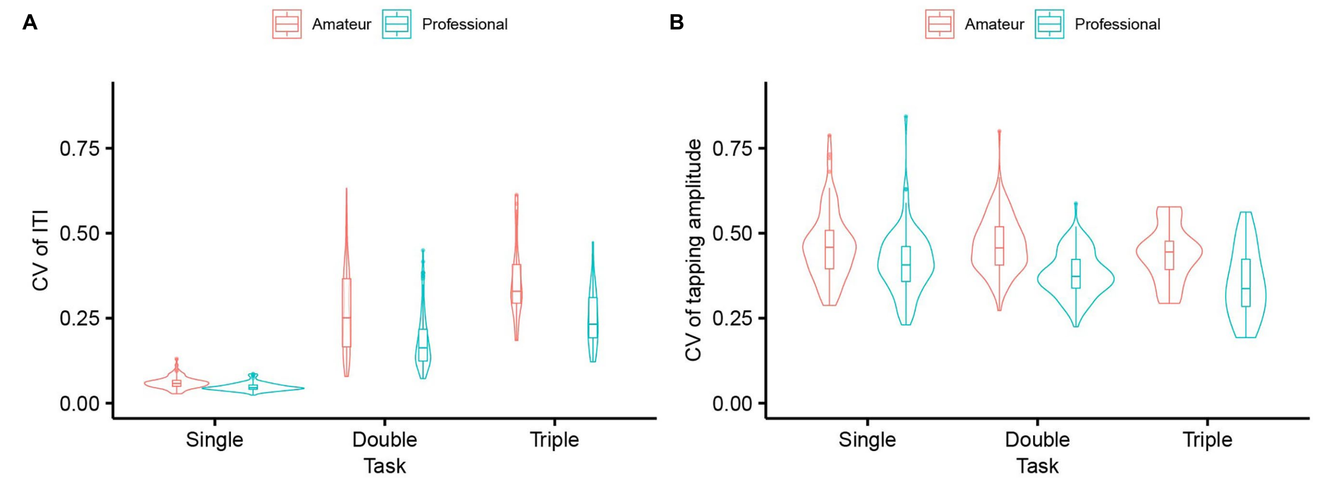

FIGURE 6 | (A) Coefficient of variation (CV) of inter-tap interval (ITI) of professional and amateur darbuka players in the single-, double- and triple-finger tapping tasks ($n = 8$ for the professional group and $n = 8$ for the amateur group). **(B)** CV of tapping amplitude of professional and amateur darbuka players in the single-, double- and triple-finger tapping tasks ($n = 8$ for the professional group and $n = 8$ for the amateur group).

First, we did not find any significant difference in the tapping speed at left-index, left-ring, and right-ring fingers between professional and amateur players in the single-finger tapping task. Thus, the result of this study did not support the first hypothesis. Second, we found that the professional players had less tapping-speed asymmetry than the amateur players. This result did not support the second hypothesis. Third, the professional players showed faster tapping performance in the double-finger tapping task than the amateur players. However, we could not find any significant interaction between the effects of Group and Familiarity in the LMMs in the double-finger tapping task. Thus, the results partially supported the third hypothesis. The professional players showed faster tapping performance when they tapped with not only their familiar fingers but also with unfamiliar fingers.

The Speed of Single-Finger Tapping

We hypothesized that right-handed skilled professional darbuka players would show faster tapping speed in the single-finger tapping task when they tapped with a left-index finger, a left-ring finger, and a right-ring finger. This was because the darbuka players usually used these fingers for playing the instrument. However, the speed in the single-finger tapping task was not significantly different between the professional and the amateur players. The result is inconsistent with the previous study by Aoki et al. (2005) who found a significant difference in the single-finger tapping speed between the pianists and the non-pianists. We suggest that this inconsistency may be attributed to the following two reasons.

First, the data distribution of musical training background could be wider in the previous study compared to this study. Namely, Aoki et al. (2005) compared the musicians with the non-musicians, while we compared the professional players with amateur players. The amount of experience to play musical instruments was more clearly different in the study by Aoki et al. (2005) compared with this study. Thus, it might be difficult to find the significant difference in the speed between the groups in the single-finger tapping task in this study.

Another reason may be the difference in the joint constraint during the task. In the Aoki et al. (2005) study, the participants placed the palm on a table and were allowed to use only the metacarpophalangeal joint movement but not the other joints (e.g., wrist and elbow joints). On the other hand, the participants in this study were allowed to use upper-arm joints without any constraints to make the task compared with the actual performance. In such unconstrained single-finger tapping, the movements of wrist and elbow joints are involved (Dennerlein et al., 2007). Namely, the participants in this study used not only the finger joint but also the other joint movements (e.g., pronation and supination of the forearm). In this study, the finger was a contact element between hand and the membrane of the drum (i.e., the last element in the chain) and the darbuka players tapped with the fingers in conjunction with the arm rotations and displacements. This was different compared with the previous study by Aoki et al. (2005) in which the wrist and elbow joints were constrained. Thus, unconstrained movements of the upper limb might make it difficult to observe the difference between the professionals and amateurs in the single-finger tapping task in this study.

Tapping-Speed Asymmetry

Our second hypothesis was that both professional and amateur darbuka players would show similar tapping-speed asymmetry in the single-finger tapping task. This was because both of the professional and amateur darbuka players had used the preferred hand more than the non-preferred hand in their daily performance. Our result showed that both professional and amateur players showed faster performance with the

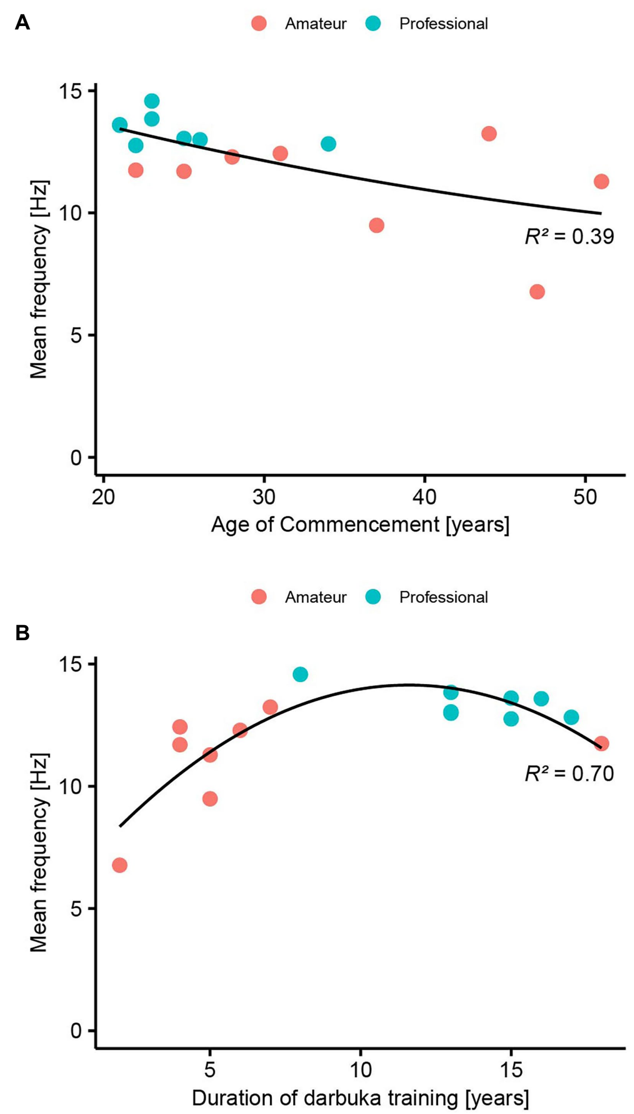

FIGURE 7 | (A) Correlation between age at the commencement of darbuka training and tapping frequency in double-finger tapping task. A polynomial fitting curve and the R-squared value are shown. **(B)** Correlation between duration of darbuka training and tapping frequency in double-finger tapping task. A polynomial fitting curve and the *R*-squared value are shown.

preferred right hand compared with the non-preferred left hand in the single-finger tapping tasks. However, the professional players showed less degree of tapping-speed asymmetry than the amateur players. The result does not support the hypothesis that both professional and amateur darbuka players show a similar degree of tapping-speed asymmetry.

The previous studies showed less tapping-speed asymmetry in musicians compared with non-musicians (Jäncke et al., 1997; Fujii and Oda, 2006). Fujii and Oda (2006) showed that drum-kit players had less degree of tapping-speed asymmetry than non-drummers when they performed the single-hand tapping task with a handheld drumstick. The result of this study was consistent with these previous studies that showed less degree of tapping-speed asymmetry in musicians compared to non-musicians. Drum-kit players have asymmetrical drum setups, such as striking the hi-hat and the snare drum with the right and left hands, respectively. However, in the daily practice of drumming, it is common to use the left and right hands equally, as played in rudiments which are the fundamental drum playing technique. Although the darbuka players use the right hand more than the left hand to play the instrument, motor control of both left and right hands is considered to be important to achieve dexterous musical performance. In addition, the darbuka players usually practice a tremolo technique such as the symmetrical bimanual tapping (Lr–Rr). Taken together, we suggest that acquisition of control skills of both left and right hands may lead to less degree of tapping-speed asymmetry in professional darbuka players.

Manual Coordination

Our third hypothesis was that the professional darbuka players would show faster speed than the amateur players when they tapped with the left-index, left-ring, and right-ring fingers. This was because the darbuka players use these fingers to play the darbuka. In the double-finger tapping task, our results showed that the professional players performed faster than the amateur players not only when they tapped with the left-index, left-ring, and right-ring fingers (familiar condition), but also when they tapped with the other combinations of fingers (unfamiliar condition).

Why did professional players perform faster tapping in the finger combinations which are not familiar in the usual musical performance? We assume that there might be a transfer or generalization of the motor learning effect from the practiced fingers. In fact, previous studies on finger tapping have shown that the learning effect was transferred from a practiced finger to the other fingers (Schulze et al., 2002; Koeneke et al., 2009; Furuya et al., 2013). For example, Koeneke et al. (2009) made the participants practice tapping 6 days per week for 2 weeks with the left or right middle finger. Interestingly, they found improvements in tapping speed not only in the practiced middle finger but also in the other unpracticed fingers. They assumed that the practice might improve general pacing circuit whose output could be routed to send motor commands to any of the fingers (Koeneke et al., 2009). Thus, although the darbuka players coordinate the left-index, left-ring, and right-ring fingers in their daily practice, the effect might be transferred to the other fingers resulting in the improvement of tapping speed in all the combinations of fingers.

Variability of Tapping Performance

We found that the professional players showed less variability of ITI and tapping amplitude. While the tapping speed was comparable between the professional and amateur players in the single-finger and triple-finger tasks, the variability was different between the two groups. Moreover, the professional players showed not only faster but also more stable performance compared to the amateur players in the double-finger tapping task. In other words, the professional's performance was more regular and even in terms of the timing and amplitude when they alternatively tapped with two fingers. The finding was consistent with the previous studies on drummers that showed stable tapping performance in professional players (Fujii and Oda, 2006; Fujii et al., 2010). Producing a regular rhythm and controlling the loudness of sounds are arguably important elements for achieving dexterous musical performance. The results suggest that the professional darbuka players have acquired the stable performance to play the instrument dexterously.

Age of Commencement and Duration of Darbuka Training

To assess if the intensive practice of darbuka had improved the tapping speed, we analyzed the correlation between the tapping frequency of the double-finger tapping tasks and the experience of the practice of darbuka. As the results, we found a significant negative correlation between the age of commencement and the tapping speed and a positive correlation between the training duration and the tapping speed in the data from all participants. The earlier and the longer they had practiced the darbuka, the faster they showed the tapping performance when alternately coordinating the fingers. The results indicate that the prolonged practice of darbuka from an earlier age of years had improved the manual coordination skill.

We found that the R-squared values of the polynomial fitting models were larger than those of linear fitting models. The polynomial fitting model for the data between the duration of darbuka training and tapping frequency showed inversed U-shaped or ceiling relationship between the two valuables. This suggests more improvement in the early stage of darbuka training than in the later stage. There may be a decay or ceiling effect of tapping speed improvement in the later stage of darbuka training.

The previous study suggested that the tapping skill of musicians was related to the age of commencement of musical practice but not to the duration of musical practice (Jäncke et al., 1997). The previous behavioral and neuroimaging studies also suggest that manual dexterity and the structural brain adaptation in musicians were related to the age of commencement of musical training (Jäncke et al., 1997; Kopiez et al., 2010; Bailey and Penhune, 2012; Baer et al., 2015). These studies suggest that the age of commencement is significant because it influences the developing brain structure and functions. However, it was noteworthy that the age of commencement of musical practice in this study was relatively late compared with the previous studies. The darbuka players in this study started their training over 20 years old while the previous studies emphasize that the age of seven is the critical age to differentiate the course of brain development (Jäncke et al., 1997; Kopiez et al., 2010; Bailey and Penhune, 2012; Baer et al., 2015). Our results suggest that the early commencement of musical training may be important for improving tapping performance even over the age of 20. Nevertheless, we need to interpret the results with caution because there was a significant correlation between the age of commencement and the duration of darbuka training in this study ($r = -0.62$ and $p = 0.013$). For future studies, it would be interesting to control either the age of comment of darbuka training or the duration of darbuka training to investigate how each factor contributes to the improvement of tapping performance. Another limitation of this study was that we could not measure the amount of practice or played hours of the participants. For future studies, it would also be important to assess how the amount of practice or played hours affects the tapping performance of darbuka players.

CONCLUSION

The right-handed professional darbuka (hand percussion) players showed significantly faster and more stable tapping performance compared to the amateur players when they tapped with the two fingers as fast and alternate as possible. Interestingly, the professional players showed faster tapping speed in both familiar and unfamiliar patterns of finger coordination. The earlier and the longer they had the darbuka training, the faster they coordinated the fingers. When they tapped with a single finger as fast as possible or tapped with three fingers as fast and even as possible, the speed was similar between the professional and amateur players, but the professionals showed more stable performance. The results suggest that professional darbuka players have acquired fast and stable tapping performance over the prolonged practice.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Keio University Shonan Fujisawa Campus. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

KH and SF conceived, designed the study, interpreted the data, and wrote the paper. KH performed the experiment and analyzed the data. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Thinking rhythm objects

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The focus of this mini-review is on *rhythm objects,* defined as strongly coherent chunks of combined sound and body motion in music, typically in the duration range of a few seconds, as may for instance be found in a fragment of dance music, in an energetic drum fill, in a flute ornament, or in a cascade of sounds of a rapid harp glissando. Although there has been much research on rhythm in continuous musical sound and its links with behavior, including the neurocognitive aspects of periodicity, synchrony, and entrainment, there has been much less focus on the generation and perception of singular coherent rhythm objects. This mini-review aims to enhance our understanding of such rhythm objects by pointing to relevant literature on coherence-enhancing elements such as *coarticulation*, i.e., the fusion of motion events into more extended rhythm objects, and *intermittent motor control,* i.e., the discontinuous, instant-by-instant control and triggering of rhythm objects.

KEYWORDS

rhythm, music, objects, constraints, intermittency, coherence

Introduction

We may experience music as continuous streams of sound and motion, yet also perceive music as sequences of distinct events at different timescales, be that as singular sounds, groups of sounds, motives, phrases, or more extended sections. We seem to be capable of spontaneously *parsing* sound streams (Bregman, 1990) and transforming, or *recoding*, ephemeral sensations into more solid entities in our minds by *chunking* (Miller, 1956; Gobet et al., 2016), chunking which also applies to sensations of rhythm, ending up with what we here call *rhythm objects*. *Thinking rhythm objects* is about the transition from continuous sensations to more discontinuous mental images of music-related sound and motion, and importantly, also the other way around, about generating continuous motion and sound from more solid images in our minds.

This could be seen as an *ephemeral-to-solid* (and the other way around) transition, and is a very extensive topic with ramifications to fundamental epistemological issues that were discussed by Edmund Husserl and colleagues in some remarkable publications toward the end of the 19th and beginning of the 20th century (Husserl, 1991; Godøy, 2010). Husserl's view of perception, partly inherited from his teacher Franz Brentano, was that we need to step out of any continuous stream of sensations in order to get an overview of what we are perceiving by making some kind of cumulative and solid image of what we have been sensing. If we are continuously immersed in streams of sensations, we will not have any temporally cumulative image, i.e., not be able to have overview images, hence unable to make sense of these streams. This has later been termed by Paul Ricoeur as a need for *interrupting* continuous sensory streams in order to get an overview of what is going on (Ricoeur, 1981). Husserl came to suggest that perception proceeds by a series of such moments of cumulative overview, of what he called *now-points*, and that these now-points are composite, with traces not only of past sensations and of ongoing sensations, but importantly, also of expectations of what is to come in the future.

Significantly so, we find similar ideas of continuity-discontinuity coexistence in current theories of human motor control such as in the theory of *intermittent control,* i.e., a theory of instant-by-instant control (Craik, 1947; Gawthrop et al., 2011; Loram et al., 2011, 2014; Karniel, 2013; Sakaguchi, 2013) and in *posture-based theory,* i.e., in control by discontinuous postures (Rosenbaum, 2009, 2010, 2017; Kirsh, 2011; Warburton et al., 2013), as well as in *coarticulation*, i.e., continuous transitions between quasi-stationary postures of the effectors (vocal apparatus, fingers, and hands), where each momentary posture is conditioned by what was just done, what is done right now, and what is going to be done next (Hardcastle and Hewlett, 1999; Grafton and Hamilton, 2007; Godøy, 2014).

The core issue here is that in order to perceive any instance of rhythm, we need to perceive, and keep in memory, an extended excerpt of sound or motion. For instance, to perceive a drum pattern, we need to hear, and have some mental image of, a minimum number of successive drum sounds, just as in order to perceive a visual pattern, we need to see a minimum number of elements to decide that we actually see a visual pattern. The point of this seemingly trivial observation is to remind us that rhythm requires extension, and furthermore, that there is a qualitative transition from individual lower-level elements (i.e., individual sounds) to fused and coherent higher-level features (i.e., some pattern) in rhythm, a transition engendering features non-existent at lower levels of organization.

Yet how does the transition from an extended substrate to a compressed image of rhythm (and the other way around) work in music? This is indeed an extensive question and involves several issues of human perception and cognition; however, the focus in this mini-review will be on the role of sound-producing body motion in this transition. The main assumption here is that sound-producing motion is present in the minds and bodies of performers, but by the so-called *motor theory of perception* (Liberman and Mattingly, 1985; Galantucci et al., 2006), and by what may be called *motor-mimetic cognition* (Godøy, 2001, 2003), also present in the minds and bodies of the perceivers. Thinking rhythm as body motion objects in this way is a departure from more abstract Western notation-based concepts by studying music-related features in relation to body motion shapes (Godøy et al., 2016, 2017). To develop this line of thought in the present mini-review, we shall first have a brief overview of some main rhythm perspectives in music, followed by a section on object focus in music cognition, and sections on motor features and what may be called *quantal elements* in music, i.e., on how crucial musical features may be conceived in a discontinuous manner, before a final discussion section with some reflections on how to develop further this object-focused view of rhythm.

Rhythm perspectives

The word "rhythm" is used with so many different significations that it may not be possible to give it a concise definition. Typically, it is taken to signify something recurrent, regular in pace, or even fluid and elegant in body motion, yet sometimes also energetic or jerky body motion. In the opinion of Shima Arom, any temporal distribution of events could conceivably be included in "rhythm" (Arom, 1992, p. 202), and with our focus on rhythm objects, adopting a general notion of rhythm makes sense, provided that occurring events can be integrated into a coherent entity, i.e., into an 'object'.

As for the different perspectives on what musical rhythm might be, there are some instructive overview texts available (e.g., Hasty, 1997; Sethares, 2007; London, 2012). These texts also provide material on groupings of sound into what may be related to rhythm objects in our context. For instance, manifestations of meter may be instances of rhythm objects; however, our present concept of rhythm objects is more in line with Arom's general view, and will also include complex sound masses like those of Lutoslawski (1961) or Xenakis (1992), as well as other rhythm objects in twentieth-century Western *avant garde* music (Schäffer, 1976). In particular, there are highly salient examples of rhythm objects in the theoretical and musical works of Olivier Messiaen, going back to his early work (Messiaen, 1944), including non-European music as well as bird song. In a different vein, there have been attempts to designate characteristic rhythm patterns as "signatures" of various styles (Cope, 1991), as well as more recent work with computer-assisted surveys of rhythm patterns (Cocharro et al., 2021). Furthermore, we have seen work related to gestalt phenomena (Fraisse, 1975), such as in Tenny and Polansky (1980) where coherence is associated with principles of tone proximity, as well as in work on low-level groupings of sounds based on spectral features (Bregman, 1990).

Also, we have in recent decades seen a surge in rhythm-related research in the cognitive sciences, and it seems that the boundaries between music theory and music-related neuroscience are becoming less rigid (see, e.g., London, 2012). Of particular interest here is the focus on motor components of rhythm perception and cognition playing an active role in both the generation and the perception of rhythm, be that in more periodic kinds of rhythm (Repp, 2005; Patel and Iversen, 2014; Morillon et al., 2016; Ross et al., 2016) or in more singular event-centered kinds of rhythm (Schubotz, 2007; Zimnik and Churchland, 2021). Importantly, notation-based perspectives on rhythm will have limitations in that they do not represent directly the actual output sound, and on the other hand, sound-based approaches may have difficulties in picking out groupings of rhythmic events based on sound data alone (Sethares, 2007). What is needed then is an approach that includes both sound and sound-producing motion, as these two modalities may mutually enhance the perception of coherent rhythm objects.

Object focus

The term "object" should here be understood as designating some coherent mental entity, and not as designating something devoid of any subjective sensations. A crucial feature of "object" here is that of being present all-at-once, or in-a-now, *cf.* the mentioned idea of Husserl that perception proceeds by a series of now-points, each point encompassing a whole chunk and its internal context of recent past, present, and near future.

The main source of the object perspective here is in the theory of sound objects developed by Pierre Schaeffer and co-workers in the early days of the *musique concrète* (Godøy, 1997, 2006, 2021a; Schaeffer, 1998, 2012, 2017; Chion, 2009). Closely related to Husserl's theories, this is an extensive theory where the main focus is on detecting and qualifying subjectively experienced features of sound objects, based on sound fragments typically in the duration range of 0.5–5 s. Any sound object should be perceived as a coherent entity, and all sequentially occurring features within the sound object will contribute to the holistic image of the sound object in question, e.g., the attack and sustain segments of a sound both contribute to the overall sensation of the sound. This object-focus grew out of the experience of the so-called "cut bell," i.e., the removal of the attack segment of bell sounds and the resultant significant change of the perceived sound features, as well as experiences of the so-called "closed groove," or looped sound used in the *musique concrète*, demonstrating that salient musical features are temporally distributed throughout any sound object, kept in memory as a holistic entity (Godøy, 2021a).

Furthermore, this sound object theory worked by taking sound fragments from any instrumental, vocal, environmental, or synthesis source, and then proceeding in a top-down manner by asking seemingly naïve questions as to what we are hearing, i.e., what are the shapes of the various features we are detecting. This results in the *typology* and *morphology* of sound objects, differentiating main feature dimensions such as the overall dynamic shape, overall pitch-related and/or timbral shapes, and several sub-dimensions as well as sub-sub-dimensions, all in view of highlighting esthetically salient features as shapes. Other approaches to auditory objects (e.g., Bizley and Cohen, 2013) investigate the role of top-down perceptual schemas; however, they do not go on to systematically differentiating subjectively perceived features.

Schaeffer's typology of sound objects is based on the energy envelopes of their generation, with the main categories *impulsive*, *sustained*, and *iterative*, and reflects similar body motion categories. Also, some of the feature categories of the morphology are linked with motion features such as *gait* and *fluctuation*; hence, it made sense to extend this sound object theory to include combined sound and motion energy shapes (Godøy, 2006).

Recognizing the motor-mimetic component of music perception means that we can also recognize motor gestalts (Klapp and Jagacinski, 2011), i.e., highly coherent body motion entities, as integral to rhythm gestalts. Furthermore, the notion of motor gestalts seems to fit well with the idea of an optimal timescale for motion control in the 0.5–5 s range (Loram et al., 2014), something that in turn also seems to fit well with assumed optimal durations of sensory input in perception in the vicinity of 3 s (Pöppel, 1997), as well as with the approximate duration range of short-term memory (Snyder, 2000). Crucially, the object focus enables detecting features not found at other timescales, by enabling cumulative and/or prospective overview images of the entire rhythm object. Interestingly, similar kinds of object focus seem to be optimal also in other domains, such as in reading, with the so-called *object superiority effect* of words being easier to perceive than letters (Starrfelt et al., 2013).

Motor features

Adopting notions of *abstract* vs. *concrete* from Pierre Schaeffer's music theory (Schaeffer, 2017), we can classify Western music notation as abstract in the sense of generic symbols, whereas the sound-producing body motion and output sound would be concrete in the sense of continuous spatiotemporal phenomena. And although we may distinguish between sound-producing and sound-accompanying music-related body motion (Godøy and Leman, 2010), there will usually be some kind of similar motion and energy shapes between these two categories, making the motor component crucial for both production and perception of rhythm. Motor-mimetic cognition is concrete in projecting motor schemas onto sound, with motor features and sensations contributing to shaping images of sound.

One simple yet important constraint of motion and rhythm objects (as well as of gestalt perception in general, see, e.g., Bregman, 1990) is that of *exclusive allocation*, meaning here that sound-producing events cannot belong to more than one motion scheme at a time, as is the case with to so-called bistable figures (e.g., the Neckar cube or Jastrow's duck-rabbit figure). For instance, the classic 6/8 vs. 3/4 metrical schemes can be subject to exclusive allocation in one of two gestalt figures, either as 6/8 by having two gestures with 3 eight notes in each, or as 3/4 by having three gestures with 2 eight notes in each. Also, there may be similar gestural sound event grouping in cases of polyrhythm, with concurrent rhythm motion layers becoming a single-layer motion, e.g., a three against four polyrhythm may become a monophonic series of durations (Klapp et al., 1998), and syncopations and/or offbeat events could similarly be allocated to concrete motion shapes.

Furthermore, the phenomenon of coarticulation will cause a spillover of motion from one event to another. Coarticulation happens because effector motion takes time, so that there is a constraint-based temporal smearing from one motion event to another, hence often also from one output sound to another. Most prominent in vocal performance, coarticulation can also be observed in instrumental music, enhancing coherence in the sound-producing motion as well as in the output sound, clearly contributing to the sensation of rhythm objects. Furthermore, changes in the variables of duration, rate, amplitude, and tempo may bring about changes in the degree of coarticulation (Sosnik et al., 2004; Godøy, 2014), and furthermore, changes in the degree of coarticulation may lead to changes in the category of sound-producing motion by so-called *phase transition* (Haken et al., 1985), e.g., with increased tempo from singular to fused iterative sounds.

Based on constraints of the motor control system, in particular on the so-called *psychological refractory period* entailing limitations on the ability to initiate new motion during the course of an ongoing motion (Klapp and Jagacinski, 2011), intermittent control has been seen as a workaround in that control impulses only need to occur at discontinuous points in time, with intermittent motor control variously referred to as *serial ballistic* (van de Kamp et al., 2013), *feedforward*, or *open loop*, i.e., motor control not needing continuous feedback. Related to pre-programming and hierarchization (Grafton and Hamilton, 2007), and to so-called posture-based motion (Rosenbaum, 2010, 2017), as well as so-called "marking" in dance (Kirsh, 2011; Warburton et al., 2013), one idea here is that motion can emerge by interpolating between so-called *goal postures* (Rosenbaum, 2010). Additionally, high degrees of pre-programming could also entail a fine-tuning of effort so that the force and muscular tension-relaxation activity is optimal in view of envisaged goals for the motion, as suggested by the theory of so-called *muscle synergy* (d'Avella and Lacquaniti, 2013).

Quantal elements

Given the listed constraints of sound-producing motion in combination with constraints of perception and cognition (Godøy, 2021b), we arrive at rhythm objects as multimodal sound-motion chunks having what we could call *quantal elements* (Godøy, 2013). The term "quantal" here designates the coherent nature of a rhythm object and its associated features, containing anything between a single sound and a complex group of sounds within the confines of the rhythm object. Also, "quantal" signifies that the rhythm object is triggered by an intermittent sound-producing impulse. The point of quantal here is to recognize discontinuity as optimal for both the sound-producing motion and the coherence of the output sound object (see Godøy, 2018 for some examples), *cf.* the mentioned discontinuous now-points of Husserl.

This quantal element can make rhythm object production *divisive* (de Leeuw, 2005) in the sense that the object content stems from the spreading out of impulse energy into detailed motion events, e.g., that a single impulse may trigger an elaborate and rapid ornament, a drum fill, or any other rapid textural figure. In this way, quantal may apply also to quite complex musical material, yet at the same time optimize effort by high degrees of pre-programming, as well as enabling shifts between bursts of energy and relaxation, enabling endurance in performance, and helping avoid strain injury.

In the sense of quantal as a time-delimited sound-producing effort and time-delimited sound output, we find quantal elements in the notion of *motor gestalts* (Klapp and Jagacinski, 2011), *intermittent control* (Loram et al., 2014), and *sound objects* (Schaeffer, 2017), i.e., there are intrinsic quantal features in motion, control, triggering, and sound objects, all converging in thinking rhythm objects as coherent entities. In short, quantal elements converge in highlighting optimal features of the object timescale, i.e., ~0.5–5 s duration range, *cf.* the mentioned object superiority effect.

It remains to be further explored how such a triggering of pre-programmed motion quanta works, but so-called *startle reactions* could be interesting to explore as a general trigger of pre-planned motor chunks, and not just as a reactive pattern, *cf.* suggestions of this in (Valls-Solé et al., 1999, 2008). In our current work, we are looking at how EMG recordings combined with motion capture recordings can tell us more about the temporal aspects of impulsive motion, and EMG data from other research (Aoki et al., 1989) have suggested that shifts between effort spikes and relaxation are optimal for typically ballistic motion.

Discussion

In summary, thinking rhythm objects means focusing on the overall shapes and perceptual features of sound and motion chunks in the 0.5–5 s range (Godøy, 2006; Schaeffer, 2017). Also, thinking rhythm objects means understanding the constraint-based unequal distribution of control and effort in music performance, i.e., understanding what may be summarized in the phenomenon of intermittency. Furthermore, intermittency may be seen as optimal in performance by enabling bypassing limitations of the psychological refractory period and by minimizing physical effort through coarticulation. Concretely, thinking rhythm objects means practicing divisive rhythm generation in the sense of top-down, hierarchical, and impulse-driven triggering of event sequences, resulting in motion within the confines of coherent rhythm objects, e.g., as ornaments, fills, ostinato figures, etc., typically in the 0.5–5 s duration range. Also, thinking rhythm objects may enhance the coherence of output sound by focusing on the overall emergent shapes of sound objects (e.g., the overall dynamic, timbral, and pitch-related envelopes). Additionally, thinking rhythm objects means exploring rhythm as sound and motion objects in the more general framework of the mentioned typological and morphological sound object features, something that could open for more cross-cultural perspectives on rhythm.

Yet, thinking rhythm objects entails some substantial challenges for future research. Firstly, there is the need to make sound-producing body motion an integral component in all kinds of rhythm research, not only in research concerned with entrainment, and secondly, to make a critical assessment of inherited Western concepts that tend to infiltrate ways of thinking rhythm as something primarily concerned with notation-related elements such as durations, meter, and metrical grids. Furthermore, thinking rhythm objects will require extensive investigations of sound-motion relationships, including developing means for correlating low-level acoustic features with more high-level typological and morphological features in analysis tools, e.g., with the *MIRtoolbox* (Lartillot and Toiviainen, 2007), and using such tools to study larger collections of rhythm objects (Godøy, 2021a). Also, we need more detailed motion capture data on sound-producing body motion to tell us more about coarticulation and posture-based motor control, as well as synced electromyographic data to tell us more about the corresponding muscular activity. Last but not least, thinking rhythm objects will require exploring intermittency in musical experience, including working toward a more fine-tuned distinction between the different timescales involved in rhythm generation and perception.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A trio of biological rhythms and their relevance in rhythmic mechanical stimulation of cell cultures

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The primary aim of this article is to provide a biological rhythm model based on previous theoretical and experimental findings to promote more comprehensive studies of rhythmic mechanical stimulation of cell cultures, which relates to tissue engineering and regenerative medicine fields. Through an interdisciplinary approach where different standpoints from biology and musicology are combined, we explore some of the core rhythmic features of biological and cellular rhythmic processes and present them as a trio model that aims to afford a basic but fundamental understanding of the connections between various biological rhythms. It is vital to highlight such links since rhythmic mechanical stimulation and its effect on cell cultures are vastly underexplored even though the cellular response to mechanical stimuli (mechanotransduction) has been studied widely and relevant experimental evidence suggests mechanotransduction processes are rhythmic.

KEYWORDS

biological rhythms, cellular rhythms, rhythmic mechanical stimulation, cell cultures, tissue engineering, regenerative medicine

Introduction

Rhythm is one of the most basic and important elements in music. It usually has a repetitive structure typical of rhythmic signals but is also characterized by small and large deviations from that structure. Accordingly, we think of rhythms as ordered patterns in time. The importance of rhythm in music is comparable with that of rhythm in biological systems: rhythm in music is not trivial but one of the essential devices for musical expressions and an element that makes music "alive," and likewise, rhythm in biological systems is not only an observable phenomenon but necessary for sustaining life. As fundamental biological phenomena (Haken and Koepchen, 1991), rhythmic biological processes are related to the tendency to stay in balance between chaos and order (i.e., homeostasis; Crutchfield, 2003; Gnocchi and Bruscalupi, 2017). We contend that this rhythmic "balancing act" of homeostasis is one of the key biological elements that is insufficiently accentuated and overlooked in the research area of mechanical stimulation of cell cultures in relation to tissue engineering and regenerative medicine fields, in which providing and mimicking a dynamic *in vivo* environment for *in vitro* cell culture models is an important question.

One of the major developments in tissue engineering has been related to micro-scale structural engineering. For example, spatial variations and their effects on cell cultures have been studied extensively by using various types of technologies such as 3D culturing systems, bioprinting, and organ-on-chip designs (Kim and Hayward, 2012; Lee and Cho, 2016; Jensen and Teng, 2020; Low et al., 2021). The main advantages provided by the intricate structural designs include growing cells in various patterns and shapes and on different material stiffness (e.g., gel or PDMS), which create specific types and varying degrees of mechanical restrictions and forces on the cell cultures. As a result of such improvements, along with recent developments in stem cell technologies, it is now possible to generate organoids and mini tissues that represent the functional characteristics of the organ from which the stem cells were derived (Kratochvil et al., 2019). Optimization of the structural environment of cell culture systems is actively being pursued to advance the development of personalized medicine and drug screening (Kim et al., 2020). However, as biological processes occur spatiotemporally (Grace and Hütt, 2015), what should be as critical as optimal mechanical stimulation by structural cues (i.e., ordered patterns in space) is the optimization of temporal patterns of the mechanical stimulation (i.e., ordered patterns in time). Rhythmic stimulations have been explored, but only in a small number of areas, such as microfluidic systems used on blood vessel cells (endothelial cells; Novo et al., 2016; Yeom et al., 2017; Ortseifen et al., 2020), electrical stimulations used on cardiac cells (cardiomyocytes; Laasmaa et al., 2019), and application of cyclic tensile strain to mimic respiratory motions in lung-on-chip platforms (Huh et al., 2010).

In this article, firstly, we briefly present an overview of biological rhythms in different temporal scales. Secondly, we present a trio biological rhythm model in terms of central rhythm, internal/external rhythm, and reflex/consequential rhythm and discuss how these rhythms are interconnected to regulate homeostasis in a biological system. Thirdly, we explore selected biological and cellular rhythms with critical functions that demonstrate the trio rhythm model in human body organ systems, such as the cardiovascular system (specifically rhythms in relation to blood pressure, blood vessels, and smooth muscle cells) and the digestive system (pancreas, β-cells, and insulin secretion). Lastly, we discuss the potential relevance of the presented trio rhythm model and cellular rhythm examples in the context of rhythmic mechanical stimulation—using various types of experimental apparatuses that can generate controlled mechanical/physical forces such as compression, tension, and shear force directly on the cell cultures—of cell cultures. This article aims to shed light on the rhythmic mechanical stimulation of cell cultures as an area that deserves more consideration in terms of the design of cell culture systems and other cellular experiments in general, but not to provide exhaustive descriptions of biological rhythms or to investigate the origin of biological rhythms, which has been previously discussed in-depth in Haken and Koepchen (1991) and Glass (2001).

Rhythms in different temporal scales

The biological rhythms can be subdivided largely into three levels in terms of temporal scales. Firstly, as shown in Figure 1, ultradian rhythms refer to recurring cycles that are completed more than once per day. For example, molecular and cellular rhythms can occur within seconds to several hours (Goldbeter et al., 2012). Larger structures like cardiovascular and respiratory systems also have rhythms functioning within this scale (Haken and Koepchen, 1991). Secondly, circadian rhythms, which are studied more broadly than the other two rhythms, are recurring cycles completed daily. These rhythms are mainly activated by light and dark patterns. A generally known example would be sleep and wake cycles (Van Someren, 2000; Tähkämö et al., 2019). Thirdly, infradian rhythms refer to recurring cycles which can last longer than a day. The cycles in this time scale can last for months and years. These rhythms include menstrual cycles, human life cycles, and generations of life.

Even though these three rhythm levels are presented as independent levels, there are possible interactions between them (Laje et al., 2018). For example, ultradian rhythms may be harmonics—integer multiples of the fundamental frequency—of 24-h circadian rhythms (Zhu et al., 2018). In some cases, interactions may result in entrainment—the interaction of independent rhythmic systems—between rhythms at different time scales (Kuhlman et al., 2018). This pertains to cellular rhythms *in vivo* that involve changes in melatonin levels and sleep–wake cycles (Gnocchi and Bruscalupi, 2017). For example, one of the main factors that regulate insulin secretion rhythms in β-cells (ultradian and circadian), apart from other factors such as rhythmic inter- and intracellular calcium ion (Ca^{2+}) levels (Daraio et al., 2017), is the circadian melatonin rhythm in the body (Perelis et al., 2016). We will discuss some of these fundamental rhythms and their interrelationship in the following section.

Homeostatic rhythms

A trio of rhythms

We here illustrate biological rhythms as a trio model (Figure 2A). The three rhythms act as stimuli hierarchically, sequentially, and reciprocally depending on the context. The main objective of the trio is to maintain and regulate homeostasis in a given system. The trio model resembles the homeostatic model suggested by Modell et al. (2015). According to their model, there must be (a) sensors or receptors, (b) a control

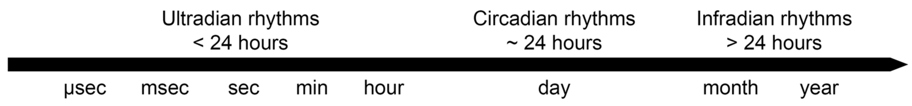

FIGURE 1
A basic illustration of three levels of biological rhythm cycles in different time scales.

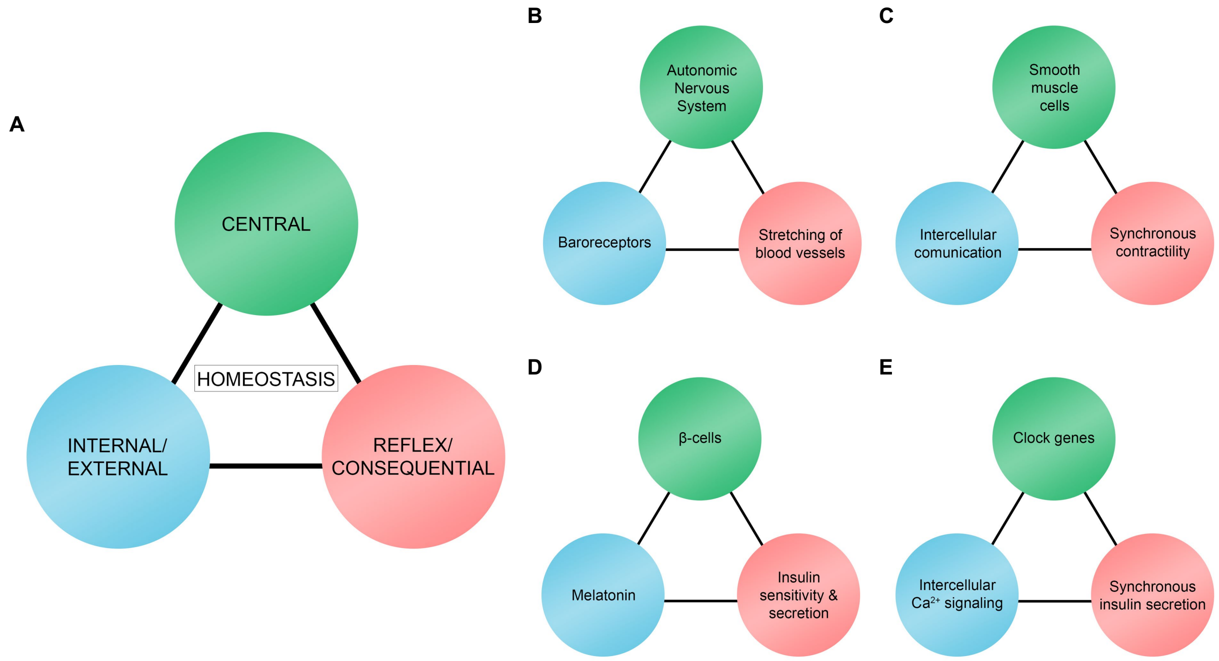

FIGURE 2
Trio model of central rhythms, internal/external rhythms, and reflex/consequential rhythms. **(A)** Homeostasis results from interactions between the trio rhythms. **(B)** Interaction between the autonomic nervous system, baroreceptors, and mechanical stretching of blood vessels to regulate and maintain blood pressure. **(C)** Interaction between smooth muscle cells, intercellular communication, and synchronous contractility of the cells to regulate and maintain rhythmic contractility of smooth muscle cells. **(D)** Interaction between β-cells, melatonin, and insulin sensitivity and secretion as one of the mechanisms to regulate and maintain glucose levels. **(E)** Interaction between clock genes, intracellular Ca^{2+} signaling, and synchronous insulin secretion as one of the mechanisms to regulate and maintain glucose levels.

center for integrating and processing received information, and (c) effectors in homeostatic systems. These are comparable to what we will refer to as central rhythms (control center), internal/external rhythms (sensors or receptors), and reflex/consequential rhythms (effectors). Although our model is similar to the one presented by Modell et al. (2015), there are some differences. In our trio model, internal/external rhythms are not always sensors or receptors. They are more comprehensive and include rhythmic phenomena (e.g., intercellular communication, Ca^{2+} signaling, and melatonin level) that have an essential role in maintaining homeostasis processes in different temporal scales. Moreover, reflex/consequential rhythms pertain more to rhythmic biological responses or phenomena that are different from effectors. Effectors are typically locations or targets that the control center sends signals to, including cells, tissues, and organs (Modell et al., 2015).

In our model, central rhythms are often coming from a specific central location [e.g., Autonomic Nervous System (ANS), smooth muscle cells, and pancreatic β-cells in our examples, which are discussed in the next section] where information is gathered, integrated, and processed. Some typical examples of central rhythms can be the brain, the nervous system, and the nucleus of the cells. Central rhythms are also rhythmic biological phenomena that play a central role in the trio, such as the clock genes regulating synchronous insulin secretion in β-cells.

Central rhythms receive information from and work synchronously with internal/external rhythms. Internal rhythms are endogenous (located or generated within the location of the central rhythms), such as intercellular communication within the group of smooth muscle cells (Figure 2C) and intracellular Ca^{2+} signaling in β-cells (Figure 2E). External rhythms are exogenous (located or generated outside the central rhythms), such as baroreceptors (Figure 2B) and melatonin (Figure 2D) that are located and generated, respectively, outside the location of the central rhythms. Internal/external rhythms signal the central rhythms of the changes occurring in their immediate environment. Internal/external rhythms are often used as experimental variables that are manipulatable such as levels of melatonin (Pourhanifeh et al., 2020) and Ca^{2+} (Cavieres-Lepe and Ewer, 2021), and electrically activated baroreceptors (Tohyama et al., 2020).

As a result of interactions between central and internal/external rhythms, reflex/consequential rhythms take place. They are either negative or positive deterministic results of the interaction between the first two rhythms. For example, these rhythms are shown through stretching of blood vessels to maintain blood pressure homeostasis (Figure 2B; reflex), enhanced or activation of synchronous smooth muscle cells contractility (Figure 2C; consequential), and increased insulin sensitivity and secretion in β-cells (Figures 2D,E; consequential and reflex respectively). However, they can also interact with other rhythms to create a feedback loop. For instance, the stretching rate of the blood vessel walls keeps baroreceptors updated (Figure 2B).

The three rhythms have their unique rhythmicity and they constantly interact. This is another point that we agree with the model given by Modell et al. (2015), where the signal flow is perpetual. The interactions result in rhythms that are balanced (not chaotic but not rigidly regular) observed as homeostasis in healthy biological systems.

What is interesting is that the three homeostatic rhythms may be interconnected in a broader network of trio rhythm models at different temporal scales. For example, Figures 2B,C are linked in a way that the smooth muscle cells (central rhythms in Figure 2C) are located within blood vessels (reflex/consequential rhythms in Figure 2B) as a sub-rhythmic component and Figures 2D,E are linked in a way that the clock genes (central rhythms in Figure 2E) are located within β-cells (central rhythms in Figure 2D).

In the following section, we look into selected examples of vital rhythmic phenomena in human organ systems. These examples show that taking rhythms and their interplay into consideration provides a holistic perspective of the biological rhythmic system. All three rhythms in the trio must be continuously and simultaneously active to maintain balance, and each set might be coupled to another within and across different spatial and temporal scales. Thus, the pattern may exist regardless of the size of the system, such as the human body, organ systems, or cells.

Cardiovascular rhythms

Heart rate is one of the rhythmic biological phenomena in the human body that are noticeable and crucial for sustaining life (Thaulow and Erikssen, 1991). In the regulation process of heart rates and blood pressure, baroreceptors are one of the components of the cardiovascular system that play an important role. Baroreceptors are sensors that detect mechanical properties of blood vessels that can be divided into two types: high-pressure arterial and low-pressure volume receptors (Armstrong et al., 2021). Both subtypes are stimulated by the stretching of blood vessel walls and transmit nerve impulses rhythmically to the ANS (Suarez-Roca et al., 2019; Armstrong et al., 2021). As a result of the rhythmic systole and diastole of the heart, blood vessels rhythmically and passively stretch to accommodate the pulsatile blood flow (Camasão and Mantovani, 2021). For example, when the stretching rate of the blood vessels is increased, the impulse firing rate of the baroreceptors will also be higher. Consequently, stimulation of the nucleus tractus solitarius region in the brain stem will lead to increased inhibition of cardiac output (i.e., decreased blood volume and pressure). Thus, a negative feedback loop is created that lowers the stretching rate of the blood vessel walls (Armstrong et al., 2021). This perpetual rhythmic process is called the baroreceptor reflex (Armstrong et al., 2021). Blood pressure is maintained and regulated (homeostasis; Figure 2) through interaction between the ANS (central rhythm), baroreceptors (external rhythm), and blood vessels (reflex rhythm). This interaction is one of the main components that make up the rhythmicity of the cardiovascular system. The rhythmic balance in this particular system is vital. Baroreceptors may influence blood pressure variability, and their decreased function is related to severe medical conditions such as hypertension (Tohyama et al., 2020; Ziegler, 2021).

In this model, mechanical changes of blood vessels (reflex rhythm) are due to continuous dynamic changes in blood flow depending on the blood pressure and volume that generates distension pressure on the vessel walls (Anwar et al., 2012). Apart from the baroreceptor reflex, evidence suggests that the communication between single cells is also important for synchronous rhythmic contractility of the blood vessels.

Blood vessels are a multilayered structure consisting of inner (tunica intima), middle (tunica media), and outer (tunica adventitia) cell layers (Tucker et al., 2021). Smooth muscle cells are found in the middle layer and contribute to the strength and contractility of blood vessels (Anwar et al., 2012). Interestingly, blood vessels display rhythmic activities when nerve signaling has been blocked (denervation; Siegel et al., 1991). It has been shown that this autorhythmic behavior of smooth muscle cells is regulated by intercellular communication (Koepchen, 1991; Siegel et al., 1991). This is achieved through gap junctions which are channels that permit the transfer of ions and small molecules between cells (Ross and Pawlina, 2003). Through the gap junctions, the levels of Ca^{2+} are synchronized between cells, thus resulting in autorhythmic activities (Slovut, 2004). When the gap junctions are chemically inhibited, the rhythmic activities decrease substantially (Slovut, 2004).

Taken together, a rhythmic phenomenon arises from the interaction between smooth muscle cells (central rhythm), intercellular communication (internal rhythm), and synchronization (consequential rhythm) that results in a continuation of rhythmic activities and possibly contributes to the entire cardiovascular rhythms (homeostasis; Figure 2C).

Pancreatic rhythms

The pancreas is part of the digestive organ system in the human body formed around weeks 4 and 5 of gestation (Pandol, 2010), and it consists of glands that can be largely divided into two components: exocrine and endocrine glands (Netter, 2011). Although the pancreas has been studied for many years—possibly since ancient times (Ceranowicz et al., 2015)—rhythmic activities, such as more ribosome synthesis during the day in the exocrine part of the organ, were observed and reported only a few decades ago (Volkl and Poort, 1983). Subsequently, more evidence has been accumulating to support that the pancreas is a rhythmic system. In particular, there has been growing interest in understanding more about possible correlations between circadian rhythms and core activities in the endocrine of the pancreas (e.g., insulin production and secretion), which are related to diseases such as diabetes (Marcheva et al., 2010; Sadacca et al., 2011; Vieira et al., 2013, 2014; García-Costela et al., 2020; Seshadri and Doucette, 2021).

In the pancreas, the exocrine glands help to break down nutrients by producing pancreatic enzymes, whereas the endocrine glands produce hormones, which enter directly into the bloodstream, including glucagon and insulin, to regulate the blood sugar level (Edlund, 2002). In endocrine glands, specialized groups of cells are found. These clusters, also known as the islets of Langerhans, mainly consist of four different cell types: α-, β-, δ-, and pancreatic polypeptide (PP) cells (Zhong and Jiang, 2019). Among these cells, β-cells take up the most mass of an islet (60–80%; Edlund, 2002), and they are responsible for controlling blood glucose levels by secreting hormones (i.e., insulin) in the bloodstream. Although the β-cells start to form in the early gestation stages, glucose-stimulated insulin secretion is insufficient in β-cells in neonates (Seshadri and Doucette, 2021). β-cells continue to develop during the perinatal period and show rhythmic activities only after birth.

Among various intra- and extracellular factors that are involved in the rhythmicity of β-cells (Heart and Smith, 2007; Perelis et al., 2016), rhythmic stimulation and entrainment to fasting-feeding cycles and the activation of specific circadian clock genes (*ARNTL*, *PER*, and *CRY*) may be critical factors for the postnatal maturation of β-cells (Alvarez-Dominguez et al., 2020; Seshadri and Doucette, 2021). It has been shown that the deletion of *ARNTL* (also known as *BMAL1*) inhibited the complete maturation of β-cells in rodent models (Rakshit et al., 2018). Moreover, inhibiting circadian clock genes reduced glucose-stimulated insulin secretion in β-cells even in fully matured isolated islets from both rodent and human models (Perelis et al., 2016; Saini et al., 2016). Therefore, internal and external rhythmic stimulation and entrainment of β-cells are essential for insulin secretion both in immature (during the perinatal period) and mature cells.

As an external rhythmic stimulation, the circadian rhythmic variation in melatonin protein level plays a crucial role in regulating insulin sensitivity and secretion by β-cells. Melatonin is also referred to as *Zeitgeber*, the German word for "time giver" (Pandi-Perumal et al., 2006). It is produced and secreted predominantly from a small endocrine gland in the brain called the pineal gland (Pandi-Perumal et al., 2006). However, other parts of the human body, such as the retina and skin, can also produce melatonin (Srinivasan et al., 2009). As accumulating evidence shows that circadian rhythm is an important factor in type 2 diabetes, although further investigation is necessary, it has been hypothesized that melatonin may have a therapeutic property in treating type 2 diabetes (Sharma et al., 2015). This is in line with the results from separate experimental studies. For example, treating isolated islets from rodents with melatonin overnight to mimic an *in vivo* environment promoted subsequent insulin sensitivity and secretion the following morning (Kemp et al., 2002). In a separate experimental study, a similar relationship between insulin secretion and melatonin in human type 2 diabetic patients was found: patients with decreased insulin secretion and glucose tolerance had reduced melatonin productions (Pourhanifeh et al., 2020). In this specific context, homeostatic interaction arises between β-cells (central rhythm), melatonin (external rhythm), and insulin sensitivity and secretion (reflex rhythm), which is one of the mechanisms that leads to the constant maintenance of glucose level (homeostasis) in the human body (Figure 2D).

Aside from extracellular rhythms involved in insulin secretion, such as melatonin rhythms, isolated β-cells show cell-autonomous rhythms by maintaining and regulating the rhythmic insulin secretion independently (Pulimeno et al., 2013; Perelis et al., 2015). This endogenous rhythmicity is known as basal insulin secretion (Saini et al., 2016). Basal insulin secretion is only between 0.5 and 1.0 units per hour and seems insignificant compared to the total amount of about 40 units of insulin secreted in an adult in a day (Ramchandani et al., 2010). However, basal secretion occurs continuously during the fasting periods throughout the day and accounts for approximately 50% of the total daily insulin secretion (Ramchandani et al., 2010). In *ex vivo* and *in vitro* models of the pancreatic islets, master circadian clock genes called *CLOCK* and *ARNTL* regulate synchronous cell-autonomous rhythms (Perelis et al., 2015; Saini et al., 2016). These clock genes regulate intracellular Ca^{2+} signaling pathways; the disruption of normal functions of *ARNTL* results in the inhibition of intracellular Ca^{2+} rhythms (Cavieres-Lepe and Ewer, 2021). The Ca^{2+} rhythm is an essential factor in insulin secretion and at the level of individual β-cells, receptor-mediated glucose uptake generates increased levels of adenosine triphosphate (ATP), leading to membrane depolarization followed by the opening of Ca^{2+} channels. Consequently, this influx of extracellular Ca^{2+} into β-cells activates the insulin secretory machinery and release of insulin from the cells (Campbell and Newgard, 2021). Synchronized rhythmic insulin secretion from a group of β-cells within an islet is mediated by Ca^{2+} flux through the gap junction channels that connect adjacent β-cells (Daraio et al., 2017; Idevall-Hagren and Tengholm, 2020). Accordingly, there is a possible interaction between the clock genes (central rhythm), Ca^{2+}

signaling (internal rhythm), and synchronous insulin secretion (consequential rhythm) that contributes to the continuous regulation of glucose levels (homeostasis; Figure 2E).

Biological rhythms in the context of mechanical stimulation of cell cultures

Given the above, biological rhythms are regulated both endogenously and exogenously, which occur cooperatively to regulate complex biological processes and maintain homeostasis in the system. We have classified these rhythms as a trio involving central rhythms, internal/external rhythms, and reflex/consequential rhythms, and the connections between the rhythms are essential. We will now discuss the relevance of biological rhythms in the context of mechanical stimulation of cell cultures.

When mechanically stimulating cell cultures for tissue engineering and regenerative medicine, it is necessary to consider mechanical parameters, which take place in the position of external rhythms in Figure 2A, as rhythmic variables and not as "static" variables. Rhythmic mechanical stimulation of cells could be organized as micro-rhythms (milliseconds, seconds, and minutes; ultradian rhythms) and macro-rhythms (~24 h and days; circadian and infradian rhythms). Here, we discuss the importance of this consideration in relation to the fact that the cellular mechanical response and sensitivity, which take place in the position of reflex/consequential rhythms in Figure 2A, are rhythmic (Thompson et al., 2020), rapid (ion channel activation; Matthews et al., 2010), and reduced over time (aging; Yang et al., 2017).

Firstly, cellular mechanical sensitivity and response can be rhythmic. It has been shown previously that cellular clock genes can regulate mechanical cellular functions such as cell migration—directed cell movement or change of position—in fibroblasts (Hoyle et al., 2017), resulting in showing patterns in cell migration over time. One of the cellular mechanisms that is actively involved in cell migration and mechanosensing is the cytoskeleton—a cellular component that is mainly responsible for the mechanical and structural aspects of the cells (Dominguez and Holmes, 2011). The dynamic structural alterations of F-actin filaments—a subcomponent of the cytoskeleton—in the form of lamellipodia and filopodia drive the migration at the cell front (Krause and Gautreau, 2014). Interestingly, the dynamics of F-actin filament formation can also be rhythmic. This is evident through the rhythmic intracellular expression of cofilin (Hoyle et al., 2017), a protein that regulates actin dynamics (Bravo-Cordero et al., 2013). Another example of rhythmic activities of the cytoskeleton is the fluctuating rate of wound healing which exhibits circadian rhythms where wounds (fibroblast cell cultures, skin wounds in rodents, and burn injuries in humans) are healed faster during the daytime (Hoyle et al., 2017). Furthermore, Ihara et al. (2017) illustrated that clock genes, such as *CLOCK* and *ARNTL*, can regulate the mechanosensing of the mucosa in the bladder of rodents. Healthy rodent models showed rhythmic expression of the mechanosensors, *Connexin26* (*Cx26*) and vesicular nucleotide transporter (*Vnut*), in the mucosa, which is more active during the day than at night. The disruption of the clock genes resulted in disturbed rhythmicity of the mechanosensing of *Cx26* and *Vnut* and showed an abnormally sensitive bladder during the night (Ihara et al., 2017).

Secondly, cellular sensitivity and response to mechanical stimulation can be rapid. In the process of fast cellular mechanosensing, integrins—transmembrane proteins that mediate the adhesion of cells to the extracellular matrix—play a central role (Chen et al., 2017; Martino et al., 2018). Integrins are also essential components of the focal adhesion (FA) points—multiprotein complexes that link the extracellular matrix to the actin filaments of the cytoskeleton (Wu, 2007). Generally, mechanotransduction—intracellular conversion of sensed mechanical stimulus into electrochemical signals—of integrins occurs within 500 ms after the cells were mechanically stimulated (Strohmeyer et al., 2017). However, it has been shown that the initiation of integrin-mediated intracellular Ca^{2+} influx happens as prompt as four milliseconds after mechanical stimulation was applied directly to the integrins, although the Ca^{2+} influx only peaked around 300 to 400 ms after the mechanical stimulation (Matthews et al., 2010). Moreover, integrin-mediated activation of the FA protein *SRC*—a signaling protein involved in cellular processes like migration, division, and differentiation—has been shown to take around 300 ms (Na et al., 2008). These dynamic and fast-responding cellular mechanisms are closely interrelated with cellular rhythms. For instance, *NR1D1*—a circadian rhythm clock gene—regulates FA formations in fibroblast cultures (Cunningham et al., 2020). Additionally, changes in the mechanical stiffness of the microenvironment are sensed by FA complexes and can lead to both altered circadian rhythmicity in mammary and lung epithelial cell cultures (Yang et al., 2017) and changes in rhythmic Ca^{2+} signaling between smooth muscle cells (Stasiak et al., 2020).

Thirdly, rhythmicity in cells and tissues dampens with age, which has been suggested to be partially due to the stiffening of tissue (Yang et al., 2017). The stiffening of *in vivo* tissue has a significant impact on the homeostasis of the human body in general (Sherratt, 2013; Heinz, 2021; Ryu et al., 2021). By using *in vitro* models, the substrate or extracellular matrix stiffness can be altered to mimic the physiological changes observed during aging to illustrate reduced rhythmicity. Accordingly, mammary and lung epithelial cells grown in a soft microenvironment (3D culture with stiffness ~30 Pa) exhibited functional circadian rhythmicity, whereas cell cultures grown in a hard microenvironment (2D culture with stiffness >100 MPa) exhibited reduced rhythmicity (Yang et al., 2017).

Collectively, there is adequate evidence to show that cellular processes of mechanotransduction are rhythmic, and these rhythmic cellular processes may occur in different temporal scales (micro- and macro-rhythms). A deeper understanding of mechanotransduction is crucial since many diseases arise from cellular mechanotransduction defection (Jaalouk and Lammerding, 2009). The effects of micro- and macro-rhythmic mechanical stimulations have been reported in recent experimental findings. For instance, Rogers et al. reported on the effect of rhythmic mechanical stimulation using a flexible silicone growth substrate stretching at regular rhythmic intervals (the frequency of 1 Hz) on human stem cell cultures. Following cycles of 12 h of regular rhythmic stretching and 12 h resting period for three days, they demonstrated synchronization of the clock genes (*ARNTL*, *PER1*, *PER2*, and *NR1D1*) in human stem cells (Rogers et al., 2017). Moreover, Vágó et al. demonstrated the effect of rhythmic mechanical stimulation using a uniaxial compression force on chondroprogenitor cells (from chicken). The stimulation was one h/day for six days and rhythmic mechanical stimulation entrained circadian clock genes (*ARNTL*, *CRY1*, and *PER3*), leading to enhanced tissue homeostasis and histogenesis (Vágó et al., 2021). In both studies, the trio rhythm model has been demonstrated: synchronization of specific clock genes (central rhythm), rhythmic mechanical stimulation (external rhythm), and cellular responses (e.g., stem cell differentiation capability and tissue homeostasis; consequential rhythms).

The regulation of clock genes without chemical or temperature-related stimuli potentially increases the utility of tissue engineering research in terms of cell transplantation, apart from personalized medicine and drug screening, even further. In particular, a clock gene such as *ARNTL* is reported to be an important factor in the WNT signaling pathway (Guo et al., 2012), which is a crucial stem cell mechanism that initiates the differentiation process—a stem cell process when its potential is lost and forms into adult cells, for example, cardiac muscle cells or skin cells. These findings are encouraging, but it must be noted that stem cells from different locations in the body respond differently to the same type of rhythmic mechanical stimulation (Rogers et al., 2017). Therefore, more extensive studies on optimization of the rhythmic mechanical stimuli that can closely mimic *in vivo* cellular environments for cell cultures are necessary.

In particular, microphysiological systems or organ-on-chips provide a great advantage in growing and studying cellular responses in dynamic cell culture systems (Wikswo, 2014). Compared to conventional static cell culture systems, implementing cell cultures in microfluidic chip systems offers the possibility to mimic key aspects of human physiology more accurately, including rhythmic stimulation (Zhang et al., 2018). Thus, growing cells in micro-devices allow to control (magnitude and rhythmicity), mechanical forces (e.g., stretching, pulling, compression, and shear forces), chemical signaling (e.g., growth factors, hormones, and nutrients), and electrical stimulation that the cells are exposed to (Ergir et al., 2018).

Conclusion

In this article, we have classified biological rhythms using a trio model (central rhythms, internal/external rhythms, and reflex/consequential rhythms). It is imperative that all three rhythms in the trio function continuously to regulate homeostasis in a given biological system. Thus, the link between the three rhythms is important and relevant in tissue engineering and regenerative medicine as rhythmic interactions, whether in micro- or macro-rhythms, are vital in the early development of endogenous biological rhythms. This is evident through the lack of endogenous rhythms (e.g., transcriptional-translational feedback loop) in embryonic stem cells in general compared to adult stem cells (e.g., bone marrow mesenchymal stem cells; Rogers et al., 2017). For instance, circadian rhythmic patterns observed in neonates' heart rates disappear shortly after birth and return only 3 to 4 weeks later (Ardura et al., 1997). The rhythmicity observed in the early neonatal stage is presumed to be due to maternal influence and endogenous rhythmicity is fully developed only at a later stage, but there are conflicting views on whether external rhythms (e.g., light and dark cycles) have any effect on the development of circadian rhythms in neonates (Begum et al., 2006). Moreover, it has been shown previously that insulin secretion by pancreatic β-cells depends on external rhythms (e.g., fasting and feeding cycles) to develop endogenous rhythms and to be fully matured (Seshadri and Doucette, 2021). As these experimental observations illustrate, the importance of interactions between the rhythms in the entrainment and development of fully functioning biological rhythms should not be minimized.

As the name suggests, the trio rhythms are like a musical ensemble in that each rhythm is individually important, but they attentively listen and interact with one another and even with the audience to achieve a successful performance. Furthermore, as the ensemble starts to interact with other ensembles, it becomes a structure like an orchestral ensemble where the interactions between different sections of the orchestra are extremely sensitive and intricate to form some kind of homeostasis usually led by a conductor. The model is intentionally reductive and can be made more specific by exploring additional physical examples such as the seven-step model (stimulus, receptor, input, integrating center, output, effector, and response) presented by Chirillo et al. (2021). Still, we think it is also essential to try to pin down the core patterns from complex processes to get an overview and understanding of the discussed rhythms in this article at a macroscale. We hope that the trio model provides a framework that makes it possible to focus in and out of different spatial and temporal scales to get a basic but fundamental understanding of how biological, particularly cellular, rhythms function and interact with one another.

Author contributions

DK, AD, and AJ contributed to the conception of the study. DK wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The sweet spot between predictability and surprise: musical groove in brain, body, and social interactions

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Groove—defined as the pleasurable urge to move to a rhythm—depends on a fine-tuned interplay between predictability arising from repetitive rhythmic patterns, and surprise arising from rhythmic deviations, for example in the form of syncopation. The perfect balance between predictability and surprise is commonly found in rhythmic patterns with a moderate level of rhythmic complexity and represents the sweet spot of the groove experience. In contrast, rhythms with low or high complexity are usually associated with a weaker experience of groove because they are too boring to be engaging or too complex to be interpreted, respectively. Consequently, the relationship between rhythmic complexity and groove experience can be described by an inverted U-shaped function. We interpret this inverted U shape in light of the theory of predictive processing and provide perspectives on how rhythmic complexity and groove can help us to understand the underlying neural mechanisms linking temporal predictions, movement, and reward. A better understanding of these mechanisms can guide future approaches to improve treatments for patients with motor impairments, such as Parkinson's disease, and to investigate prosocial aspects of interpersonal interactions that feature music, such as dancing. Finally, we present some open questions and ideas for future research.

KEYWORDS

music, entrainment, rhythm, movement, dance, Parkinson's, predictive coding, syncopation

Introduction

In the field of musicology, the term groove was coined in the context of African-American musical genres, such as R&B, jazz, soul, disco, funk, and hip-hop, where it can refer to esthetic qualities of the music, specific rhythmic patterns, or the musicians' way of effortlessly synchronizing and interacting with each other (Senn et al., 2019; Câmara and Danielsen, 2020; Duman et al., 2021). In contrast to this multifaceted understanding, recent studies in music perception and cognition agree on a sharper definition of groove as the pleasurable urge to move one's body in relation to the rhythm of music (Madison, 2006; Janata et al., 2012; Stupacher et al., 2013; Senn et al., 2020). These different approaches to defining groove are discussed, for example, by Câmara and Danielsen (2020), who distinguish three aspects of groove: (1) a rhythmic pattern and performance, (2) a pleasurable urge to move, and (3) a state of being.

Here, we focus on the pleasurable, movement-inducing aspect of groove. In this approach, groove is genre-independent, in that every rhythmic pattern and performance evoking the pleasurable urge to move possesses the quality of groove. Although soul, disco, funk and related genres may be more likely to induce groove, the pleasurable urge to move can also be experienced while listening to rock, jazz, electronic dance music, and many other genres.

We argue that groove, when defined as the pleasurable urge to move to a rhythm, depends on a fine-tuned interplay between predictability and surprise. The predictability arises from repetitive rhythmic patterns, and the surprise arises from slight deviations from these patterns, for example in the form of syncopation. This tension represents the sweet spot of the groove experience, and is commonly found in rhythmic patterns that are simple enough for us to interpret and predict, but complex enough to keep us challenged and engaged (Vuust and Witek, 2014; Witek et al., 2014). We will use this perspective to discuss the experience of groove in body, brain, and social interactions.

Groove in body and brain

The neural mechanisms that are engaged from the moment we start to listen to music to the moment we are tapping our foot in time with the beat or start dancing, rely on the human brain's ability to integrate external stimuli with internal representations, expectations, or predictions (Koelsch et al., 2019; Pando-Naude et al., 2021). This continuous flow of stimulus-driven bottom-up information and top-down processes requires specialized neural processing, such as audio-motor coupling (Jäncke, 2012), a phenomenon driven by temporal predictions (Vuust et al., 2009; Schröger et al., 2015) that is associated with reward, pleasure, and other cognitive and emotional mechanisms (Koelsch, 2010, 2014, 2020; Koelsch et al., 2013; Salimpoor et al., 2015). How accurately we can predict a rhythm and how pleasurable a rhythm is, therefore depend, on the one hand, on an individual's long-term priors, such as listening biography, cultural background, musical expertise, dance training, and general cognitive and motor abilities, and on the other hand, on the rhythm's complexity. Both aspects are integrated in the predictive coding framework (PC), which proposes that the brain minimizes prediction errors by using Bayesian inference when comparing a real-time internal model to a given sensory input (Friston, 2005). When listening to music, this means that we constantly check and update the predictive model of a rhythm by comparing it to the actual musical input (Vuust and Witek, 2014).

Groove and predictive processing

Within the context of groove, PC has predominately been deployed to interpret the inverted U-shaped relationship between groove ratings and the degree of rhythmic complexity (Vuust and Witek, 2014; Vuust et al., 2018; Koelsch et al., 2019). Rhythmic complexity can depend on different factors, such as meter or microtiming, but is most often operationalized as syncopation, which is when notes occur on weak metrical positions, and are followed by silences on stronger metrical positions (Longuet-Higgins and Lee, 1984). The inverted U shape suggests that moderately syncopated rhythms elicit the strongest sensation of groove (Sioros et al., 2014; Witek et al., 2014; Matthews et al., 2019; Stupacher et al., 2022). Under PC, this effect arises from the fact that moderately syncopated rhythms give rise to the greatest number of strongly weighted prediction errors. Prediction errors result from a mismatch between an internally generated model—here, the beat and meter—and the sensory input (Friston, 2005). Together, beat and meter form a predictive scaffold that determines how strongly we expect a note to occur at each time point (Vuust and Witek, 2014).

Panels A and B of **Figure 1** illustrate how beat- and meter-based temporal predictions can be conceptualized as probability distributions (Large and Jones, 1999; Danielsen et al., 2019; Koelsch et al., 2019; Cannon, 2021), with their mean and spread reflecting the accuracy and certainty of these predictions, respectively. Prediction certainty determines the weight of the prediction error, that is, the degree to which it affects the metrical model. Syncopations violate meter-based predictions, and thus can introduce uncertainty into the metrical model and the subsequent predictions. Therefore, all else being equal, the degree of syncopation in a rhythm determines both the number and certainty of prediction errors. As shown in panels A and B of **Figure 1**, moderately syncopated rhythms combine a moderate number of prediction errors with a moderate degree of certainty. They therefore elicit the strongest top-down engagement to

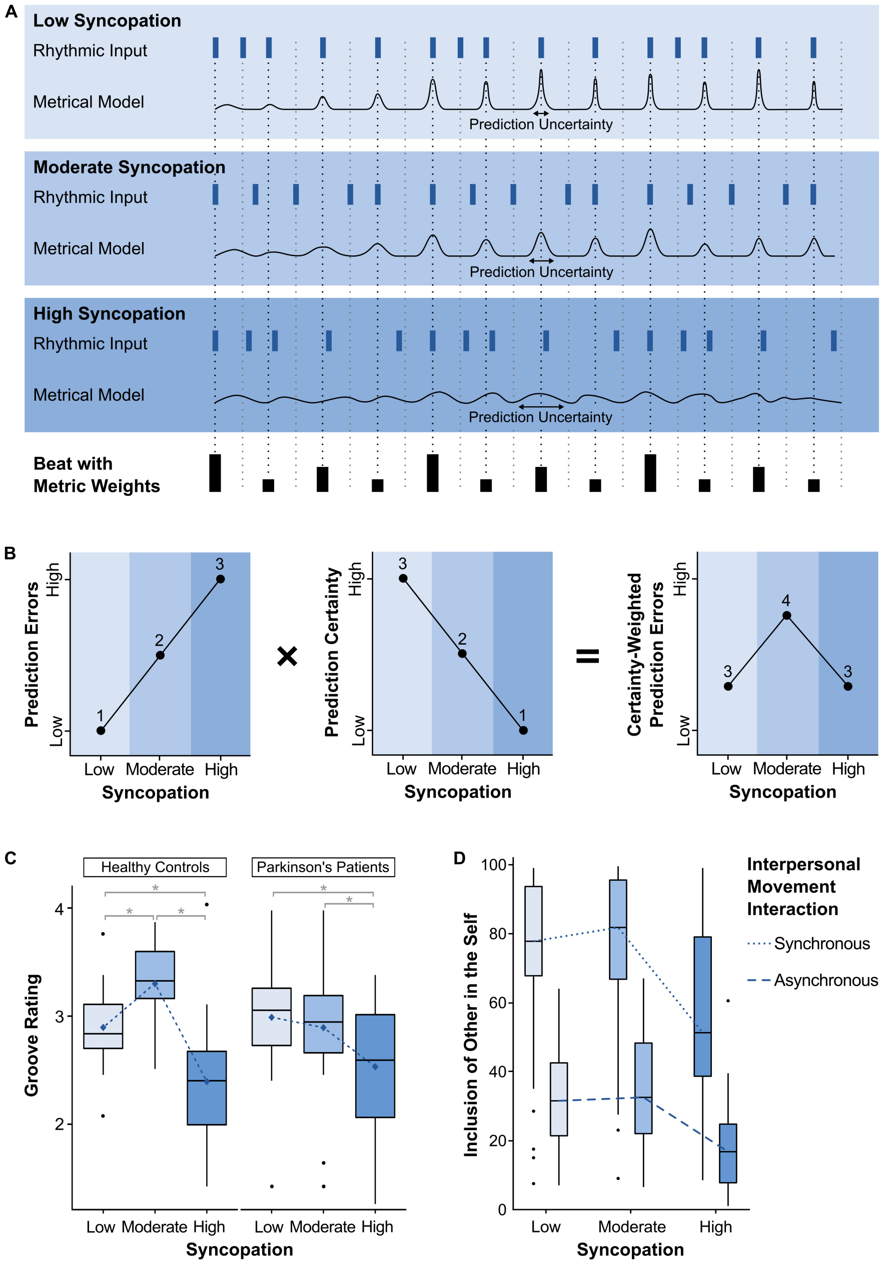

FIGURE 1
(A) Beat-based predictions, prediction uncertainty, and prediction errors for three rhythms with low, medium, and high degrees of complexity, taken from Matthews et al. (2019). Dark blue rectangles denote the onsets of the rhythms and black rectangles denote the underlying beat with the height indicating the metric weight of each beat point according to (Longuet-Higgins and Lee, 1984). The black traces represent metrical models with beat-based predictions delineated as probability distributions wherein the mean of the distribution reflects the predicted onset times, and the width of the distribution reflects the certainty of that prediction. As can be seen across the three traces, the predictions and their certainty depend on the degree of syncopation, the metric weights of each beat, and the progression through the rhythm. That is, prediction accuracy and certainty start out relatively low for all three rhythms as it takes several onsets before a beat and meter is induced. Meter-based predictions can occur for each metric level relevant to a given rhythm, and depending on musical training (Palmer and Krumhansl, 1990), however, for simplicity, only beat-based predictions at the quarter note level are shown. **(B)** The inverted U shape arises from the product of the number of prediction errors and prediction certainty. Prediction errors increase from low syncopation rhythms to high, while the degree of prediction certainty decreases. Multiplying these functions reveals that moderately syncopated rhythms elicit the greatest number of strongly weighted prediction errors. **(C)** Groove ratings in Parkinson's disease patients ($N = 24$) and healthy individuals ($N = 27$) from Pando-Naude et al. (in preparation). The inverted U-shaped relationship is shifted from moderately complex rhythms in healthy individuals, toward less complex rhythms in PD patients. Blue diamonds indicate mean values. Asterisks indicate significant differences ($p < 0.05$) in pairwise comparisons adjusted with the Tukey method. Boxplots: The centerline represents the median. The lower and upper ends of the boxes correspond to the first and third quartiles. Whiskers represent lowest and highest values within 1.5 × interquartile range (IQR) from the lower and upper quartiles, respectively. Dots represent values outside 1.5 × IQR. **(D)** The tendency of an inverted U shape in relation to the level of syncopation can also be found in social bonding with another person, as measured by Inclusion of Other in the Self (Stupacher et al., 2020).

update and maintain the metrical model, that is, to minimize further prediction errors and uncertainty.

According to PC, there are two ways to minimize prediction errors and thereby reduce uncertainty (Friston, 2003). One way is to change the model to better fit the input, either by shifting the phase of the meter, i.e., 'resetting,' to better align with the rhythm (Fitch and Rosenfeld, 2007), or switching to a different meter altogether, e.g., from a duple to a triple meter. Recent empirical and theoretical work implicates the motor system in the phase resetting and dynamic maintenance of temporal predictive processes during rhythmic auditory tasks (Morillon and Baillet, 2017; Rimmele et al., 2018). The second way to minimize prediction error is to move one's body in time with the beat (Koelsch et al., 2019). Moving to the beat results in rhythmically timed proprioceptive input that reinforces the metrical model. Therefore, by optimally challenging the predictive model, moderately syncopated rhythms lead to greater engagement of the underlying motor systems, which is experienced as an automatic urge to move.

Uncertainty reduction also engenders the pleasurable component of groove. Within PC, this uncertainty reduction, as driven by improving the correspondence between model and input, corresponds to learning. In this context, learning is thought to be inherently rewarding as it serves the innate drive for competence (Ryan and Deci, 2000) and satisfies the intrinsic motivation for information gain (i.e., curiosity; Schmidhuber, 2010; Kidd and Hayden, 2015; Friston et al., 2017; Gottlieb and Oudeyer, 2018). Therefore, organisms are intrinsically motivated to seek out and attend to activities that afford maximal uncertainty reduction, in other words "learnable activities that are just beyond [their] current predictive capacities" (Oudeyer et al., 2016, p.9). In this context, moderately syncopated rhythms elicit pleasure by maximizing the intrinsic reward derived from actively refining our predictive processes *via* covert or overt motor processes. Recent work has demonstrated a direct link between music-evoked reward and moderate levels of prediction error and uncertainty in the context of melodic and harmonic expectations (Cheung et al., 2019; Gold et al., 2019b; Shany et al., 2019). We believe that applying a similar approach to groove will be crucial to understanding why a rhythmic sweet spot has such power to move us, and to uncovering the neural mechanisms that drive this effect.

Intriguingly, the basal ganglia (BG), a set of subcortical nuclei involved in motivation and motor control, along with dopaminergic transmission within the BG, have been implicated in all of the processes discussed above, including beat and meter-based perceptual and motor timing (Schubotz et al., 2000; Grahn and Brett, 2007; Grahn and Rowe, 2009; Schwartze et al., 2011; Kung et al., 2013), music-evoked pleasure (Salimpoor et al., 2011, 2013; Gold et al., 2019a), and prediction certainty (Friston et al., 2014; Owens et al., 2018; Gershman and Uchida, 2019). This suggests that the BG and dopamine play a crucial role in groove, a perspective that is supported by a recent fMRI study linking groove ratings to activity within limbic- and motor-associated BG nuclei (Matthews et al., 2020). Based on these results, the authors proposed a theoretical model wherein beat-based temporal predictions and the associated reward are integrated in the BG *via* parallel striato-cortical loops, particularly the limbic, motor, and associative loops (Alexander et al., 1986; Obeso et al., 2008).

Groove and Parkinson's disease

One way to test the role of the BG and dopamine in groove is to compare Parkinson's disease (PD) patients with healthy controls. PD results from dopaminergic dysfunctions in the BG caused by neuronal degeneration of the substantia nigra pars compacta (SNc). Such dopaminergic depletion disrupts disinhibitory mechanisms between the BG and the motor thalamus, altering the fine-tuning between initiation and suppression of the activity in the motor loop, and giving rise to the characteristic motor symptomatology. In terms of groove, a recent study showed that the inverted U-shaped relationship between rhythmic complexity and pleasurable desire to move is shifted from moderately complex rhythms in healthy individuals, toward less complex rhythms in PD patients, who seem to prefer little incongruence between the internal predictive model and the stimulus (**Figure 1C**; Pando-Naude et al., in preparation). Notably, PD patients do not show an overall reduction in groove ratings, suggesting that PD does not reduce the overall urge to move to the rhythm, but only alters which types of stimuli elicit these responses, potentially as a function of altered predictive processes.

Research into auditory-motor activity and the neural correlates of rhythm perception (Schubotz et al., 2000; Grahn and Brett, 2007; Chen et al., 2008; Bengtsson et al., 2009; Grahn and Rowe, 2009; Grahn, 2012) has led to new approaches for developing movement therapies. Rhythmic auditory stimulation improves motor deficits in patients with PD by providing a regularly-timed cue, such as a metronome, with which patients can synchronize their gait (Thaut et al., 1996; Pau et al., 2016; Dalla Bella et al., 2017; Lei et al., 2019). However, the low rhythmic complexity of the metronome may restrict the method's benefits (Dalla Bella et al., 2015; Cochen De Cock et al., 2018). In contrast, ecologically valid stimuli incorporating both rhythmic and harmonic elements may lead to a richer set of predictions, potentially promoting better guidance for temporal models of movements (Vuust et al., 2014). Dancing might offer an even more ecologically valid and rich PD intervention that can improve gait symmetry, decrease dual task costs (Fontanesi and DeSouza, 2021), and reduce disease severity (Krotinger and Loui, 2021). As discussed above, moderately complex stimuli are likely to increase engagement of motor timing and reward processes involving the BG (Matthews et al., 2020), potentially boosting motor benefits by increasing dopaminergic signaling in these nuclei (Salimpoor et al., 2013; Hansen et al., 2017; Matthews et al., 2020). A challenge for future research on music-supported movement and dance therapies is to investigate whether an individual PD patient's preference for a certain level of rhythmic complexity may depend on the progression of the disease. One objective of future studies could therefore be to find individualized sweet spots of rhythmic complexity for PD patients with different levels of auditory, sensorimotor, and timing deficits.

By comparing the experience of groove in PD patients and healthy controls, we contribute to our understanding of the underlying neural mechanisms linking temporal predictions, movement, and reward. In turn, a better understanding of these mechanisms can guide future approaches to better treat motor deficits, and improve the quality of PD patients' personal and social life.

Groove in social interactions

When people come together to listen to or make music, the level of rhythmic complexity that hits an individual's sweet spot for an optimal groove experience depends on their biology and cultural background. In his interviews with musicians, Charles Keil noted that "each person has a unique feel for time and that bringing different or discrepant personalities together generates different kinds of groove" (Keil, 1995, p.8). Keil calls the intentional deviations in timing that result from the constant relating and negotiating between players *participatory discrepancies* and hypothesizes that they are necessary to make music involving and socially meaningful (Keil, 1987, 1995). This type of involvement may be especially strong with syncopated rhythms, as performers—live or recorded—can invite listeners and dancers to participate in the relating and negotiating by filling in the gaps in the syncopated rhythmic structure (Witek, 2017).

Groove and dance

Music and dance are so intertwined that some cultures do not distinguish between them (Haugen, 2021), and groove is an important element in understanding this connection (Foster Vander Elst et al., 2021). Fitch argues that "if we want to understand the rhythmic origins of a musical style, it behooves us to know how contemporaries would have moved to that music" (2016, p.6). Dance is also an intrinsically social activity that encourages social bonding (Tarr et al., 2014, 2015; Launay et al., 2016). Indeed, compared to synchronizing movements in silence or with a metronome, music can increase social closeness with another person (Stupacher et al., 2017, 2021). Furthermore, the number of people who can easily converse together is usually limited to four (Robertson et al., 2017), but much larger groups regularly form when people dance together. It has therefore been posited that the prosocial and emotional effects of group music-making and dancing might be evolutionary adaptations (Huron, 2001; Loersch and Arbuckle, 2013; Trainor, 2015).

From the perspective of predictive processing, beat and meter are mental models that can be shared by all dancers and musicians in a group. If the models are alike, i.e., 'distributed' across dancers, they facilitate synchronous movements, which in turn can promote shared affective experiences (Witek, 2019). In addition to strict synchronization, dance is commonly also concerned with the expression of creativity and "individual flourish" (Merker et al., 2009) within the framework of a mental model of beat and meter. When dancing together, moderately syncopated rhythms may provide the ideal stimulus for facilitating both united synchrony and individual creativity. On the one hand, moderately syncopated rhythms include enough notes on strong metrical positions that allow the dancers to form shared beat- and meter-based predictions. On the other hand, these rhythms also include notes on weak metrical positions, "injecting energy" into upbeats (Fitch, 2016), and pauses on strong metrical positions, inviting dancers to fill the "open spaces" with creative movements (Witek, 2017). Therefore, moderately syncopated rhythms may provide a common temporal framework within which dancers can share basic movements, but also inspire each other with individual creative movements—a combination that may facilitate the experience of shared emotions. This perspective is supported by a recent study suggesting that social bonding with another person tends to follow an inverted U shape in relation to the degree of syncopation (**Figure 1D**; Stupacher et al., 2020). A certain level of complexity is also preferred when playing the Mirror Game, in which two individuals move as coordinated and synchronously as possible (Ravreby et al., 2022). Ravreby and colleagues found that social bonding with the partner increases with increasing interpersonal synchronization, but also with movement complexity. Although simple movements benefit from greater synchronization accuracy, more complex and novel movements may be introduced to keep each other interested and engaged.

Both dancing and performing music in a group involve moving in time together. However, dance and music improve sensorimotor integration in both shared and unique ways (Giacosa et al., 2016, 2019; Karpati et al., 2017). For example, musicians perform better than dancers when synchronizing finger taps with auditory rhythms, whereas expert dancers perform better than musicians when imitating whole-body dance movements (Karpati et al., 2016). To date, most of the research investigating long-term-priors, such as the effects of expertise and listening biographies on groove is concerned with effects of musical training and preferred musical style. Musicians show greater neural activity in motor-related areas of the brain when listening to high-groove music (Stupacher et al., 2013), and a more pronounced U-shaped relationship between groove ratings and degree of syncopation (Matthews et al., 2019, 2022). Additionally, Senn and colleagues note that "listeners' susceptibility to bodily entrainment as a response to music is strengthened when the music agrees with their taste" (Senn et al., 2018, p.26). The rare studies on groove that have tested the effect of dance experience are limited to behavioral paradigms, which suggest that participants with greater frequency and enjoyment of dancing experience more groove (Witek et al., 2014; Matthews et al., 2019). However, while both of these studies differentiate sharply between musicians and non-musicians based on years of training, the differentiation between dancers and non-dancers is less clear. Given the unique ways in which dancing affects whole-body sensorimotor integration (Giacosa et al., 2016, 2019), it would be beneficial for future work on the experience and neurophysiology of groove to use similarly sharp selection criteria for dancers. Groove is a universal phenomenon, but some effects may be more pronounced in experienced dancers, who are experienced in using their entire bodies to actively and creatively engage with music.

Conclusion

In dance, music making, and music listening, groove research can help us to better understand the interactions between temporal processing, movement, social behavior, and pleasure in both the general population and individuals with motor impairments. Elucidating the neural mechanisms underlying groove—especially the role of the basal ganglia—will contribute to our understanding of the integration of motor driven predictive timing and reward processes more generally.

One open question is how the experience of groove differs when comparing individual versus collective situations of music listening or dancing. It is also unclear how the type of rhythm-related movements affects groove experiences. Future research could, for example, compare whole body engagement in dance with specific movements of particular body parts, such as finger tapping or playing an instrument. Another future direction of groove research could be to investigate activities outside the field of music. Senn and colleagues define the verb to groove as "playing music together in an effortless and rhythmically well-coordinated manner" (Senn et al., 2020, p.46). This use of groove can also be applied to other coordinated interindividual activities, such as playing team sports, verbal communication, or gestural mimicking. Based on the relationship between rhythmic complexity and groove in music, it could be expected that in these activities rhythmic complexity follow similar U-shaped functions when measuring pleasure and engagement.

Data availability statement

The original contributions presented in this study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

JS: conceptualization and writing – original draft, review and editing. TEM, VP-N, and OVFE: writing – original draft, review and editing. PV: writing – review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Synchronization between music dynamics and heart rhythm is modulated by the musician's emotional involvement: A single case study

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In this study we evaluated heart rate variability (HRV) changes in a pianist, playing in a laboratory, to investigate whether HRV changes are guided by music temporal features or by technical difficulty and/or subjective factors (e.g., experienced effort). The pianist was equipped with a wearable telemetry device for ECG recording during the execution of 4 classical and 5 jazz pieces. From ECG we derived the RR intervals series (tachogram), and, for each piece, analyzed HRV in the time (RR, RMSSD, Stress Index) and frequency domains (Total spectral power) and performed non-linear analysis (Multiscale Entropy). We also studied the correlation (Pearson) between the time course of music volume envelope and tachogram. Results showed a general reduction of parasympathetic and an increase of sympathetic activity, with the greatest changes during the classical pieces execution, the pianist appraised as more demanding than the jazz ones. The most marked changes occurred during the most technically/emotionally demanding piece, and correlation analysis revealed a negative association between music volume envelope time course and tachogram only for this piece, suggesting a modulation of the limbic system on the synchronization between heart rhythm and music temporal features. Classical music was also associated with the increase of entropy (1st scale) with respect to rest, indicating its effectiveness in driving flexible, healthy, heart dynamics. In conclusion, HRV seems modulated not only by the music temporal features, but also by the pianist's emotional involvement, which is greatly influenced, in a non-trivial manner, by the technical demands and musician expertise.

KEYWORDS

musician, live performance, music-heart synchronization, emotions, technical demands

Introduction

A musical performance in front of an audience is a highly challenging situation and, thus, performance success or failure depends on the ability of the musician to manage physical, cognitive and emotional demands. The psychophysical effort is typically accompanied by autonomic changes, such as increased heart rate and blood pressure and a decreased heart rate variability (HRV) that are sustained by an increased sympathetic activation (Williamon et al., 2013).

In a previous study (Sebastiani et al., 2020) we evaluated changes in heart autonomic modulation in a skilled pianist, during the execution of a live concert. Throughout the whole musical session, it was observed a general trend, in particular, a decrease of HRV parasympathetic indices and an increase of the sympathetic ones. Nonetheless for each musical piece, the dynamics of the autonomic modulation were very different. This piece-specific modulation could be accounted for by the different effort required to play pieces with different technical difficulty and/or by the peculiar expressive/emotional features of each performance. Interestingly, we also found a negative correlation between the temporal dynamic of music volume envelope that is a measure of the time course of sound intensity, and the series of beat-to-beat RR intervals, which could be interpreted as the expression of music-heart rhythm synchronization (Sebastiani et al., 2020).

In the present single-case study, carried out in a laboratory setting, we evaluated HRV changes in a pianist while playing, before a small audience, two different types of music, namely classical and jazz, characterized by different levels of technical difficulty. The pianist was not a professional musician and possible motor learning effects were unlikely since the pianist knew the played musical pieces but no in-depth training of them had preceded the live performance. The rationale of the present study was that music features and also music technical difficulties could interfere with the emotional status of the pianist while playing music. Thus, we explored whether HRV changes are guided by specific music features or rather by music technical difficulty and/or subjective factors (e.g., experienced effort).

Materials and methods

Participant

The music player was a young healthy man of 35 age. He was not a professional musician, but he had studied classical piano and regularly played jazz in public as well. The experiment consisted of a single music session performed in a laboratory setting with the experimenters and a few more people as the audience, for a total of nine persons. This study was approved by the Committee on Bioethics of the University of Pisa (Review No. 15/2021) and the participant signed the informed consent to participate in the study.

Experimental protocol

The pianist played 9 pieces with a MIDI keyboard connected to a computer. The interval among the musical pieces was 2 min. Four pieces were excerpts from the "Das Wohltemperierte Klavier, I, of J.S. Bach, and the other 5 were jazz pieces (see **Supplementary Table 1**). The music player practiced both classical and jazz pieces in the 4 weeks proceeding the experimental session for a total of about 16 h.

At the end of the performance the pianist was asked to score the technical difficulty of each piece as well as the subjective, experienced difficulty in playing each piece in a 5-points Likert scale (1 = very easy, 5 = very difficult). The music player was equipped with the wearable telemetry device (Bioharness 3 Zephyr) for recording of ECG (sampling rate 250 Hz) during a relaxation period (5 min) preceding the performance and during the execution of the 9 music pieces.

Heart rate variability analysis

We analyzed ECG by means of Kubios HRV Premiums software, which is nowadays a standard validated tool that allows the ECG analysis from the artifact removal to the evaluation of time, frequency and non-linear indices[1]. The signals were controlled for artifacts and ectopic beats were removed by means of a threshold-based correction as well as through a validated automatic artifact correction method (Lipponen and Tarvainen, 2019). When necessary, beat detections were corrected manually. We derived the beat-to-beat RR intervals, thus obtaining the RR time series (tachogram), and carried on the analysis of HRV in time [mean RR, root mean square of successive (RR) differences (RMSSD), Stress Index (SI)] and frequency domains (Total spectral power, TP). This was done in order to evaluate the autonomic changes associated with the different musical pieces. RMSSD is an index of parasympathetic activity within the autonomic regulation and is calculated as the square root from the sum of squared differences of sequential RR intervals. RMSSD normal values are usually within the range of 20–50 ms and the higher RMSSD, the more active parasympathetic regulation. The evaluation of SI is based on the histogram of RR interval distribution. Specifically, it is computed as the square root of the ratio of histogram height to width (Baevsky and Chernikova, 2017) and its increment reflects sympathetic tone rise.

TP is a standard measure of HRV in the frequency domain (see text footnote 1) and is evaluated by means of the square

1 https://www.kubios.com/hrv-analysis-methods/

of the Fast Fourier Transform (FFT) applied to RR signal. Following standard HRV frequency analysis, we estimated the TP in the 0.003–0.4 Hz band. TP is highly correlated with the square root of the standard deviation of the RR intervals (SDNN) and has been interpreted as a marker of stress (Baevsky and Chernikova, 2017; Shaffer and Ginsberg, 2017).

We also carried out non-linear analysis of the tachogram. In fact, previous studies indicated that tachograms fluctuate in a complex way, and suggested that non-linear methods, such as sample entropy (SE) are able to describe changes in HRV that cannot be caught by linear methods (Shekatkar et al., 2017; Solís-Montufar et al., 2020). In short, SE applied to HRV provides information about the predictability of the fluctuations in successive RR intervals, which reflects the complexity of HRV regulatory mechanisms: large values indicate low predictability of fluctuations and/or high randomness, while small values indicate high predictability and regularity (smoothness) of the RR series. In the present study we applied Multiscale Entropy (MSE), which is an extension of Sample entropy (SE) to multiple time scales of measurement and allows to quantify the degree of predictability and irregularity over a range of coarse-grained scales (Costa et al., 2002, 2005).

Analysis of the correlation between music envelope time course and tachogram

In order to investigate the possible association between specific music temporal features and heart rate we derived from the MIDI recording of the performance the time course of the music volume envelope of each piece, which is a measure of the temporal dynamics of music loudness. We measured music volume envelope by means of the Root Mean Square (RMS) which allows calculating the average of audio signals over a period of time. The signal amplitude is squared, averaged over a period of time (0.5 s), then the square root of the result is calculated. The resulting value is proportional to the effective power of the signal.

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{1}^{N}|X_n|^2}$$

Sampling Rate = 44,100

Segments duration = 0.5 s

*N = 0.5*44,100 = 22,050*

We then studied the correlation (Pearson Correlation analysis) between RMS and the RR time series recorded during each piece. We set the correlation coefficient cutoff at $\pm$ 0.3. We analyzed the statistical significance of the correlation by means of Student's t-test. Significance was set at $p < 0.05$.

Results

Following the structured interview, the pianist evaluated the classical pieces as technically more difficult than the jazz ones (see **Supplementary Table 1**). Also, he reported a subjective greater difficulty in playing two classical pieces, namely the 2nd scored 4 and the 4th scored 5, with respect to all the other pieces (score 3) (see **Supplementary Table 1**). Besides, the pianist reported a very strong emotional involvement ("I felt under pressure"; "I was afraid to make mistakes") while playing the 4th classical piece, which he defined as "his cursed piece."

Figure 1 shows the mean value of RR, RMSSD, Stress Index and Total power recorded in the pianist during the basal period and each of the 9 pieces.

As can be observed a decrease of mean RR and of RMSSD was found in the music session with respect to the basal period. However, the reduction in mean RR and RMSSD was greater during the classical music sub-session than in the jazz one. An increase of SI was also found during the music session with respect to the basal period, with higher values during the classical music sub-session than the jazz one. The highest level of SI occurred during the performance of the 4th classical piece (3.6 times greater than the basal value).

During the music session, a remarkable reduction of TP, that was more pronounced during the classical music sub-session, was observed (**Figure 1**). Indeed, TP recovery occurred during the jazz session in which TP mean value was similar to the basal one in the last jazz piece.

Figure 2 shows the results of the MSE analysis for the first 4 scale factors. In general, for both the rest condition and all the musical pieces, MSE values tended to increase for higher scale factors. The result indicated higher SE for the classical pieces than for the jazz ones when the first scale is considered.

Pearson correlation analysis between the time course of the music volume envelope and the RR time series recorded in the pianist during the execution of each piece revealed a moderate negative linear association ($r = -0.46125$, $p < 1.5848\ e^{-14}$) only for the 4th classical piece. In **Table 1** the correlation coefficients (r) relative to all the music pieces are reported, while in **Figure 3** the time course of the music volume envelope (upper panel) and the RR time series (lower panel) of the 4 classical (**Figure 3A**) and the 5 jazz pieces (**Figure 3B**) are shown.

Discussion

The present study explores HRV changes in a pianist while playing in a laboratory setting in order to investigate whether these changes are guided by specific music features or rather by music technical difficulty and/or subjective factors (e.g., experienced effort). The emotions experienced by the pianist were not directly assessed by means of specific tests, but only through the analysis of HRV, which is an indirect

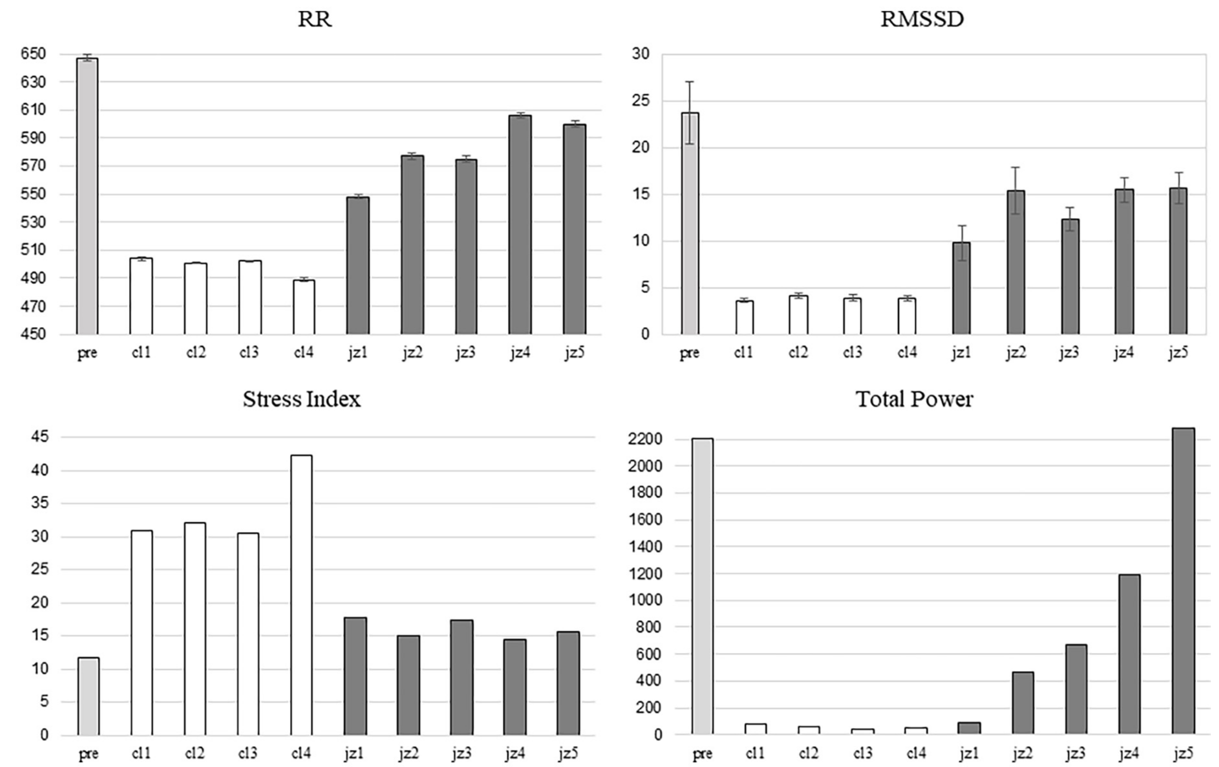

FIGURE 1
Mean value of RR, RMSSD, Stress Index and Total power recorded in the pianist during the basal period (pre, light grey bars), the 4 classical pieces (cl1-cl4, white bars) and the 5 jazz pieces (jz1-jz5, grey bars) are shown.

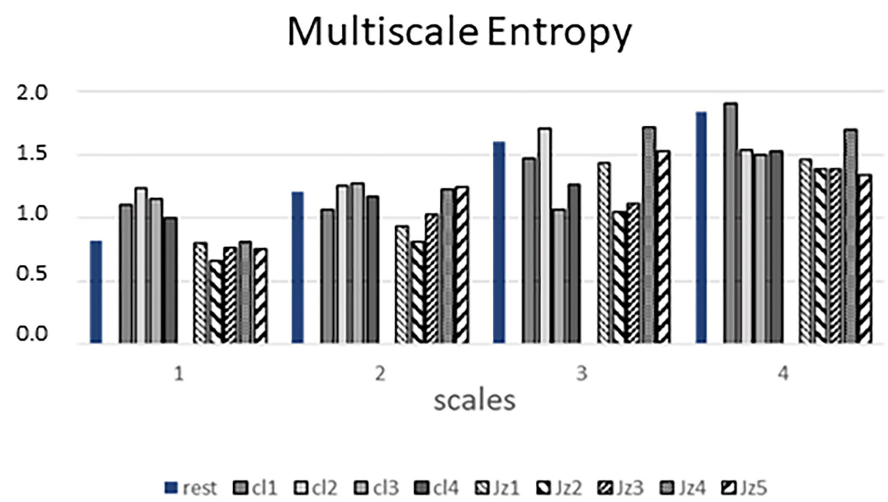

FIGURE 2
Figure shows the results of the Multi Sample Entropy analysis for the first 4 scale factors relative to the basal period (rest, blue bars), the 4 classical pieces (cl1-cl4, grey bars) and the 5 jazz pieces (jz1-jz5, striped bars).

expression of affective dimension, perceived anxiety and stress (Kim et al., 2018).

The results of this single-case study showed a general reduction of parasympathetic activity associated with an increase of the sympathetic activation in the pianist during the musical performance with greater changes during the execution of the classical pieces than the jazz ones.

TABLE 1 Correlation analysis between music envelope and RR.

Music	Piece n°	*r*	*P*
Classic	1	0.024419	0.74076
	2	0.052422	0.38564
	3	0.20727	0.0045305
	4	**−0.46125**	**1.5848 e^{-14}**
Jazz	5	0.14438	0.0097035
	6	0.14823	0.010271
	7	0.26408	4.10*E* − 02
	8	0.085211	0.071574
	9	0.032208	0.50986

Significative values are indicated in bold.

Specifically, RR were lower than the basal values across the whole music session with the lowest values during the classical sub-session and a gradual increase toward basal values from the 1st to the 5th jazz piece. A similar pattern was observable for RMSSD whose values dropped below 4 during the classical music performance, thus indicating a strong parasympathetic withdrawal.

These findings are in accord with those of Harmat and Theorell (2010), which found increased HR and suppressed HRV during high-stress musical performances than in low-stress ones.

Furthermore, the sharp reduction of TP during classical music performance is in line with a strong inhibition of parasympathetic control. TP provides the range of HRV around its mean value and is highly correlated with SDNN (Baevsky and Chernikova, 2017; Shaffer and Ginsberg, 2017).

The reduction of both measures suggests the activation of sympathetic regulation that inhibits the autonomic parasympathetic, mainly respiratory, regulation of heart rate. TP and SDNN have been found to decrease in stressful conditions and, in general, low values of these measures have

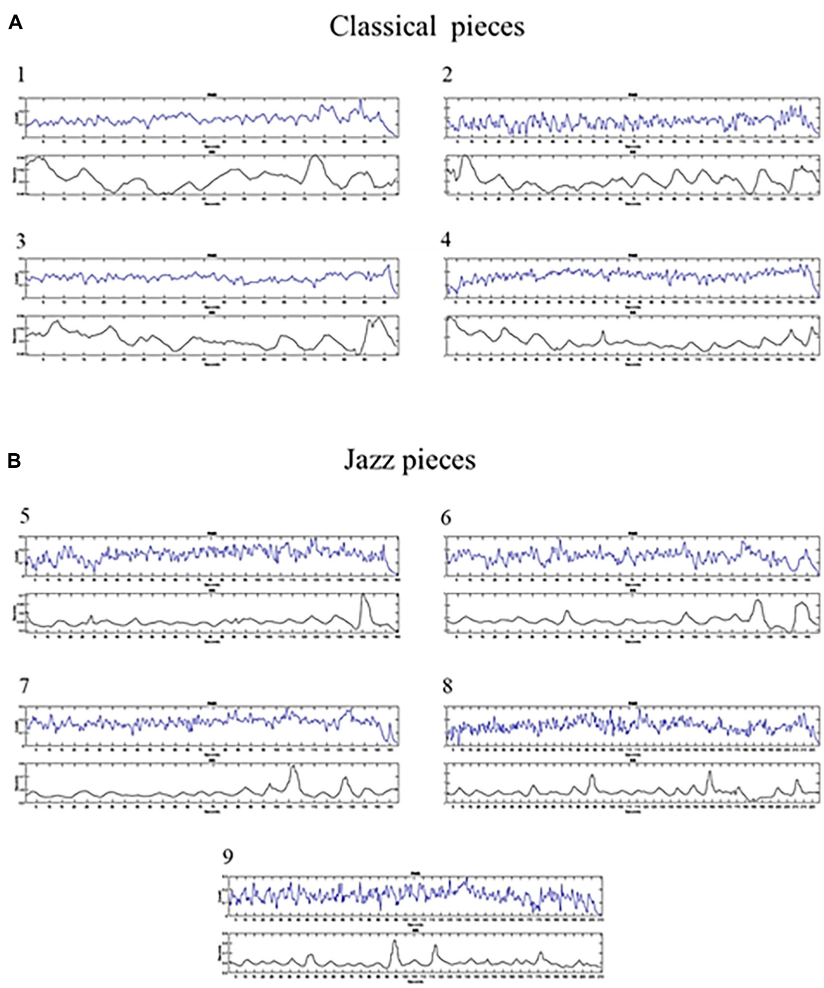

FIGURE 3
Figure shows the time course of the music volume envelope (upper panel) and the RR time series (lower panel) of the 9 pieces [1–4 classical pieces, **(A)**; 5–9 jazz pieces, **(B)**].

been associated with negative feelings and lowered ability to cope with emotional/physical stress (Baevsky and Chernikova, 2017; Shaffer and Ginsberg, 2017; Kim et al., 2018).

Changes in this parasympathetic index are associated with a strong increase of SI, which characterizes the activity of sympathetic regulation (Baevsky and Chernikova, 2017). Activation of sympathetic regulation during mental/physical stresses manifests itself with heart rate stabilization, decrease of the range of RR intervals duration, and increase of the number of RR intervals with similar duration. In the histogram of RR interval distribution, it corresponds to the narrowing of the distribution and growth in height that is an increment of SI. SI, in fact, is very sensitive to sympathetic tone rise: a mild physical/emotional stress produces a 1.5–2-fold increase in the index, while intense stress a 5–10-fold increase (Baevsky and Chernikova, 2017).

In line with these previous data, our results show that SI reaches a peak value during the 4th classical piece, which, indeed, is considered by the player the most technically difficult and the most demanding from a personal point of view.

These results are in accordance with what we found in our previous study on the virtuoso pianist during a live concert (Sebastiani et al., 2020). In fact, also in that case a general reduction of parasympathetic variability and an increase of sympathetic indices throughout the whole musical session was observed.

The pattern of the observed autonomic changes could reflect music performance anxiety which is known to be associated with different factors including the difficulty of the performance (Kenny, 2011), the performance environment and the importance attributed by the musician to his performance (Le Blanc et al., 1997; Spahn et al., 2021). Thus, we cannot exclude that also the lab experimental context may have contributed to increase the musician anxiety being the whole experimental session centered on his performance.

Results of non-linear analysis based on the measure of MSE showed that the execution of the classical pieces, which was associated with low HRV, yielded an increase of Sample Entropy (1st scale factor of MSE) with respect to both the rest condition and the jazz session. This observation confirms that variability and complexity indices do not necessarily describe the same features of dynamical signals- e.g., a sinusoidal signal has high variability but low entropy- and that classical music could be particularly effective in driving flexible, thus healthy, heart rate dynamics.

However, the difference in the 1st scale factor of MSE between classical music and both rest condition and jazz music was not maintained in the other scales. In fact, a general increase of MSE from the 1st to the 4th scale occurred in all the conditions (see **Figure 2**).

Entropy of a dynamical system is a measure of its complexity that refers to information contained in its actual state: increased values indicate a more complex signal while decreased values less complexity. Time-series with high degree of regularity have the lowest entropy values, while signals fluctuating more freely have high entropy values (Xiong et al., 2017). Complexity is recognized as an intrinsic property of healthy biological systems, and the loss of complexity, for example with aging and disease, has been interpreted as a marker of reduced adaptive capabilities of the individual. Also, studies on HRV complexity based on entropy approaches, either Approximate, Sample or Multiscale, suggested that complexity is lowest during states of high stress (Buchman and Karsch, 2009; Turianikova et al., 2011; Williamon et al., 2013; Solís-Montufar et al., 2020).

Present findings on MSE contrast with the results we previously obtained in the skilled pianist's performance. In that case, throughout the whole musical session, we found a substantial decrease of Approximate Entropy with respect to the pre-performance rest condition, which was consistent with previous evidence of lowest complexity in states of high stress (Williamon et al., 2013).

Interestingly, in a recent study Solís-Montufar et al. (2020) associated changes in HRV entropy to fatigue. In particular, the authors described an increase of HRV entropy in trained persons during moderate physical activity and a decrease when the physical activity lasted for a long period, that is when fatigue accumulates. Similarly, our results showed that SE values increased in the first part of the performance, began to decrease starting from the execution of the highly demanding piece (the 4th classical piece) and remained a little below, even if close, to the rest values during the second part of the musical session. Thus, we cannot exclude that this decrease in entropy could reflect both physical and mental fatigue. On the other hand, the whole musical performance of the virtuoso pianist was highly demanding from both a technical and expressive/emotional point of view, which could justify the marked decrease of entropy from the very beginning of the performance.

Analysis of correlation between the temporal dynamics of music volume envelope and the RR series revealed a significant negative association between them only for the 4th classical piece. As previously underlined, this piece was very difficult, and it also evoked in the performer intense negative feelings. The match between heart rhythm and this temporal feature of music could, thus, reflect the pianist's emotional response to music, and we may assume that this association could be the expression of the entrainment between emotionally meaningful music and activity in brain areas involved in the physiological expression of emotion (Juslin et al., 2014). Previous studies showed that specific acoustic features of music are linked with particular emotional responses (Gabrielson and Juslin, 2003; Schubert, 2004) and are able to differentially modulate the activity of neural regions involved in emotional/cognitive processing (Trost et al., 2015, 2017; Wollman et al., 2020). For instance, energy-related musical features have been found to be negatively correlated with the activity in the limbic system (i.e., left amygdala and nucleus accumbens) (Trost et al., 2015).

Conclusion

This preliminary study, which was carried out on a single musician, gave interesting results about the interplay between music features and HRV of the musician. In summary, HRV seems mostly modulated by classical music, which, likely owing to its temporal (e.g., sound intensity fluctuation over time) but also non-temporal (e.g., harmony) features, appears to be particularly able to entrain activity in emotional-related brain regions that control heart rhythm. However, the technical demands, the musician's expertise as well as the environment are all factors that affect a pianist's subjective emotional involvement, likely shaping (i.e., increasing or decreasing) heart-music synchronization.

In our opinion, the present results, which cannot be generalized in the present form, could provide hints for developing experimental protocols in future investigations extending the statistical sample to a group of musicians. Further studies are needed, not only to include more pianists, but also to assess, through specific tests and questionnaires, other aspects that may modulate the complex dynamical interplay between music and heart rhythm, such as personality properties, personal stress resistance, anxiety, affective lability, and fatigue.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study involving human participants was reviewed and approved by the Committee on Bioethics, University of Pisa (Review No. 15/2021). The participant provided his written informed consent to participate in this study.

Author contributions

LS and PP developed the main idea of the manuscript. All authors participated in the development of the experimental protocol and carried out the experimental session. LS and MM analyzed the recorded variables and performed the statistical analysis. LS drafted the manuscript. All authors revised and edited the manuscript, read and approved the final version of the manuscript, and agreed with the order of presentation of the authors.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.908488/full#supplementary-material

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VisualEars: How an immersive art exhibit impacts mood during the COVID-19 pandemic

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This paper explores the positive impact of viewing a virtual art exhibit on mood during the COVID-19 Pandemic. During global lockdowns, depression, anxiety, and the burden of other mental illnesses have increased even among prior psychiatrically healthy individuals. Art and music-based interventions have shown to be effective clinical interventions in individuals with mental illness. The VisualEars project explored whether a virtual activity involving vision and auditory stimuli could improve positive and negative affect. Eight musical pieces were selected, and 28 visual artists from around the world visualized two musical pieces. A total of 56 works of art were created and hung in eight 3D virtual rooms. Visitors were randomly selected to either view the art exhibit without music (non-immersive) or view the art exhibit while listening to music (immersive). Visitors were asked to complete a positive and negative affect schedule (PANAS) in three languages (English, French, and Farsi) pre and post their virtual visit. A total of 160 participants completed baseline PANAS, 58 of which completed the follow-up PANAS. Linear mixed-effects models found that older participants had lower negative affect scores overall ($b = -0.3$, $p = 0.003$), while male participants had lower positive affect scores overall ($b = -0.27$, $p = 0.02$). Following the virtual exhibit participants of both conditions had higher positive ($b = 0.17$, $p = 0.03$), and lower negative affect scores ($b = -0.19$, $p = 0.007$). We found that the virtual art exhibit increased positive affect and decreased negative affect in participants, suggesting an overall improvement in mood attributable to the virtual exhibit. This suggests that virtual exhibits may serve as a beneficial and accessible intervention to improve mood during a pandemic.

KEYWORDS
visual art, music, mood enhancement, PANAS, virtual art exhibit, mental health, COVID-19 pandemic

Introduction

The COVID-19 pandemic declared on March 11th, 2020, had a devastating impact on people's physical and mental health across the globe. Sars-COVID 2 generated an infectious disease that took the lives of millions and infected around 1.5 to 2 billion people globally (Ioannidis, 2021). Governments introduced major lockdowns and tight restrictions to curb the spread and protect people from infecting one another. The anxiety of an unknown possibly deadly disease, fear of subsequent mutations, and the loss of jobs, family members, and inability to maintain a balanced life in addition to social isolations caused by the restrictions led to an increase in mental health problems such as major depressive disorder and anxiety disorders in many countries (COVID-19 Mental Disorders Collaborators, 2021COVID-19 Mental Disorders Collaborators, 2021). Technological solutions created opportunities for people to socialize, learn, and work virtually as much as possible. However, the ongoing speaking to a screen also resulted in other phenomena such as zoom fatigue (Bailenson, 2021). In the United States, surveys from spring 2020 to January 2021 showed 41% of adults reported symptoms of anxiety and/or depressive disorder. Additionally, 13% of adults reported new or increased substance use as a result of COVID-19-related stress, and in January 2021 11% of adults reported contemplating suicide in the past 30 days (Panchal et al., 2021). According to 6 surveys conducted by Leger for the Canadian Centre on Substance Use and Addiction and the Mental Health Commission of Canada on the Canadian youth and adult population from October 2020 to July 2021, mental health issues became more prevalent as a result of the pandemic. Youth (aged 16 to 24) reported more mental health and substance use concerns during the pandemic, and decreased ability to handle pandemic-related stress. Further, 45% of Youth reported moderate-severe anxiety. Substance use habits increased during the pandemic, with 40% of youth and 20% of older adults reporting an increase in use (Canadian Centre on Substance Use and Addiction & Mental Health Commission of Canada, 2021). This is a further concern as individuals with substance use concerns were reported to show signs of worsening mental health during the pandemic.

According to a study by the Canadian Centre on Substance Use and Addiction, only 22% of the surveyed population who showed symptoms of mental health issues received necessary treatment from March to December 2020 (Canadian Centre on Substance Use and Addiction & Mental Health Commission of Canada, 2021). Nonetheless, due to the continued stigma around mental health issues, it can be safely assumed that these numbers are much higher than reported in reality. Given the dire situation of mental health globally, adverse side effects from medications, and the stigmatization of mental disorders, this study aims to explore how immersive experiences such as those proposed by this study can serve as a potential alternative and highly affordable and accessible intervention for mood disturbances in the general population.

The visual arts' positive benefits on mood and wellbeing have been used for centuries as powerful healing agents in many societies. Having visual works of art in early hospitals, churches and Buddhist shrines is believed to improve our wellbeing, and more specifically "bring about a change in consciousness and to promote healing and hope" (Samuels and Lane, 2013). This holistic approach supports the fact that mental and physical health are interconnected. Moreover, the significant role of emotions and thoughts have been widely discussed in health-related research (Sapolsky, 2000). A phenomenon called "The Museum Effect" has been reported in literature, and accounts for an individuals' positive change in attitude toward other people while visiting an art exhibition (Smith, 2014).

The implications of visual arts in our surroundings have been documented in both clinical and non-clinical settings (Staricoff, 2004). Within the clinical setting, the environment in which the patients are placed in the hospital, and the amount of natural light and the scenery they are exposed to impacts their blood pressure, levels of stress and clinical outcomes as well as promote a safe place, connect them to the outside world, create an opportunity for socialization, and pain reduction (Frandsen et al., 2009; O'Bróin, 2015; Nielsen et al., 2017). Museums and the arts improve the wellbeing of communities through cultural contributions that can complement conventional medicine (White, 2009). In Germany, the ARTEMIS project (an art museum-based intervention) measured quality of life and mood in individuals with dementia, finding that they had improved quality of life with a decrease in negative affects such as depression and anxiety (Schall et al., 2018). This improvement in overall mood and wellbeing in individuals with dementia has been supported through other studies involving artistic interventions (Belver et al., 2018). Additionally, engaging in art practices such as the visual arts helps cancer patients in meaning-making and building a positive identity (Stuckey and Nobel, 2010). Furthermore, art activities foster hopefulness, and facilitates recovery in people with mental illness (Stickley et al., 2018). Overall, it appears that art as an intervention (either passively or through active engagement) can benefit individuals in a clinical setting.

While the majority of the studies conducted on the arts assess its impact on human physiology and psychology within the clinical settings, there are several studies evaluating arts-based interventions to improve mental health and wellbeing in the non-clinical populations. These studies offer a promising potential for the future of research on how visual arts impact the general population. Within the general population, individuals who engaged with the arts for 100 or more hours annually had significantly higher mental wellbeing than others with less engagement (Davies et al., 2015). This artistic engagement may extend past the unimodal system of consumption, as shown by Stratton and Zalanowski (1989) who found that in combining the experience of paintings and music, which either prompted depression, positive affects, or neutrality, a participant's mood could be influenced, whereas each medium by itself did not induce such effects. As is relevant in a pandemic context, an artistic virtual reality tool was shown to be effective in improving participants' mood (Habak et al., 2020). Given the apparent beneficial effects of artistic interventions on mood, Scandinavian countries such as Sweden and Norway have developed a wide range of art programs which have been shown to improve mood, mental health, and overall wellbeing in their population (Jensen et al., 2017).

Given these findings, the purpose of this study was to investigate whether a virtual arts platform would improve the mood of attendees during the COVID-19 pandemic. The primary hypothesis was that negative affective scores would decrease, and positive affective scores would increase following the attendance of a virtual art exhibit. The secondary hypothesis was that the addition of music to the art exhibit would elicit a greater decrease in negative emotion and a greater increase in positive emotion.

Materials and methods

The project's inception

The initial plan for this project in 2014 was an immersive experience where visitors could jointly observe visual arts in a gallery while listening to the corresponding pieces of music. However, due to the COVID-19 pandemic in 2020, this project was altered to align with the restrictions on people's gatherings and public spaces, which proved to be a challenging task because of technological complexities and hurdles in creating a user-friendly yet realistic experience as well as visitors' requirements to have stable internet connection and follow detailed instructions. Eight pieces of music were selected for the project and 28 artists were instructed to create visual works representing two out of the eight pieces of music. The artworks were shown in two formats, immersive and non-immersive. The two formats were identical except for the presentation of music in the immersive format.

Artist recruitment and procedure

Artists (n = 28) were recruited for participation in the project from around the world through a referral basis and through searches on the Internet, online galleries, and museums. Each artist signed an informed consent form which included a description of the project, instructions, and additional information. Artists were selected from different countries (Canada = 9, Iran = 9, United Kingdom = 2, Netherlands = 1, Serbia = 1, Ukraine = 1, Denmark = 1, Germany = 1, Ghana = 1, South Africa = 1, Japan = 1) different education levels (Academic education in arts = 17, Private education = 4, High school art education = 1, self-taught = 6) and different musical background (No musical training = 11, beginner/intermediate level = 10, advanced/self-taught musician = 7). Only one artist had synesthesia. The participating artists were asked to visualize two different musical pieces into two works of visual art, to translate what they hear into what can be seen. The musical pieces were selected among a pool of 100 pieces (initially selected by SH) from various cultures and genres specifically for their emotive characteristics. Out of the selection of eight pieces chosen for this study, the artists were each randomly assigned one musical piece as per the researcher's discretion and then asked to select a second piece from the rest of the list of eight pieces provided to them.

The musical pieces selected from different musical cultures for this project were *Avminnast* by Nils Økland, *A Trace of Grace* by Michel Godard, Alim Qasimov, Rauf Islamov, and Hüsnü Şenlendirici (for example, see **Figure 1A**), *Malka Moma si se bogu moli* by Neli Andreeva and Georgi Genov (for example, see **Figure 1B**), Etude for Piano in C Sharp minor Op. 2, No 1. by Alexander Scriabin performed by Vladimir Horowitz, *Oro Santo* by Javier Limón featuring Buika (for example, see **Figure 1C**), *A Place for Us* by Brian Weafer, *The Puzzle* by Dawn Davi (for example, see **Figure 1D**) *Elegy for Viola* by Peter Cavallo. Out of these 8 pieces, five were instrumental, and three featured vocals. Artists were compensated with $ 50 (CAD) per work of art according to the CARFAC (Canadian Artists' Representation) guidelines in Canada.

Materials and measures

Positive and negative affects survey (PANAS)

The positive and negative affects questionnaire (PANAS) (Watson et al., 1988) originally developed and validated as a 20-item measurement. PANAS is used to measure the changes in positive and negative effects of an individual and has been shown to be reliable (Positive Affect Scale, Cronbach's α = 0.88; Negative Affect Scale, Cronbach's α = 0.87; Watson et al., 1988). For this project, the English version as well as the French and Farsi (Shokri et al., 2014) translations were used. The version in Farsi shows comparable reliability within positive affects (Cronbach's α = 0.83) and negative affect (Cronbach's α = 0.78) dimensions (Shokri et al., 2014). Within our sample, the PANAS scale was sufficiently reliable within the English (Positive, Cronbach's α = 0.92; Negative, Cronbach's α = 0.94) and Farsi (Positive, Cronbach's α = 0.84; Negative, Cronbach's α = 0.85) translations. Alternatively, the French version should be interpreted with caution, due to the small sample size, individual evaluation of the scales was not possible, and 3 items (Item 7, 17, and 19) had to be removed due to lack of

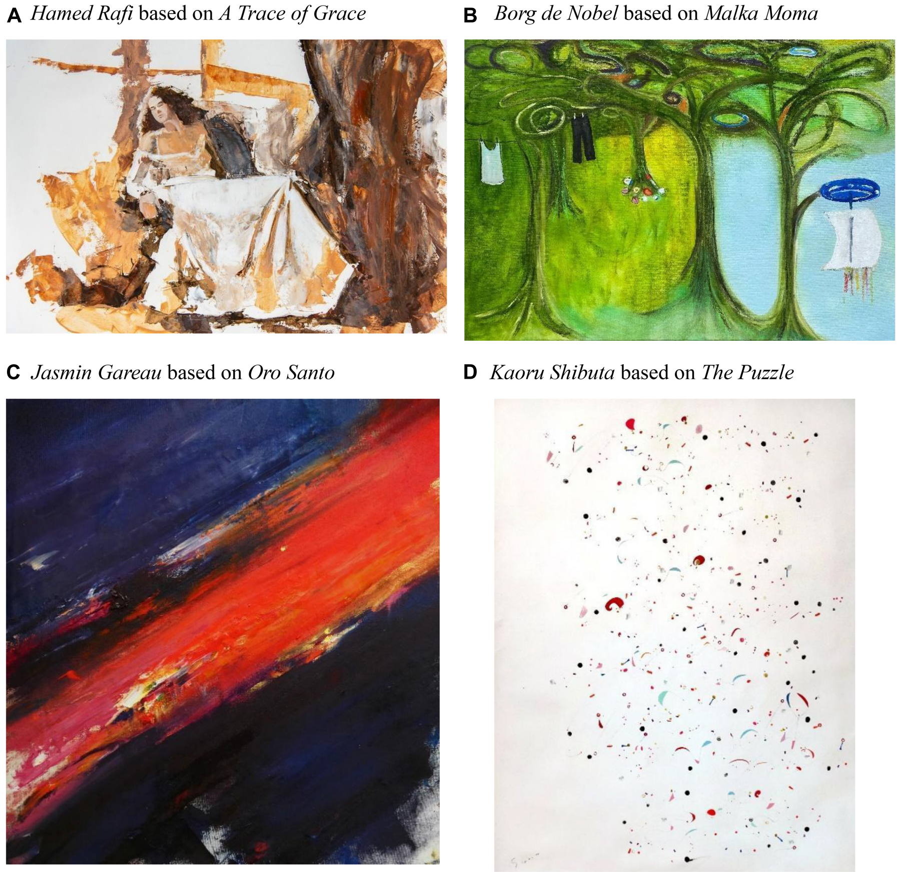

FIGURE 1
Excerpts of projects created for VisualEars exhibit and room. **(A)** Hamed Rafi based on A Trace of Grace. **(B)** Borg de Nobel based on Malka Moma. **(C)** Jasmin Gareau based on Oro Santo. **(D)** Kaoru Shibuta based on The Puzzle. Source: www.visualearsproject.com. Reproduced with permission.

variance. Nonetheless, reliability was relatively adequate within the French translation of the PANAS within our small sample (Cronbach's $\alpha = 0.93$).

Virtual exhibition

The exhibition was designed in two formats (immersive and non-immersive) on Kunstmatrix platform which hosts virtual 3D exhibitions that allow the visitors to interact closely with the visual arts hung on the walls, simultaneously listen to the music selected by the curator, and navigate the space by clicking on directional arrows. The two formats of the exhibition consist of a non-immersive version where there were artworks on the walls while the immersive version also included the musical piece which the visual arts were based upon. Therefore, in each room of the immersive format, the piece of music based on which the works of art were created was playing while the visitors were viewing the works of art. Both immersive and non-immersive versions consisted of eight separate rooms which were linked and navigated by clicking on designated buttons. Each room was slightly different in terms of the color of the walls and the layout in order to give the visitors a realistic impression of a physical exhibition. The exhibition and the study were live for 4 weeks. The participants were only told that they would be visiting an art exhibit that featured 8 rooms, where there would be just the visual works of art or visual arts pieces and music playing in the rooms. However, upon clicking on the description of each artwork, participants would be informed that each work of art was a visualization of a musical piece with the title of the piece next to it. In addition, by using newly created art, there was zero chance that the participants would be viewing works with which they were familiar. Thus, the visual aspect of the project was all "new" to all participants and therefore a kind of neutralizer.

It is noted that the designs of the immersive and non-immersive versions were identical therefore keeping music the only variable for the visitors. The rooms were to be visited consecutively and in one sitting through the instructions provided upon entering the first room and the same instructions offered in the first and last panels of each room. Rooms were chosen for each musical piece where the pieces of artwork were displayed that were made for that piece, therefore, there were

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eight rooms in total for the exhibition, the number of artworks in each room varies as some of the pieces were selected by more artists. There was one room that held only two artworks and there were a few rooms that held nine artworks.

Experimental paradigm

The exhibition was launched on a dedicated website, www.visualearsproject.com and invitations were sent out to the general public through emails and instagram posts.

Participants were directed from the website to the study on Qualtrics through a link. The paradigm was designed on Qualtrics in three languages: English, French, and Farsi. Participants were asked to choose a language to complete the study and fill out an informed consent form. They were then directed to complete a pre-experience PANAS and follow by selecting their age range from three options of below 25, 25 to 50, and over 51. They were also asked to choose their gender from the categories male, female, and other.

Only participants who appropriately indicated their consent were directed to complete the study, if participants indicated dissent, they were invited to visit the immersive version without participation in the study. After the completion of the PANAS scale, participants were directed to the first room of the exhibition and were randomly assigned to either the immersive condition (music and visual) or to the non-immersive condition (visual only). Through the instructions, participants would enter room 1, and start from a panel that displayed the words "Start here." They could click on the panel and then navigate the room by clicking to the artwork on their right side. In the immersive version, once the visitor clicked on the first panel, the music started playing and kept looping until they left the room. Each artwork came with the name of the artist, the piece of music which it was visualized upon, the price, the technique and size of the artwork, and the artist's website. The visitors could zoom in on the artworks and manually navigate the room instead of using the right and left directive arrows on the page and leave for the next room by clicking on the link provided through the last panel in each room. Participants were asked to visit the exhibition and complete the relevant surveys in one sitting. In the last room, there was a panel through which participants were directed to take the post-experience PANAS once their visit was completed. The questionnaire was a duplicate of the first one followed by a question that asked visitors to describe their exhibition experience in one word.

Statistical analyses

Overall composite affective emotion scores were calculated for positive and negative affective mood from the PANAS in English, French, and Farsi by calculating the average from 10 sub-categories. The composite positive affective emotion score was calculated from the following sub-categories: Interested, Excited, Strong, Enthusiastic, Proud, Alert, Inspired, Determined, Attentive, and Active. The composite negative affective emotion score was calculated from the following sub-categories: Distressed, Upset, Guilty, Scared, Hostile, Irritable, Ashamed, Nervous, Jittery, and Afraid. If participants were missing more than two sub-category responses from the respective composite score the individual was dropped from analyses. To investigate whether demographics (i.e., age, language, or gender), or experimental group assignment had any effect on completion of the art exhibit and post PANAS χ^2 tests were conducted.

For the primary hypothesis linear mixed effects models (LME) with mood (i.e., composite positive affective emotion score), with (i) fixed effects of age, gender, music, and time (i.e., before vs. after the virtual exhibit); (ii) random effects of intercept and slope of time by subject and (iii) a first order autoregressive covariance matrix (i.e., corAR1) between time points. For the secondary hypothesis investigating moderators of the effect that attending a virtual art exhibit has on mood an additional fixed effect of the interaction between time with either age, gender, or music was included [equation: Mood $\sim$ Age + Gender + Time + Group + ($\sim$ 1 + Time | Subj), correlation = corAR1]. Additional exploratory LME analyses for each sub-category within each composite affective score were conducted. To correct for multiple comparisons a false discovery rate (FDR) using the two-stage linear step-up procedure by Benjamini et al. (2006) was applied in a family wise basis within the (i) primary hypothesis (i.e., correcting for testing the composite positive and negative score); (ii) secondary hypothesis; and (iii) exploratory hypothesis (i.e., correcting for 10 sub-categories with each composite score). All statistical analyses were conducted using R 4.0.5. Unstandardized beta values were reported as measures of effect sizes for all findings.

Results

Participants

Participants (n = 160) initially completed a pre-experience survey consisting of basic demographic information surrounding participants' gender, age category, and language choice for completing surveys. Participants locations were widely spread across the world as shown in **Figure 2**. Participants were randomly assigned into an experimental group (n = 80), or a control group, with significantly more individuals selecting the English version, than the Farsi or French; this distribution saw significant change between experimental and control groups from pre- vs. post- experience [$\chi^2(4) = 61.17$, $p < 0.001$]. Following the immersive art experience, participants (n = 60, experimental = 33) answered

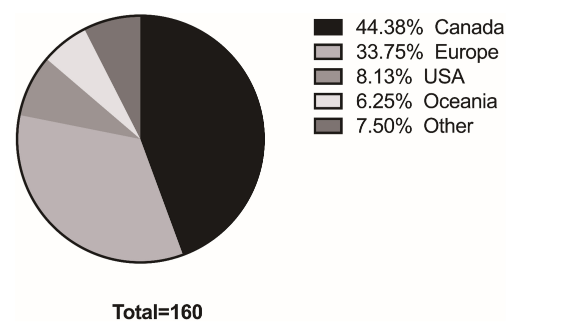

FIGURE 2
Participant's locations.

the post-experience survey. Participants attrition between pre- and post- survey varied by age, gender, and language (see Table 1). While considerable attrition was observed from pre- to post- experience survey, no significance differences were found in relation to recorded demographic variables between those who completed the pre-survey and those who completed the post-survey, in regard to the sample's gender [$\chi^2(4) = 2.42$, $p = 0.66$], age categories [$\chi^2(4) = 4.52$, $p = 0.34$], choice of language [$\chi^2(4) = 0.66$, $p = 0.96$], or group type [$\chi^2(1) = 0.60$, $p = 0.43$].

Demographic characteristics and mood

The association of age and sex with PANAS scores are presented in Table 2. Older participants had significantly lower composite scores of negative affective emotions ($b = -0.38$, $p_{FDR} = 0.002$; Figure 3B), and its sub-category questions: Distressed ($b = -0.47$, $p_{FDR} = 0.003$), Upset ($b = -0.33$, $p_{FDR} = 0.04$), Guilty ($b = -0.52$, $p_{FDR} = 0.0004$), Ashamed ($b = -0.31$, $p_{FDR} = 0.02$), Nervous ($b = -0.45$, $p_{FDR} = 0.005$), Afraid ($b = -0.31$, $p_{FDR} = 0.03$). Additionally, while age was not significantly associated with the composite positive affective emotion ($b = 0.10$, $p_{FDR} = 0.20$; Figure 3A), older participants had higher positive affective emotion in the sub-categories: Alert ($b = 0.40$, $p_{FDR} = 0.03$), Attentive ($b = 0.33$, $p_{FDR} = 0.03$). Male participants had a significantly lower composite score of positive affective emotion ($b = -0.22$, $p_{FDR} = 0.04$; Figure 3C), and higher composite score of negative affective emotion ($b = 0.26$, $p_{FDR} = 0.02$; Figure 3D) and its sub-category questions: Scared ($b = 0.35$, $p_{FDR} = 0.04$), and Hostile ($b = 0.44$, $p_{FDR} = 0.002$).

Effect of the virtual art exhibit on mood

The effect of attending a virtual art exhibit (i.e., Time) on mood questionnaire scores are presented in Table 2. Following the virtual art exhibit attendees had a higher composite score of positive affective emotion ($b = 0.17$, $p_{FDR} = 0.03$; Figure 3E), and its sub-category questions: Proud ($b = 0.43$, $p_{FDR} = 0.03$), and Inspired ($b = 0.47$, $p_{FDR} = 0.03$). Additionally, following the virtual art exhibit attendees had a lower composite score of negative affective emotion ($b = -0.19$, $p_{FDR} = 0.02$; Figure 3F), and its sub-category questions: Scared ($b = -0.24$, $p_{FDR} = 0.03$), and Jittery ($b = -0.27$, $p_{FDR} = 0.04$).

Moderators of the virtual art exhibit on mood

The moderating effects of incorporating music into some participant's virtual art exhibit, age and gender are presented in Table 3. Age was a significant moderator of the effect that attending a virtual art exhibit has on mood. Younger participants had a greater increase in the composite positive affective score ($b = -0.29$, $p_{FDR} = 0.02$). and its sub-category: Inspired ($b = -0.67$, $p_{FDR} = 0.04$) than older participants. Younger participants had a greater decrease in the composite negative affective score ($b = 0.29$, $p_{FDR} = 0.02$). and its sub-category: Hostile ($b = 0.42$, $p_{FDR} = 0.04$) and Irritable ($b = 0.49$, $p_{FDR} = 0.04$) than older participants. Neither the incorporation of music alongside the virtual art exhibit or gender were significant moderators of the effect of a virtual art exhibit on mood.

Discussion

The goal of this novel research project was to find out the impact of a virtual art exhibition incorporating music and visual arts on the positive and negative affects of the general public during the COVID-19 pandemic. As in-person human interaction was limited, the pandemic took its toll on the mental wellbeing of millions around the globe, in particular, the general public and those without any known history of mental health challenges. A Dutch longitudinal study revealed that people without a mental illness showed a greater increase in symptoms during the COVID-19 pandemic as opposed to those with a mental illness (Pan et al., 2021). Although this project was initially conceived to take place in

TABLE 1 Demographic information for participants pre–and post–immersive experience.

Time-Point	Group	Gender	Language	Age
Pre-experience	Experimental (*n* = 80)	Female = 50	EN = 68	<25 = 6
		Male = 28	FR = 3	25–50 = 48
		Other = 1	FA = 9	>50 = 26
		Undisclosed = 1		
	Control (*n* = 80)	Female = 49	EN = 64	<25 = 4
		Male = 28	FR = 1	25–50 = 45
		Other = 2	FA = 15	>50 = 31
		Undisclosed = 1		
Post-experience	Experimental (*n* = 33)	Female = 18	EN = 27	<25 = 2
		Male = 15	FR = 1	25–30 = 14
			FA = 5	>50 = 17
	Control (*n* = 27)	Female = 14	EN = 21	<25 = 2
		Male = 12	FR = 0	25–50 = 13
		Other = 1	FA = 6	>50 = 12

EN, English; FA, Farsi; FR, French.

TABLE 2 Results of linear mixed effects analyses investigating the association of time, age and gender with positive and negative affect.

Measure	Mean ± SD		Predictors								
	Mean score pre	Mean score post	Time			Age			Sex		
	n = 159	*n* = 58	b	*P*	pFDR	P	*p*	pFDR	b	*P*	pFDR
Positive	3.32 ± 0.84	3.54 ± 0.98	0.17	0.03	0.03*	0.10	0.38	0.20	−0.22	0.08	0.04*
Negative	1.72 ± 0.79	1.43 ± 0.66	−0.19	0.01	0.02*	−0.31	< 0.001	0.002*	0.26	0.02	0.02*
Interested	3.92 ± 1.04	3.83 ± 1.19	−0.08	0.50	0.45	0.06	0.66	0.53	−0.26	0.10	0.20
Distressed	1.94 ± 1.1	1.55 ± 0.9	−0.28	0.02	0.06	−0.47	< 0.001	0.003*	0.31	0.04	0.11
Excited	3.15 ± 1.15	3.26 ± 1.22	0.12	0.34	0.34	−0.12	0.43	0.39	−0.16	0.35	0.39
Upset	1.77 ± 1.14	1.52 ± 0.98	−0.18	0.16	0.25	−0.33	0.02	0.04*	0.14	0.38	0.40
Strong	3.04 ± 1.14	3.17 ± 1.29	0.06	0.58	0.49	0.14	0.37	0.36	−0.30	0.08	0.19
Guilty	1.59 ± 0.96	1.33 ± 0.89	−0.10	0.34	0.34	−0.52	< 0.001	0.0004*	0.30	0.02	0.10
Scared	1.59 ± 0.92	1.29 ± 0.65	−0.24	< 0.001	0.03*	−0.19	0.07	0.10	0.35	< 0.001	0.04*
Hostile	1.43 ± 0.82	1.26 ± 0.66	−0.11	0.19	0.26	−0.13	0.21	0.24	0.44	< 0.001	0.002*
Enthusiastic	3.37 ± 1.11	3.41 ± 1.2	0.07	0.50	0.45	< 0.001	0.99	0.67	−0.18	0.29	0.34
Proud	3.11 ± 1.31	3.47 ± 1.52	0.43	0.01	0.03*	−0.07	0.71	0.54	−0.28	0.15	0.22
Irritable	1.92 ± 1.15	1.57 ± 0.86	−0.25	0.02	0.06	−0.16	0.28	0.29	0.07	0.67	0.64
Alert	3.18 ± 1.21	3.53 ± 1.25	0.13	0.33	0.34	0.40	0.01	0.03*	−0.07	0.68	0.64
Ashamed	1.47 ± 0.88	1.24 ± 0.6	−0.10	0.07	0.15	−0.31	< 0.001	0.02*	0.30	0.01	0.08
Inspired	3.34 ± 1.22	3.84 ± 1.31	0.47	< 0.001	0.03*	0.08	0.64	0.53	−0.35	0.05	0.14
Nervous	1.93 ± 1.03	1.59 ± 1.03	−0.25	0.03	0.08	−0.45	< 0.001	0.005*	0.22	0.14	0.21
Determined	3.29 ± 1.17	3.6 ± 1.32	0.21	0.14	0.23	0.21	0.18	0.23	−0.28	0.10	0.20
Attentive	3.55 ± 0.99	3.86 ± 1.13	0.15	0.22	0.28	0.33	0.01	0.03*	−0.16	0.27	0.34
Jittery	1.91 ± 1.06	1.53 ± 0.96	−0.27	0.01	0.04*	−0.27	0.06	0.09	0.18	0.24	0.33
Active	3.24 ± 1.05	3.41 ± 1.06	0.18	0.08	0.15	0.01	0.94	0.67	−0.25	0.11	0.20
Afraid	1.60 ± 0.99	1.41 ± 0.92	−0.14	0.27	0.33	−0.32	0.01	0.03*	0.31	0.03	0.10

*P-values significant at $\alpha = 0.05$.

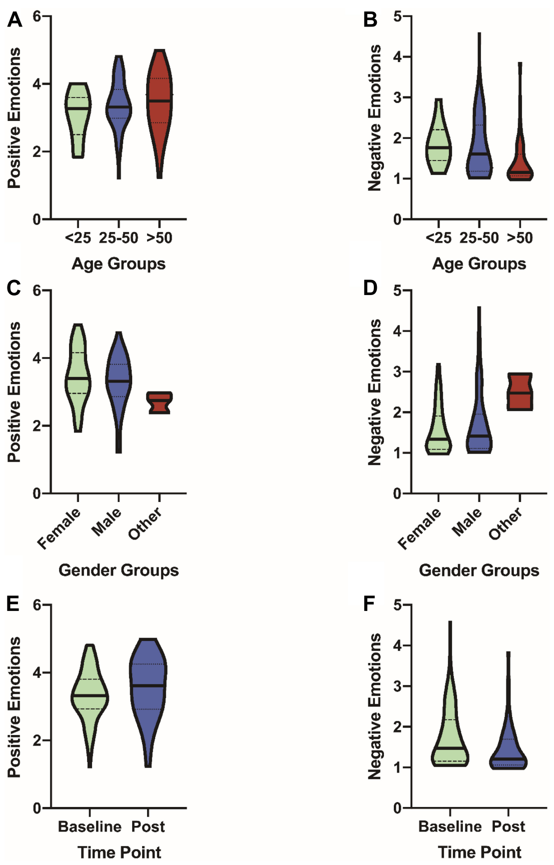

FIGURE 3
Violin plots of demographics and time with PANAS scores. **(A)** Age vs. positive emotions. **(B)** Age vs. negative emotions. **(C)** Gender vs. positive emotions. **(D)** Gender vs. negative emotions. **(E)** Time vs. positive emotions. **(F)** Time vs. negative emotions.

person, COVID-19 created an opportunity for a widespread audience.

The exhibition in this study took place in two formats, one of which contained only visual works of art, and the other contained music and visual artworks. PANAS was utilized to evaluate the positive and negative affects of the audience anonymously before and after the virtual exhibition through a randomized and controlled experiment. The study ran for 4 weeks and was accessed by a widespread audience in three languages, English, French, and Farsi. The subjects were asked to rank their positive and negative affects on a scale from 1 to 5. Each format of the exhibition consisted of 8 rooms each of which hosted a number of artworks which were visualizations of a particular musical piece. The immersive format also featured the musical pieces in each room. The rooms were visited consecutively by the audience who were randomly assigned the immersive or the non-immersive format.

This study demonstrated that a virtual art exhibition during the pandemic was able to increase the positive affect and decrease negative affect in a widespread audience. Furthermore, younger participants benefited more (i.e., higher increase in positive affect and greater decrease in negative affect) than older participants. Given the technological aspect of participating in a virtual platform, it is possible that the greater benefit observed in younger participants may be attributed to higher technological fluency in this group. Research has demonstrated younger participants frequently and fluently use computers and other technology for various tasks in order to work, socialize, study, and etc. (Olson et al., 2011). Nonetheless, prior studies by Davies et al. (2015) and Habak et al. (2020) have found that a virtual reality tool and engagement in art was associated with better mood. Furthermore, the current study supports findings from the project "Art and Wellbeing" involving four European institutions that found that "Receptive participation in the arts (visual arts, theater, dance, architecture and heritage) during the pandemic was significantly correlated to a decrease in negative feelings." Additionally, a study by Ascolani et al. (2020) indicates that 85.18% of the participants consumed different forms of art as a coping mechanism, and 64.21% declared that art makes them feel better. Therefore, suggesting that engagement in the arts may serve as a beneficial and widely accessible intervention to improve mood during a pandemic.

Interestingly our study found that older participants had lower overall negative affect, including its subcategories of distress, upset, and nervousness. Older participants also reported being more alert and attentive which are subcategories of overall positive affect. Furthermore, Male-identifying subjects had a significantly lower overall positive affect and higher overall negative affect, including its subcategories of scared and hostility. A recent study by Fenollar-Cortés et al. (2021) that also used the PANAS found that during the midst of lockdowns older participants had significantly higher positive affect and nominally lower negative affect. These results also align with another study which found that the negative psychological impact of COVID-19 pandemic hits young people harder (Justo-Alonso et al., 2020). These results might also reveal that older participants were coping better with the negative impacts of the pandemic. Regarding gender differences in affect, future research is needed as some studies find no differences (Fenollar-Cortés et al., 2021) while other studies have reported that females are hit harder by the negative psychological impact of COVID-19 pandemic (Justo-Alonso et al., 2020).

Although the initial hypothesis of the VisualEars project was that subjects visiting the rooms with music and visual

TABLE 3 Results of linear mixed effects analyses investigating the moderating effects of group, age and gender on the change in positive and negative affect from attending the virtual art exhibit.

Measure	Moderators of response								
	Group			Age			Sex		
	b	P	pFDR	b	P	pFDR	P	p	pFDR
Positive	−0.11	0.46	0.82	−0.29	0.02	0.02*	−0.06	0.71	0.75
Negative	−0.04	0.78	0.82	0.29	0.01	0.02*	0.23	0.09	0.20
Interested	−0.44	0.07	0.93	−0.28	0.17	0.27	0.01	0.98	> 0.99
Distressed	−0.22	0.34	0.93	0.31	0.12	0.24	0.20	0.40	0.69
Excited	−0.41	0.10	0.93	0.16	0.46	0.46	0.45	0.08	0.60
Upset	−0.19	0.46	0.93	0.28	0.19	0.28	0.30	0.24	0.69
Strong	0.23	0.31	0.93	−0.14	0.47	0.46	−0.10	0.65	0.98
Guilty	0.13	0.51	0.93	0.31	0.07	0.24	0.22	0.27	0.69
Scared	0.01	0.93	> 0.99	0.20	0.14	0.26	0.01	0.93	> 0.99
Hostile	0.09	0.58	0.93	0.42	< 0.001	0.04*	0.02	0.89	> 0.99
Enthusiastic	−0.14	0.54	0.93	−0.15	0.43	0.46	< 0.001	0.99	> 0.99
Proud	0.09	0.77	> 0.99	−0.09	0.73	0.69	−0.08	0.78	> 0.99
Irritable	0.17	0.43	0.93	0.49	0.01	0.04*	0.24	0.27	0.69
Alert	−0.26	0.33	0.93	−0.34	0.12	0.24	−0.23	0.38	0.69
Ashamed	0.04	0.70	0.98	< 0.001	0.98	0.88	0.12	0.29	0.69
Inspired	−0.07	0.82	> 0.99	−0.67	< 0.001	0.04*	−0.32	0.27	0.69
Nervous	−0.15	0.51	0.93	0.15	0.44	0.46	0.40	0.08	0.60
Determined	< 0.001	1.00	> 0.99	−0.36	0.12	0.24	−0.27	0.33	0.69
Attentive	< 0.001	1.00	> 0.99	−0.35	0.08	0.24	−0.19	0.43	0.69
Jittery	−0.09	0.66	0.98	0.17	0.31	0.43	0.57	< 0.001	0.08
Active	−0.28	0.16	0.93	−0.14	0.40	0.46	−0.02	0.91	> 0.99
Afraid	−0.26	0.30	0.93	0.41	0.05	0.22	0.38	0.13	0.67

SD, standard deviation; b, unstandardized beta estimate; *P-values significant at α = 0.05.

artworks would show a greater increase in the positive affects and decrease in the negative affects relative to those visiting the rooms with the visual artworks only, music did not appear to impact the results. This contrasts with a study by Stratton and Zalanowski (1989) that showed that the combination of viewing paintings and listening to music altered the mood of the participants, whereas music and paintings separately did not. Although the methods of this study differ from the VisualEars project, future research on the simultaneous pairing of art and music is warranted. Some of the challenges in this study and future opportunities are outlined below:

Firstly, technical challenges could most likely account for the hindrances, limitations, and the lack of support for the hypothesis. This virtual art exhibit was made possible through connecting three different platforms: a dedicated website to the project as a means to introduce and begin the experiment, Qualtrics on which the consent forms and the questionnaires were held, and Kunstmatrix where the 3D exhibition was offered. Although every effort was made to make the experience as seamless as possible, it would be remiss to consider it an easy-to-navigate for all. For example, the instructions were given on navigating the exhibition for best audio results. Each room would open in a new tab, and the audience were advised to close the previous tab right after opening a new tab while moving from room to room. However, some visitors reported not reading the instructions and therefore, encountered instances when multiple musical pieces were playing simultaneously. They were also directed to use their computers, the Chrome browser, and headphones while visiting to allow for the best experience; however, there were anecdotes of participants visiting on their phones or listening to the music on speakers due to lack of access to a computer or a working headphone.

Additionally, in order to create a smooth flow, the rooms were designed in a way that would not allow visitors to go back to a room, hence if a visitor accidentally closed their tab, they would have needed to start over and lose their initial consent form and questionnaire responses. Another obstacle was the bandwidth issues on some visitors' end and some internal server interruptions which happened to Qualtrics and Kunstmatrix during the time the exhibition was live. These problems resulted in many visitors not being able to follow the rooms and finish their visit as designed and expected. Therefore, the result of the positive and negative affects scores are likely to be more favorable than the current outcome and it is desirable to conduct the study again applying other platforms or at a designated lab to prevent external obstacles. It would also be crucial to run this study on a larger pool of participants to examine the further implications as a means to temporarily enhance and regulate mood as an accessible tool for self-care.

Secondly, unfamiliarity with the genres of the musical selections might have prevented some participants from connecting with the music. In addition, some participants with preference for more upbeat music might have not connected with the pieces employed in this study as all pieces were more reflective and contemplative in mood and tended to have slower tempos.

Thirdly, the three pieces of music which featured vocals in Bulgarian, Spanish, and Azerbaijani languages may have caused an unintentional disconnect between the musical piece and the visual work of art and therefore preventing the immersive format to elicit better results in terms of mood regulation for the participants. There are two potential reasons here. (1) The artists if not fluent in the language of the music piece may have envisioned it differently. (2) If participants didn't understand the language the piece was composed in, that may have impaired them connecting the art to music in the way the artist intended.

A few suggestions are noted concerning future replications of this study. (1) There were instructions on the first panel of the exhibit on how to navigate each room from start to the end for a more seamless experience, but participants were free to navigate it the way they wanted as well using the zooming in and out option, and the arrows to navigate in different directions; however, the order of the works and rooms were fixed. This order was one which the designing author thought would be aesthetically pleasing. We acknowledge that it might have had a specific impact on the audience and we suggest that the order of the artworks randomly change for each participant in any future replications of this study. (2) The fact that the visitors chose to attend the art exhibit revealed their willingness and openness to engage in an artistic activity which happened to be a novel experience as well. These participants might have been more likely to have positive experiences from an art exhibit and therefore might not have represented the general public. We suggest further data collection about each participant's level of engagement with artistic activities and the application of further scales such as Sandstrom and Russo's (2013) AIMS (Absorption in Music Scale) prior to the study to illuminate the correlation if any with the outcome of the research. (3) We strongly recommend a replication of this study with a simpler architectural design for the exhibit and reliance on simple elements of technological fluency.

In regard to the future opportunities, developing and expanding a dedicated smartphone and web application for this project can serve as a self-care tool for the majority of the general population, in particular adolescents and young people since significant improvement was observed in their age group. Furthermore, the results of this study warrant a study in clinical settings in Toronto such as CAMH, The Baycrest, The Alzheimer's Society and other mental health organizations in order to evaluate this mood enhancing intervention for their clientele. Amidst the growing increase in mental health problems especially in more vulnerable and marginalized populations, such exhibitions can offer a glimmer of hope to help with mood enhancement and regulation as alternative and temporary interventions. Since the PANAS results showed significant changes in the positive and negative affects of the general population, VisualEars may also be an accessible intervention for addressing the sub-clinical increase in anxiety and stress due to COVID-19 and other similar crises.

Streaming links to musical pieces used in this study are found below. It is noted that the digital recordings of these pieces were used in the exhibit with the permission of the artists and producers.[1, 2, 3, 4, 5, 6, 7, 8]

1 https://open.spotify.com/track/2HuURRB0fsuPmU27NKikRg?si=8c094289e3c74924

2 https://open.spotify.com/track/2uiyg1Wo0f5NwHhblrf5yb?si=a358030836444c2f

3 https://open.spotify.com/track/7utrZiOvt4WzxK0wUjE1Ze?si=7bdc70ea97cb4795

4 https://open.spotify.com/track/0yU2bE32QLoEt6BWqhRJVz?si=aaab2daca5514a09

5 https://open.spotify.com/track/1GbAJjK2MTp3TA5MNB8Efo?si=014a3c80f67c4716

6 https://open.spotify.com/track/068Ygx4bG8siAjLQo8t5rc?si=277f9ddf26554c21

7 https://music.apple.com/ca/album/malka-moma-si-se-bogu-moli/907819024?i=907819082

8 https://www.youtube.com/watch?v=cHkXM-i_1MU

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Ethics statement

The studies involving human participants were reviewed and approved by the REB York University. The patients/participants provided their written informed consent to participate in this study. This study was approved by the Certificate #: STU 2021-044 (Approval Period: April 30, 2021–2022).

Author contributions

SH designed, conceived of the experiment, and created the online interface. KK and GM conducted statistical analysis. JD supervised the entire process. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Determining factors for compensatory movements of the left arm and shoulder in violin playing

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Introduction: Despite a large number of available ergonomic aids and recommendations regarding instrument positioning, violin players at any proficiency level still display a worrying incidence of task-specific complaints of incompletely understood etiology. Compensatory movement patterns of the left upper extremity form an integral part of violin playing. They are highly variable between players but remain understudied despite their relevance for task-specific health problems.

Methods: This study investigated individual position effects of the instrument and pre-existing biomechanical factors likely determining the degree of typical compensatory movements in the left upper extremity: (1) left elbow/upper arm adduction ("Reference Angle α", deviation from the vertical axis), (2) shoulder elevation ("Coord x", in mm), and (3) shoulder protraction ("Coord y", in mm). In a group of healthy music students (N=30, 15 m, 15 f, mean age = 22.5, SD = 2.6), "Reference Angle α" was measured by 3D motion capture analysis. "Coord x" and "Coord y" were assessed and ranked by a synchronized 2D HD video monitoring while performing a pre-defined 16-s tune under laboratory conditions. These three primary outcome variables were compared between four typical, standardized violin positions varying by their sideward orientation ("LatAx-CSP") and/or inclination ("LoAx-HP") by 30°, as well as the players' usual playing position. Selected biomechanical hand parameter data were analyzed as co-factors according to Wagner's Biomechanical Hand Measurement (BHM).

Results: Mean "Reference Angle α" decreased significantly from 24.84±2.67 to 18.61±3.12° (p<0.001), "Coord x" from 22.54±7.417 to 4.75±3.488 mm (p<0.001), and "Coord y" from 5.66±3.287 to 1.94±1.901) mm (p<0.001) when increasing LatAx-CSP and LoAx-HP by 30°. Concerning the biomechanical co-factors, "Reference Angle α", "Coord y", but not "Coord x", were found to be significantly increased overall, with decreasing passive supination range (r=−0.307, p=<0.001 for "Passive Supination 250g/16Ncm", and r=−0.194, p=<0.001 for "Coord y"). Compensatory movements were larger during tune sections requiring high positioning of the left hand and when using the small finger.

Discussion: Results may enable to adapt individually suitable instrument positions to minimize strenuous and potentially unhealthy compensation movements of the left upper extremity.

KEYWORDS

violin ergonomics, 3D motion capture, 2D video analysis, biomechanics, music physiology, musicians' medicine, prevention

1. Background

There is a growing awareness and number of publications on the epidemiology of task-specific health issues in professional musicians in general (Fishbein et al., 1988; Wu, 2007; Vervainioti and Alexopoulos, 2015; Berque et al., 2016) and players of high-stringed instruments specifically. Research dedicated to the latter group reports some of the highest levels of task-specific health problems (Fry, 1986; Dawson, 2001; Berque and Gray, 2002; Aki and Yakut, 2003; Vinci et al., 2015; Kochem and Silva, 2017). Contributing co-factors may be one-sided posture and movement patterns when acquiring the necessary skills (Ericsson et al., 1993; Mornell, 2009; Ranelli et al., 2011; Gembris et al., 2020), but also the realities of professional activity encountered later on when performing and teaching (Spahn et al., 2014; Steinmetz, 2016; Smithson et al., 2017; Rensing et al., 2018; Schemmann et al., 2018; Gembris et al., 2020; Zaza and Farewell, 2001). The prevention of task-specific health problems in musicians has been receiving increased attention, with a growing number of initiatives offering musicians concepts on how to safeguard their health at various stages of their career (Spahn et al., 2001; Hildebrandt and Nübling, 2004; Hildebrandt, 2009, 2017). The scientific basis for a better understanding of ergonomics in violin playing and teaching is gaining grounds (Szende and Nemessury, 1971; Ackerman and Adams, 2004; Wagner, 2005; Wagner, 2012; Rensing et al., 2018; Chi et al., 2020), but co-exists with a wide and contradictory spectrum of long-standing teaching and performing traditions (Flesch, 1978; Galamian, 1983; Rostal, 1993; Rônez-Kubitschek, 2012). Gaining insight into the use of the left upper extremity when playing the violin is a research topic often contributed to in recent years (Blum, 1995a,b; Zaza, 1998; Künzel, 2000; Ackermann and Adams, 2003; Shan and Visentin, 2003; Nyman et al., 2007; Rabuffetti et al., 2007; Wahlström and Fjellman-Wiklund, 2009; Obata and Kinoshita, 2012; Lee et al., 2013; Reynolds et al., 2014; Möller et al., 2018). Nevertheless, only few studies focusing on individual physical predispositions concerning the instrument could be identified (Ackermann and Roger, 2003; Steinmetz et al., 2006; Storm, 2006; Rabuffetti et al., 2007; Seidel et al., 2009). The number of studies dedicated to electromyographic (EMG) measurements of violinists is growing. They examine a broad spectrum of relevant aspects, such as the influence of ergonomics, anthropometrics, and repertoire (Philipson et al., 1990; Cattarello et al., 2017, 2018; Kok et al., 2019; Chi et al., 2020; Mann et al., 2021), the comparison between muscle activation levels in healthy violinists and those reporting task-specific health problems (Spahn et al., 2001; Berque and Gray, 2002; Fjellman-Wiklund et al., 2004; Hildebrandt and Nübling, 2004; Moore et al., 2008; McCray et al., 2016), muscular variability, endurance and fatigue aspects of violin performance (Shan et al., 2004; Wagner, 2005; Gembris et al., 2020; Rousseau et al., 2020). In contrast, research comparing subjectively perceived effort levels and objective data on muscle activation when playing the violin appears to be scarcer (Chan et al., 2000; Hildebrandt et al., 2021). While contributions to the research on anthropometrics of violin playing are available (Ackermann and Adams, 2003; Visentin et al., 2008; Shan et al., 2012; Kelleher et al., 2013; Visentin et al., 2015; Chi et al., 2020), the research of Christoph Wagner on the biomechanics of musicians' hands remains a cornerstone in this area. It offers the possibility of measuring and understanding intra-individual differences between passive and active mobility ranges attributable to biomechanical co-factors. These in turn are relevant for the performance of an instrument and thus forms an element of this research and paper (see also section 3.4.3 Wagner, 1974, 1977, 2005, 2012; Wilson et al., 1991, 1993; Margulies and Hildebrandt, 2014; Hildebrandt and Margulies, 2018; Nemcova and Hildebrandt, 2018; Hildebrandt et al., 2019; Margulies et al., 2021; Zurich Centre for Musicians' Hands, 2022).

2. Aims, research question, and current status of research

2.1. General aims

This research project aims to contribute to the scientific foundation of an individualized ergonomic approach to violin positioning for playing, thereby offering ways of preventing task-specific health problems and delineating solutions for violinists in a rehabilitation or a learning environment.

2.2. Research question

For this publication, the research focuses on how an instrument's given position affects the degree of compensation movements of the left upper extremity and how individual biomechanical properties of the left upper extremity factor into the pattern of compensation movements.

2.3. Current status of own research

Summarizing recently published findings for muscle activation (EMG) and subjectively perceived effort (Borg-Scale) in violin players, it was shown that muscle activation and perceived effort within the violinists' left arm increased when the sideward orientation and inclination of the instrument in playing were smaller in angle relative to the respective plane (see Figure 1; Hildebrandt et al., 2021).

With a 30° decrease in the instrument's sideward orientation (i.e., the instrument's longitudinal axis nearer the central sagittal plane and more in front of the player) and the instrument's inclination (i.e., the instrument's lateral axis nearer the horizontal plane and flatter), mean values of overall muscle activation and subjectively perceived effort in the violinist's left arm increased highly significantly and independently. Among the four muscles measured due to their involvement in movements when playing the violin (i.e., *M. pectoralis* major, *M. biceps brachii*, *M. extensor carpi ulnaris*, and *M. extensor digitorum communis*), effects in muscle activation (EMG) were especially observable for the pectoralis major muscle which is mainly involved in moving the upperarm forward relative to the trunk. This can be considered a typical compensation movement in violin performance, the analysis of which is at the core of this paper.

2.4 Specific aims linked to this paper

This paper aims to describe:

(a) The degree of compensation movement of a player's left upper extremity when playing the violin in four standardized instrument positions and a player's normally used instrument position (see Table 1 below). The degree of compensation movement becomes observable, (i) in the player's left elbow's movements relative to the central sagittal plane, and (ii) in the movements of the player's left acromion in a combined upward and forward movement (elevation and protraction).

(b) How specific biomechanical parameters affect the other target parameters included in this study (see section 3.4 below).

2.5. Hypotheses

2.5.1. Hypotheses for compensation movements in left elbow and acromion

For compensation movements in the left elbow and acromion, the following hypotheses were formulated:

The degree of compensation movement of a violinist's left elbow expressed as "Reference Angle α" (see section 3.4.1), "Coord x" for shoulder protraction, and "Coord y" for shoulder elevation seen in the left acromion (see section 3.4.2) will increase, (1) the more the longitudinal axis (LoAx) of the instrument points toward the front, i.e., approaches the player's central sagittal plane (CSP)

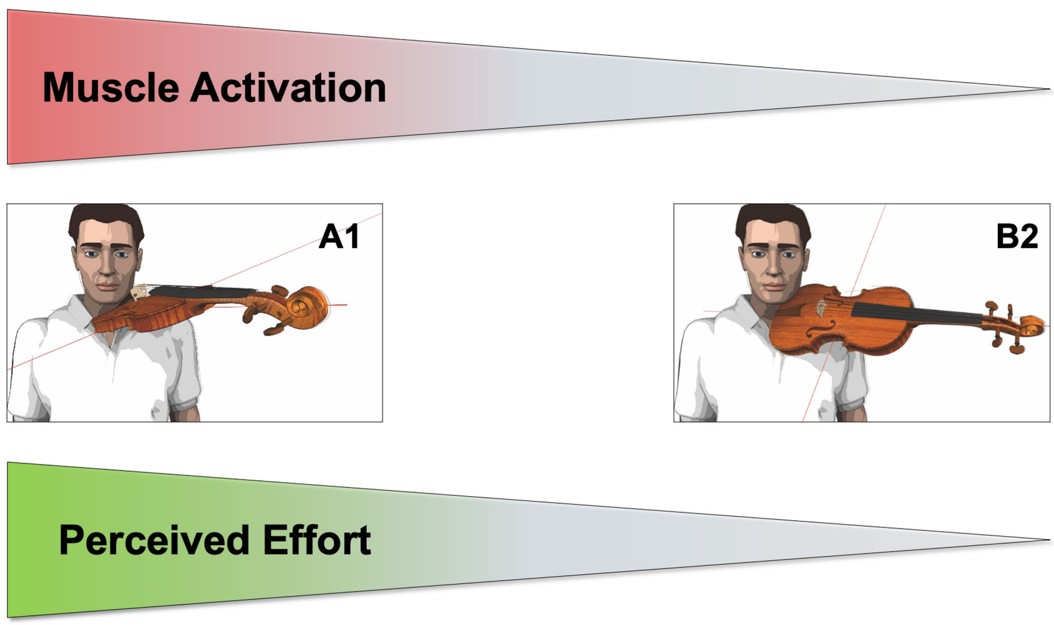


FIGURE 1
Schematic illustration of the influence of an instrument's sidewards orientation and inclination on muscle activation and perceived effort.

by reducing the angle between LoAx and CSP from 50° to 20° (see Table 1: violin positions B vs. A), and (2) the more horizontal the lateral axis (LatAx) of the instrument approaches the player's horizontal plane (HP) by reducing the angle between LatAx and HP from 50° to 20° (see Table 1: violin positions 2 vs. 1).

2.5.2. Sub-hypotheses for biomechanics

For biomechanics, the following two sub-hypotheses were formulated:

Sub-hypothesis 1: The lower the passive supination ability (see section 3.4.3), the higher the degree of compensation movement in the violinist's left arm when playing.

Sub-hypothesis 2: The shorter the length of the little finger in comparison with the length of the middle finger (see section 3.4.3) and the lower the passive thumb spreading ability (see section 3.4.3), the higher the degree of compensation movement in the violinist's left arm when playing.

3. Materials and methods

3.1. Study design

The study was designed as a cross-sectional study. It included 30 healthy violinists (15 male and 15 female) in professional formation (BA and MA studies). Study participants were recruited from Swiss music universities and the Vorarlberg State Conservatory, Feldkirch, Austria. The mean age of the study population was 22.5 years (Min. 18, Max. 29 years, SD = 2.6). The study was approved by the Canton of Zürich Ethics Committee (project no. KEK-ZH-Nr. 2014–0008). Study participants gave their informed consent prior to participation.

3.2. Measurement steps

(a) Study participants were asked to play a pre-defined 16-s tune (Figure 2) during ongoing comparative measurements of compensation movements. The tune was played in four randomized and standardized violin positions of a laboratory instrument (see Table 1 and Technical Prerequisites below).

(b) The tune was measured identically, but with study participants playing on their own instrument and with their normally used ergonomic equipment, thereby supporting the weight of the instrument as usual but remaining in the standardized body position as required for the previously measured violin positions A1 through B2 (Table 1 and Figure 3).

The tune included a total of three note sequences with a low ("a") vs. high ("b") small finger (digitus minimus, see Figure 2) in both the sixth and second hand position. Finger placement "a" represents a more rounded finger closer to the ring finger, and finger placement "b" a more extended finger abducted from the ring finger. Both fourth-finger positions are frequently required in violin performance.

(c) Biomechanical data was collected in the hand laboratory available to the research team (see section 3.4.3).

3.3. Technical prerequisites

3.3.1. Standardization of violin positions

Ensuring measurements under standardized conditions (see Table 1) required the development of a specific device (schematically depicted in Figure 3). This device meets the following requirements: (1) three-dimensional fitting of the laboratory violin to the player with precisely reproducible heights and angles, (2) minimization of excess holding work in head, neck, shoulder, arm, and hand while playing a laboratory instrument without ergonomic aids, and (3) exclusion of confounding variables such as individual playing and postural habits as well as ergonomic equipment (see also measurement procedures below).

This methodology allowed for intraindividual comparison between all violin positions tested (see Table 1). The standardized instrument positions were defined by estimates based on a range of recommendations of internationally renowned players' and teachers' instrument positions and considered typical in teaching traditions of the last few centuries (Flesch, 1978; Galamian, 1983; Rostal, 1993; Rônez-Kubitschek, 2012).

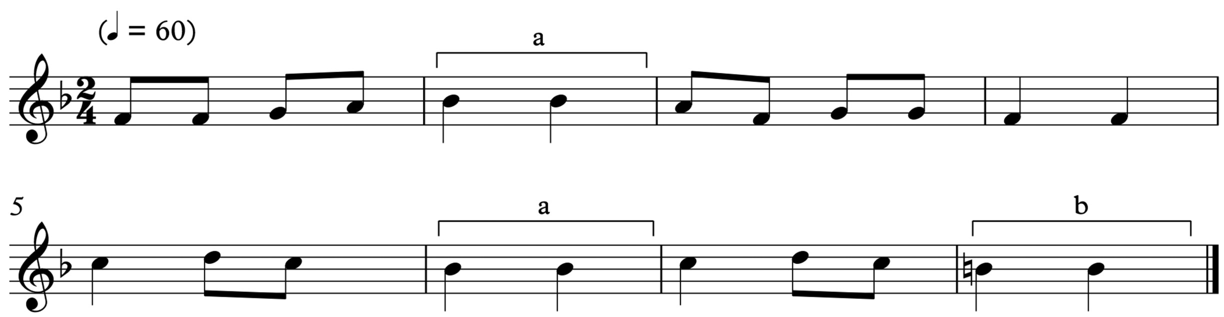
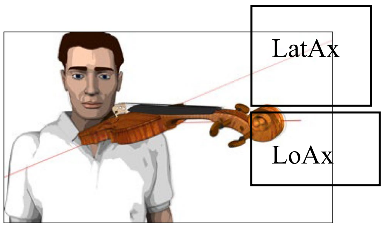
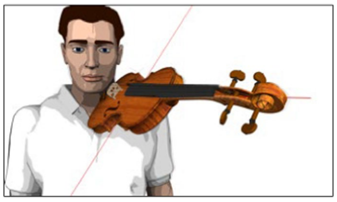


FIGURE 2
16-s tune used for measurements.

TABLE 1 Four standardized violin positions with orientation points and the free position.

Position	Description of violin position
A1 	The longitudinal central instrument axis (LoAx) is at a 20° angle to the player's central sagittal plane (CSP) and points towards the left lamina of the thyroid cartilage (vertical *via* the clavicular insertion of the left sternocleidomastoid muscle). The lateral instrument axis (LatAx) deviates 20° from the player's horizontal plane (HP).
A2 	LoAx is identical to A1 (20° deviation from player's CSP), however LatAx deviates 50° instead of 20° from HP.
B1 	LatAx is identical to A1 (20° deviation from player's HP), however, LoAx deviates 50° instead of 20° from the player's CSP (with the LoAx extension running to the clavicular insertion of the right).
B2 	LoAx is identical to B1 (50° from player's CSP), however LatAx deviates 50° instead of 20° from player's HP.
Free	Free playing position with normally used personal ergonomic adaptations to the violin as used in real-life setting by study participant.

The laboratory instrument had the following dimensions: body length = 354 mm, vibrating string length = 328 mm. These dimensions correspond to a standard, full-size violin commonly used. For measurements, it was fitted without ergonomic equipment (i.e., chin-rest or shoulder pad). String tension was specified by tuning the instrument to concert pitch 442 Hz.

3.4. Target parameters

3.4.1. 3D motion capture data for elbow compensation movements (Reference Angle α)

Data was acquired with an opto-electronic 3D movement analysis device, Model MCU 200, company Laitronic (Innsbruck, Austria). High-resolution recordings of infrared signals permit differentiated statements and documentation of the relative marker position changes in comparison with each other (Bannach et al., 2009). While the 16-s tune was played with a metronome set to 60 bpm, the system recorded changes in Reference Angle α values at a frame rate of 200.00 Hz. Throughout all measurements, the camera unit was kept at a constant height (160 cm), distance (190 cm) and angle (45°) relative to the study participant and experiment set-up.

Motion capture data were collected in the four standardized instrument positions, and the violinist's own normally used position with his/her own instrument (Table 1). Two markers define Reference Angle α:

1. Reference Marker 1 was positioned at a standardized height of 212 cm on the back wall of the device holding the instrument. It was aligned with the study participant's left acromion by a plumb hanging from Reference Marker 1.

FIGURE 3
Schematic illustration of instrument fitting device in experiment set-up.

2. Reference Marker 2 was positioned on the study participant's left olecranon (see Figure 4).

3.4.2. 2D motion capture data for acromion compensation movements ("Coord x" and "Coord y")

To record the shoulder's motion, a Panasonic HDC-HS300 video camera mounted on a tripod was used. For each study participant, the camera was positioned the following way: (i) the camera lens at the height of the left acromion, (ii) the longitudinal axis of the camera in-line with the acromion's transversal axis, and (iii) at a standardized distance between the study participants' acromion and the camera lens. Before filming shoulder motion, an "X" was marked on the study participant's skin for reference. Data for acromion motion were collected at the same time as data for Reference Angle α during the 16-s tune.

The target parameters for this data set were expressed as follows: (a) "Coord x" for the forward movement of the shoulder (protraction) and (b) "Coord y" for the upward movement of the shoulder (elevation). Data for "Coord x" and "Coord y" was collected at four points in time for each with a running metronome set to 60 bpm:

i) Five seconds before playing the tune, the left arm hanging in neutral position next to the body (see Figure 5).
ii) At the beginning of the first note of the tune (see Figure 2).
iii) At the beginning of bars 2 and 6 of the tune, where the regular fourth finger is played (see brackets marked "a", in Figure 2).
iv) At the beginning of the tune's last bar, where the extended fourth finger is played (see brackets marked "b", in Figure 2).

Shoulder data was collected post-measurement by replaying the video sequences on a 13-inch Apple® MacBook Air with the Software QuickTime Player, Version 10.5, in the full-screen setting with a transparent millimeter grid over the computer's screen. Data for "Coord x" and "Coord y" were generated by tracking the acromion's movements and marking the relevant points in time on the millimeter grid. This resulted in a data pair ("Coord x"/ "Coord y") expressing the degree of protraction and elevation per observed point in time. Data was then transferred onto a spreadsheet for further analysis.

3.4.3. Biomechanical data for hand parameters

For biomechanical data, the following target parameters were defined:

1) Passive supination ability of the left lower arm at torque levels 16 Ncm (or 250 g weight) and 30 Ncm (or 500 g weight): Indicates effort or ease of the hand reaching basic positions on the violin. Measurements result in an angle degree describing the deviation of the left forearm, hand, and wrist from the neutral position (Figure 6A).
2) Difference in finger length between the left hand's third and fifth fingers: Indicates the fifth finger's anatomical position (i.e., shortness relative to the middle finger (Figure 6B). Measurements result in a millimeter value.
3) Passive thumb spreading ability: Indicates the deviation of the thumb relative to the second metacarpal bone (Figure 6C). Measurements result in an angle degree value.

Passive movement range generated with an external torque is particularly relevant, as differences are more evident than in the assessment of *active* movement range (Wagner, 1977). Routine clinical examinations often record values for *active* movement

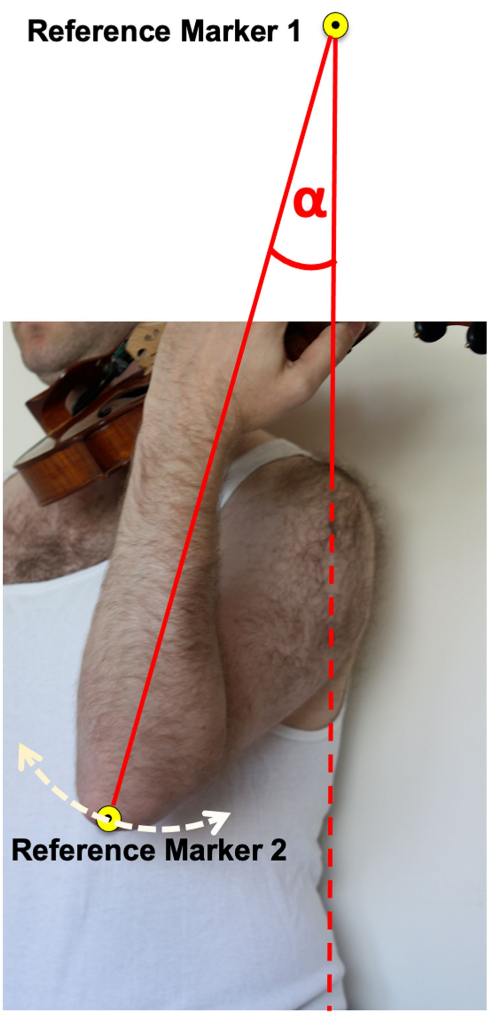


FIGURE 4
Schematic illustration of Reference Markers 1 and 2, and Reference Angle α.

range, but significant deficits in *passive* movement range with little torque remain unobserved. Such individual "movement brakes" in joint structures and tissue properties may provoke players to "force" themselves into a required playing position and provoke additional compensation movements. To measure biomechanical data, and particularly the passive movement ranges, the research team used the original laboratory apparatuses developed by Christoph Wagner for the Biomechanical Hand Measurement (BHM; Wagner, 2005; Wagner, 2012). The examination of the hand and arm only uses non-invasive, mechanical measurement methods. As a result of the measurements, an objective and differentiated image of individual, instrument-specific possibilities and limitations of the musician's hand against the background of instrument-specific comparison groups are obtained. These results then permit the comparison of individual data with the existing data pool generated over more than five decades of research from fellow professionals of a given instrument.

Finger Length Difference 3–5 is measured using a mechanical gauge with the hand in a standardized position (see Figure 6B above). For passive supination and passive thumb spreading [see Figures 6A,C above], a subject first assumes a standardized body position (standing for passive supination and sitting for passive thumb spreading). Then, the hand and arm positions of the subject are equally standardized for measurement in the apparatuses. Subjects are then instructed to remain as relaxed as possible without actively contributing to the joint movement measured. Measurements for passive mobility of the parameter are then carried out by the pre-defined torque generated by weights hanging from the apparatuses. The first moment of the hand's or arm's inner resistance against the pre-defined torque results in an angle degree. The average of three tests is then documented as the individual's measure for passive mobility. For further reference, please refer to www.zzm.ch.

3.5. Study participant positioning

The participants were asked to position themselves on the instrument fitting device's platform (see Figure 3). They stood upright, head position looking straight ahead at the music stand on which the tune was placed. Individually adjustable stabilizers were positioned on both sides of the study participants' head to ensure that no additional strain on the neck and shoulder muscles would occur during measurement. They were also instructed to choose a shoulder position they considered as relaxed as possible before going into playing position. The positions of feet and knees were defined, marked, and positioned so they could stand comfortably throughout the measurement phases. During all measurements, study participants were asked to remain relaxed but in the same body position to allow for accurate intraindividual data comparisons. The body position was documented with two video cameras (frontal and from the side).

3.6. Measurement procedure

All tests were carried out in a randomized order. Measurements for each of the four violin positions A1 to B2 (see Table 1) and the position chosen by the participant for the own instrument (Free) included the following steps:

a. Within a 10-s countdown, the participant went into playing position with the left hand.
b. The fingers were positioned over the notes specified by the tune on the lowest string in sixth position.
c. The participant played the tune (Figure 2) without a bow and then let the left hand sink back down again into the relaxed starting position.
d. During a break, the study participant relaxed the hand and arm (movements, self-massage, tapping, and shaking were avoided) (Hildebrandt et al., 2021).

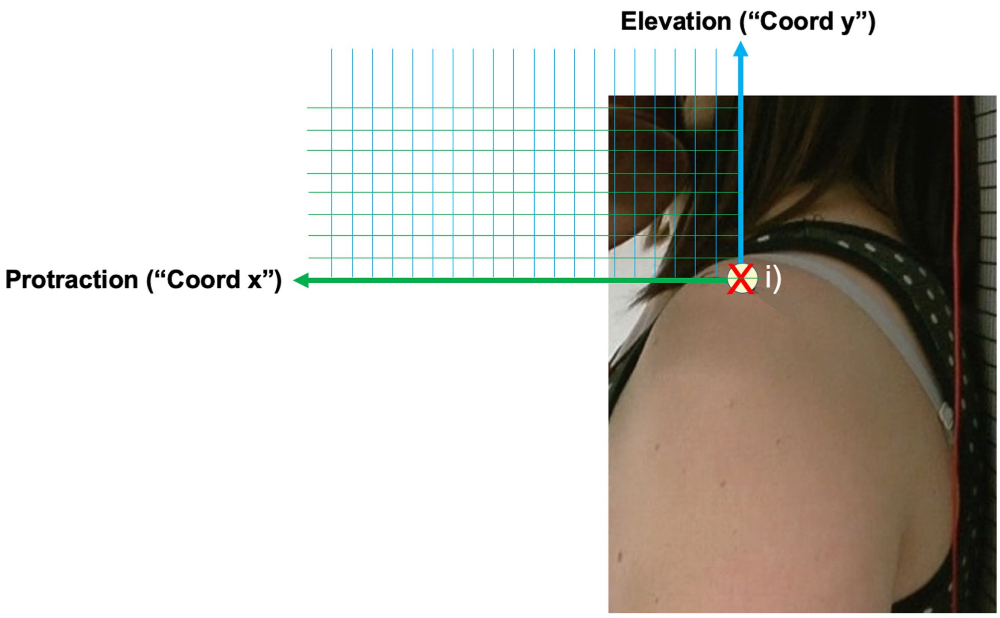


FIGURE 5
Schematic illustration of acromion motion and measuring grid.

e. The same procedure was applied when playing the tune in second position and a second time in the sixth position.

To rule out fatigue effects on compensation movement patterns attributable to playing in the more demanding sixth position for a prolonged time, alternating between the sixth and the second playing position was invariably applied for all violin positions tested. Means of the sixth and second playing positions were used to compare the five violin positions tested.

3.7. Statistical procedures

For 3D motion capture analysis describing elbow and upper arm compensation movement, measurements of the 30 study participants playing 15 repeats of the tune yielded a total of 450 observations for "Reference Angle α" For 2D motion capture data describing shoulder motion, measurements yielded a total of 450 observations per point in time observed for "Coord x" and "Coord y" each. Biomechanical data collected yielded a total data set of 30 observations per parameter (one measurement per person).

For 3D motion capture data, mean values for "Reference Angle α" were calculated by hand position for each of the five pre-defined violin positions (A1, B1, A2, B2, and Free) and the overall mean value for all 450 data points. For 2D data, mean values for "Coord x" and "Coord y" were calculated by hand position for all four points in time and all violin positions tested. For biomechanical data, mean values were calculated for each of the parameters examined.

The separate contribution of the five violin positions under test to elbow/upper arm compensation (3D), shoulder motion (2D) and biomechanical data variability was assessed by multiple linear regression analysis, choosing position A1 as the reference category, describing deviations from A1 for the other four positions.

A sub-analysis for 3D data was carried out for the entire duration of the 16-s tune as well as the time segments where the normal and high fourth (small) finger was used in both second and sixth hand position (Figure 2, brackets "a" and "b"). Differences in overall 3D and 2D values between the single instrument and finger positions were assessed for all combinations by a *post hoc* multiple comparison of means (Scheffé), with significance levels reported as $^{*}p<0.05$, $^{**}p<0.01$, and $^{***}p<0.001$. Correlations (Pearson's r) were calculated between the following parameters: (a) shoulder motion data (2D) and elbow/upper arm compensation movement (3D), (b) biomechanical parameters and elbow/upper arm compensation movement (3D) and (c) shoulder motion data (2D) and biomechanical parameters, with significance levels reported as $^{*}p<0.05$, $^{**}p<0.01$, and $^{***}p<0.001$.

All data analysis was carried out using the SPSS 20 statistics program for Windows (IBM SPSS, Armonk, NY, United States).

4. Results

4.1. Results for the entire 16-s tune by instrument position

4.1.1. Elbow/upper arm compensation movement by instrument position (Reference Angle α)

A comparison between the five tested violin positions (see Table 1) shows the highest degrees of elbow/upper arm compensation

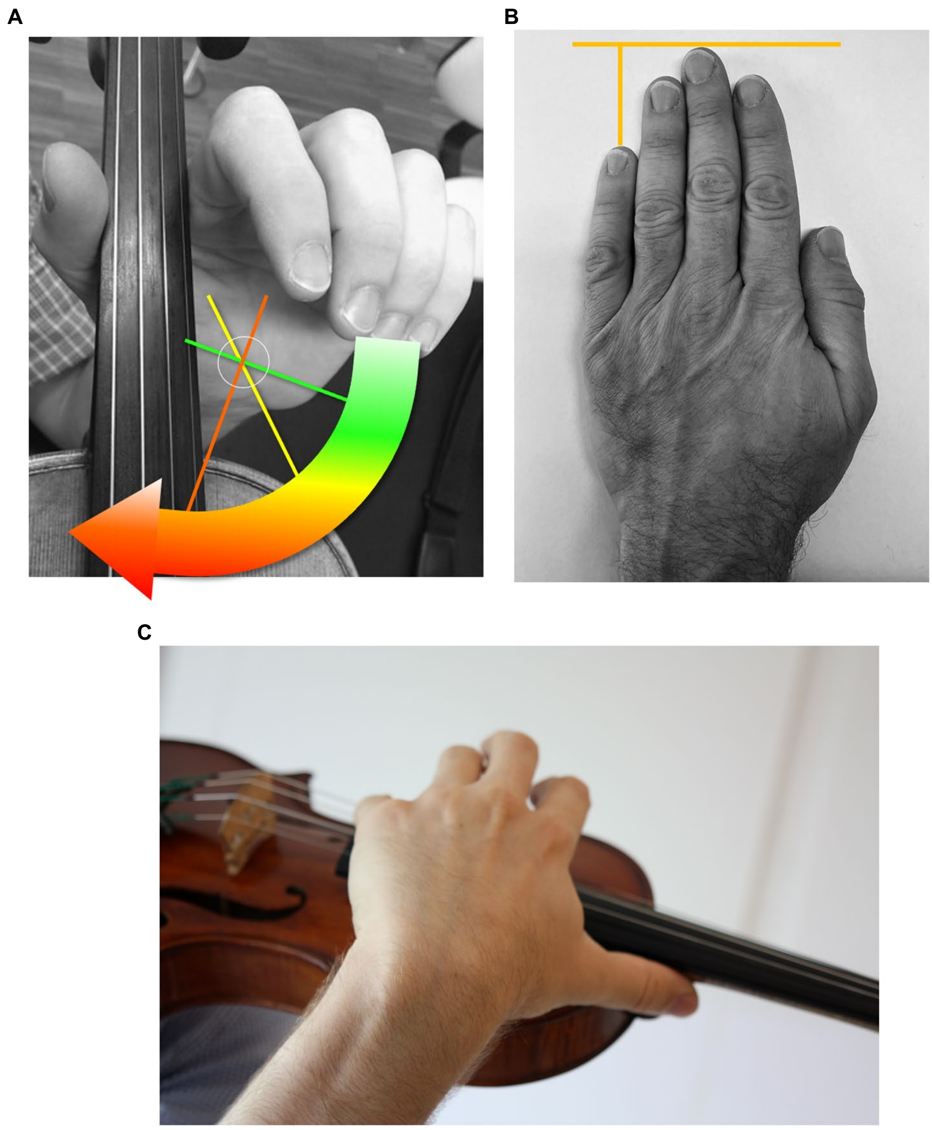


FIGURE 6
(A) Passive supination range. **(B)** Difference in finger length between third and fifth fingers. **(C)** Thumb spreading in high positions on the violin.

for violin position A1 compared to all other positions and the lowest values for violin position B2, the overall mean of aggregated data (corresponding to the dashed line in Figures 7, 8) is 3.5 points lower than A1 (see Figures 7, 8 and Supplementary Table S1).

Multiple regression analysis for "Reference Angle α" by instrument position shows highly significant differences between violin position A1 and all other instrument positions ($N=90$, $p<0.001$, $r^2=0.353$). R^2 for the entire model explains 35% variance of elbow/upper arm compensation movement considering all hand positions for a given instrument position (see Figure 9 below and detailed regression analysis in Supplementary Table S2).

A *post hoc* multiple comparison of means (Scheffé) shows that, for all hand positions united ($N=450$), mean values between single instrument positions differ highly significantly between each other ($p<0.001$), except A2 to B1 and B2 to Free ($p<0.844$ and $p<0.707$, therefore non-significant). For further details, refer to Supplementary Table S3.

4.1.2. Shoulder compensation movements by instrument position ("Coord x"/"Coord y")

For shoulder motion data in both x-and y-direction, the highest values are observed for instrument position A1 and the lowest for B2. The gradation of values follows the same pattern for both shoulder movement directions. Values for "Coord x" (protraction) are higher than for "Coord y" (elevation). Instrument Position Free shows values comparable with instrument position B1 for protraction and A1 for elevation. Overall values uniting all instrument and hand positions show higher values for protraction than for elevation (see Figure 10 above and Supplementary Table S4).

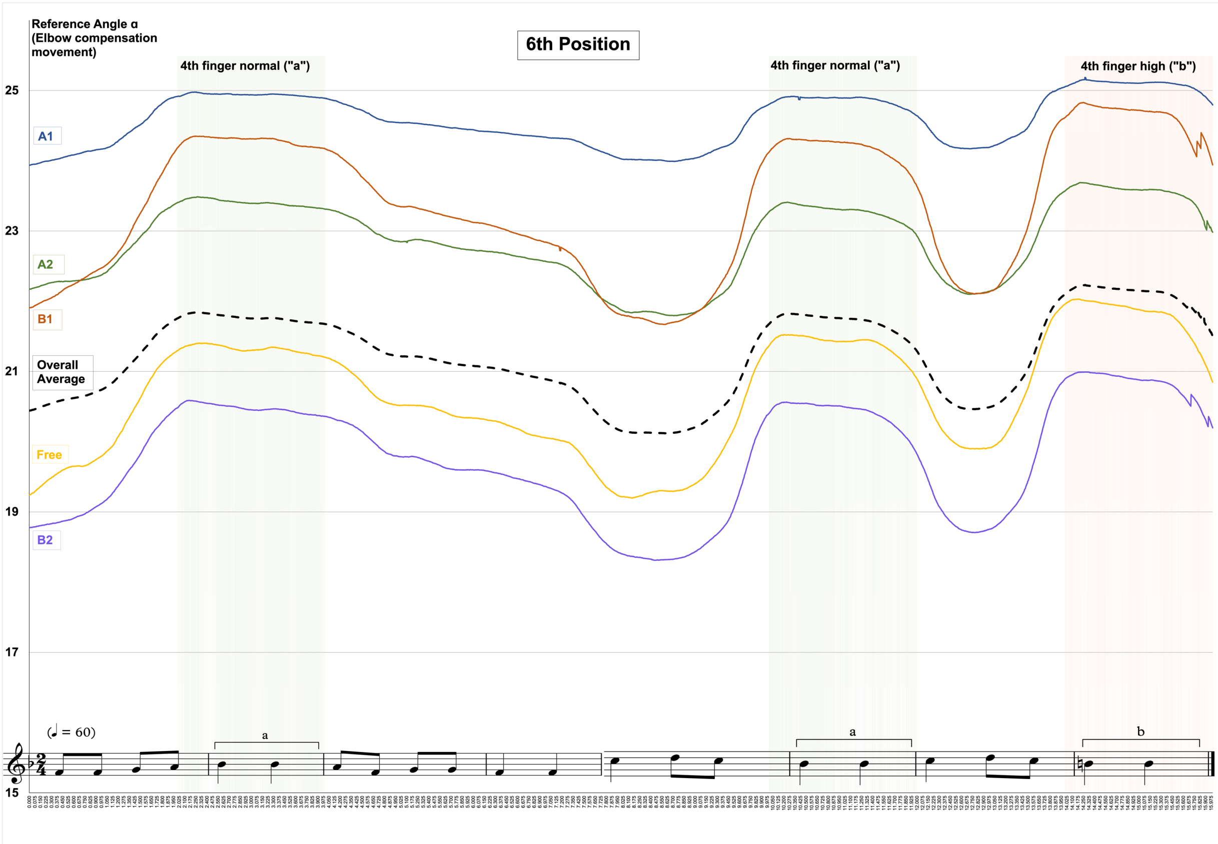


FIGURE 7
Changes in Reference Angle α by instrument position and overall mean when playing in sixth hand position.

Multiple regression analysis for "Coord x" (shoulder protraction) for the entire model, including all instrument and hand positions, shows highly significant differences between instrument position A1 and all other instrument positions ($N=90$, $p<0.001$, $r^2=0.536$), thereby explaining 53% of shoulder protraction movement variance when considering all instrument and hand positions.

Multiple regression analysis for "Coord y" (shoulder elevation) for the entire model, including all instrument and hand positions, shows highly significant differences between instrument position A1 and positions B1 ($N=90$, $p<0.001$, $r^2=0.226$) and B2 ($N=90$, $p<0.001$, $r^2=0.226$). Differences between instrument position A1 and position A2 reach the next-highest significance levels ($N=90$, $p<0.01$, $r^2=0.226$), and differences between instrument position A1 and position Free are non-significant ($N=90$, $p=0.360$, $r^2=0.226$). R^2 for the entire model is 0.226, thereby explaining between 22% of shoulder elevation movement variance when considering all instrument and hand positions (see Figure 10, above and detailed regression analysis in Supplementary Table S5).

A *post hoc* multiple comparison of means (Scheffé) shows that, for all hand positions united ($N=449$) and shoulder protraction ("Coord x") mean values between single instrument positions differ highly significantly between each other ($p<0.001$), except between instrument position B1 and Free (non-significant). The same *post hoc* test for shoulder elevation ("Coord y") shows highly significant differences in 12 out of 20 position comparisons ($p<0.001$), two significant differences between instrument positions A1 and A2 ($p<0.05$), and six non-significant differences between A1 and Free, A2 and Free as well as B1 and B2. For further details, refer to Supplementary Table S6.

Based on data presented in sections 4.1.1 and 4.1.2, the main hypothesis regarding instrument position effects on the degree of elbow and upper arm compensation (see section 2.5.1 above) is confirmed. For shoulder motion data, the main hypothesis is confirmed for shoulder protraction ("Coord x") and partially confirmed for shoulder elevation ("Coord y").

4.1.3. Results for biomechanical data

For biomechanical parameters investigated, Table 2 offers an overview of the data collected.

The linear relationship between the biomechanical parameters and "Reference Angle α" for the entire duration of the tune was assessed by computing Pearson's *r* correlation coefficient for all five instrument positions singly and aggregated, all hand positions united, and all three time points under test.

The same linear relationship was assessed for the biomechanical parameters and shoulder protraction ("Coord x")

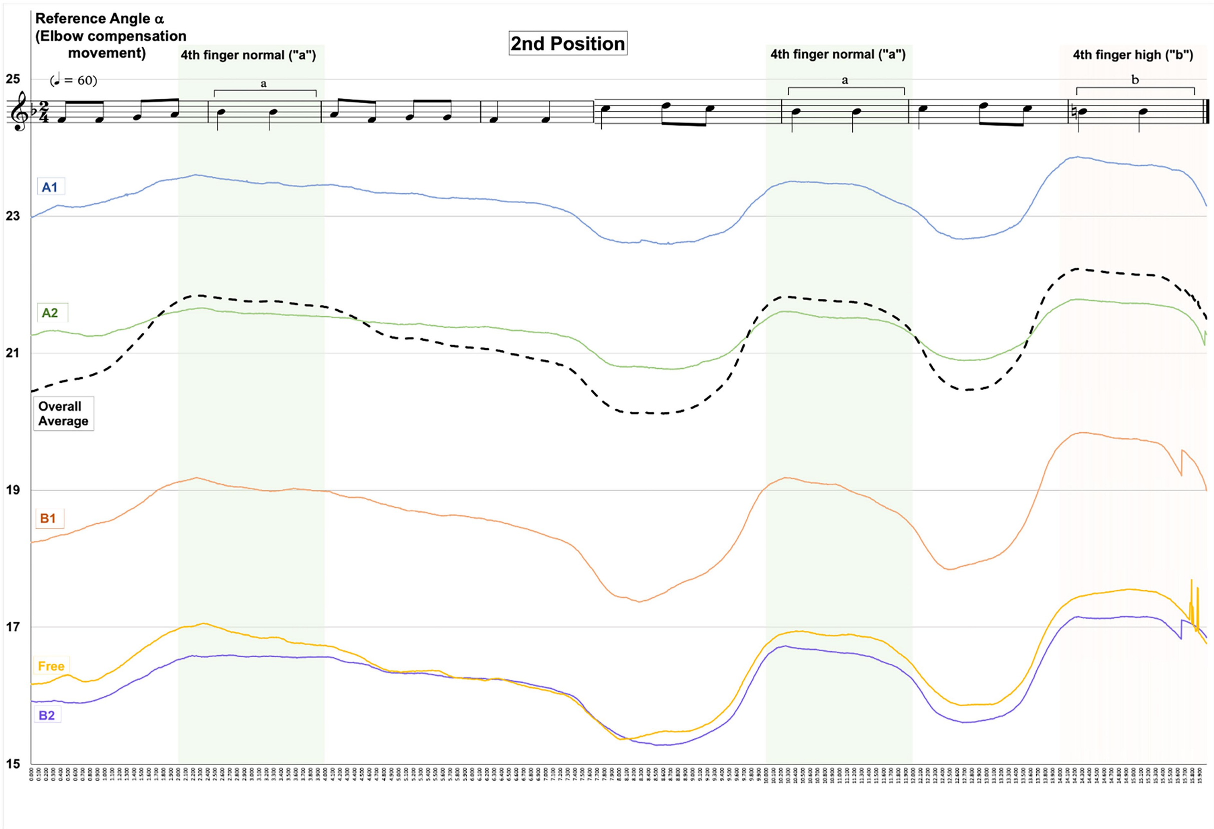


FIGURE 8
Changes in Reference Angle α by instrument position and overall mean when playing in second hand position.

as well as shoulder elevation ("Coord y") for the entire duration of the tune.

For the correlations between biomechanical parameters "Passive Supination 250 g" as well as "Passive Supination 500 g" and "Reference Angle α" for all instrument positions under test, including data for all positions aggregated ("Overall"), data shows highly significant negative correlations. The only exception to this rule is observed for "Passive Supination 250 g" for instrument position "Free", where significance levels reach the lowest level ($p < 0.05$; see Table 3).

For shoulder elevation ("Coord y"), data shows negative correlations for "Passive Supination 250 g" except for instrument position Free, and negative correlations for "Passive Supination 500 g" for instrument position A1 ($r = -0.268$, $p < 0.05$).

For the biomechanical parameter "Passive Thumb Abduction," data shows positive correlations for instrument positions A1 ($r = 0.270$, $p < 0.05$), A2 ($r = 0.255$, $p < 0.05$), B2 ($r = 0.226$, $p < 0.05$) and Overall ($r = 0.143$, $p < 0.01$). For instrument positions B1 and Free, correlations are non-significant. For biomechanical parameter "Finger Length Difference 3-5", data shows no significant correlations. For detailed regression analysis results, please refer to Supplementary Table S7.

The sub-hypotheses focusing on the contribution of biomechanical parameters to the target parameters elbow/upper arm and shoulder compensation movement (see section 2.5.2) were confirmed for "Passive Supination", not confirmed for "Passive Thumb Abduction" (positive instead of negative correlation) and not confirmed for "Finger Length Difference 3-5" (non-significant correlation).

4.2. Results for the entire 16-s tune by hand and instrument position

4.2.1. Influence of sixth and second hand position on elbow/upper arm compensation movement

The following Figures 7, 8 show the patterns and degrees of elbow/upper arm compensation movements expressed as "Reference Angle α" when playing the entire 16-s tune in each of

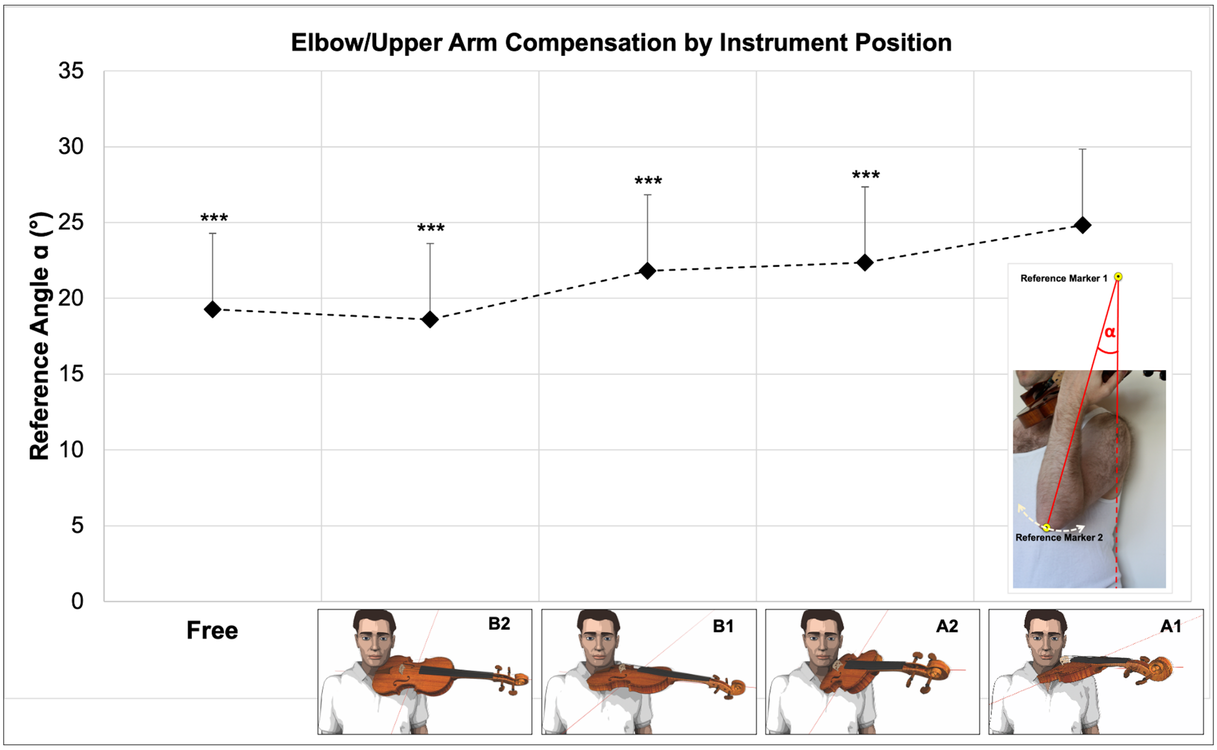


FIGURE 9
Degree of elbow/upper arm compensation movement expressed as Reference Angle α_ by instrument position. Differences between violin position A1 and all other instrument positions under test are highly significant ($p < 0.001$).

the instrument positions under test, as well as highlighted time sections for the normal fourth fingers (green sections) and high fourth finger (red section).

Changes in values for "Reference Angle α" follow a similar pattern for all instrument and hand positions with a characteristic increase during the time the fourth fingers are played. Values for "Reference Angle α" are at higher levels for sixth position than for second position, and the gradation of values for "Reference Angle α" shows the same pattern, in that instrument position A1 yields the highest, and B2 the lowest levels. However, for sixth hand position, instrument position B1 reaches higher levels than A2, whereas for second hand position A2 precedes B1.

Comparing "Reference Angle α" values of the instrument positions under test with an overall mean (all instrument and hand positions aggregated, black dashed line in Figures 7, 8) shows three instrument positions A1, A2, and B1 above average and two instrument positions Free and B2 below average for sixth hand position. For second position, one instrument position (A1) is above average, position A2 is at the same level as the overall mean, and the remaining instrument positions B1, Free, and B2 are below average. Overall mean values are approx. 4.3 points below instrument position A1. This applies both to the entire duration of the 16-s tune (see Table 4 below) and the moments when the fourth finger normal and fourth finger low are played (see Table 6 below).

Multiple regression analysis for "Reference Angle α" for sixth hand position shows highly significant differences between violin position A1 and all other instrument positions ($N = 60$, $p < 0.001$, $r^2 = 0.398$), thereby explaining nearly 40% of elbow/upper arm compensation movement variance when considering all measurements in sixth hand position for a given instrument position. Results for second hand position follow the same pattern ($N = 30$, $p < 0.001$, $r^2 = 0.529$), however, with significance levels for instrument A2 being $p < 0.01$. R^2 for this model is 0.592, thereby explaining 59% of elbow/upper arm compensation movement variance when considering all measurements in second position for a given instrument position. For detailed regression analysis results please refer to Supplementary Table S8.

For sixth hand position, a *post hoc* multiple comparison of means (Scheffé) shows that, for all hand positions united ($N = 300$), mean values between single instrument positions for the entire 16-s tune differ highly significantly between each other ($p < 0.001$) except between instrument positions A2 and B1 as well as B2 and Free (non-significant).

For second hand position, a *post hoc* multiple comparison of means (Scheffé) shows that, for all hand positions united ($N = 300$), mean values between single instrument positions for the entire 16-s tune differ highly significantly between each other ($p < 0.001$) except between instrument positions A2 and B1 ($p < 0.01$), B2 and

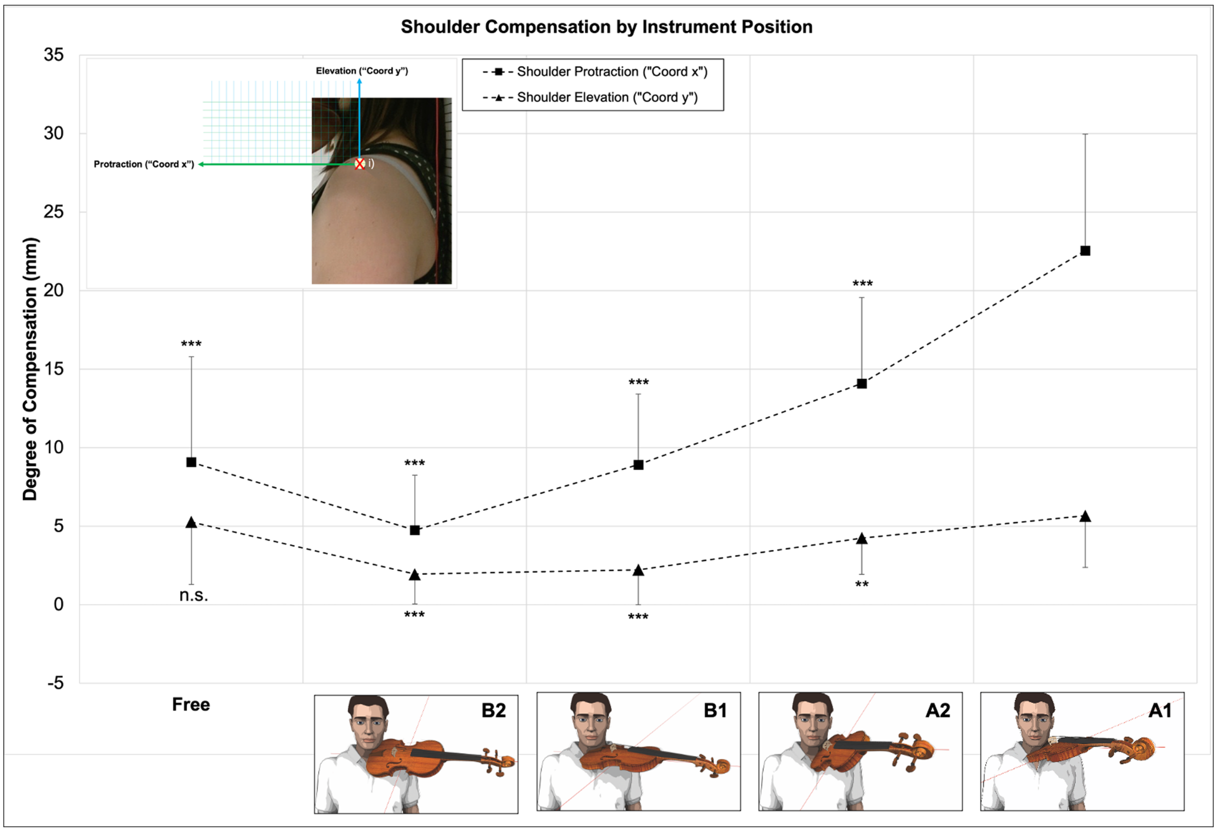


FIGURE 10
Degree of shoulder compensation movement expressed as "Coord x" and "Coord y" by instrument position. Differences between violin position A1 and all other instrument positions under test highly significant (p < 0.001), except for A2 in "Coord y" (p < 0.01) and Free in "Coord y" (n.s.).

TABLE 2 Descriptive statistics for biomechanical data (N=30 per parameter).

Biomechanical parameter	*N*	Mean	Min.	Max.	*SD*
Finger Length Difference 3-5	30	36.98	28.5	46.0	3.690
Passive Supination 250 g (16 Ncm torque)	30	51.47	5.0	106.0	34.516
Passive Supination 500 g (32 Ncm torque)	30	84.48	17.0	122.0	23.345
Passive Thumb Abduction 250 g (25 Ncm torque)	30	50.60	39.0	65.0	7.206

B1 ($p < 0.05$) as well as Free and B1 ($p < 0.05$). Differences between instrument positions A1 and A2 as well as B2 and Free are non-significant.

4.2.2. Influence of sixth and second hand position on shoulder compensation movement by instrument position ("Coord x"/"Coord y")

For shoulder motion data (all points in time aggregated, see section 3.4.2) at the level of sixth and second hand position, highest values are observed for instrument position A1 and lowest for B2 with a distinctive gradation of values, i.e., A1 > A2 > B1 > Free>B2. This gradation applies both to shoulder protraction ("Coord x") as well as to shoulder elevation ("Coord y"). Values for protraction are higher than for elevation (see Table 5 below).

For sixth hand position, multiple regression analysis for shoulder protraction ("Coord x") shows highly significant differences between violin position A1 and all other instrument positions ($N = 60$, $p < 0.001$, $r^2 = 0.711$), thereby explaining 70% of shoulder protraction variance when considering all measurements in sixth hand position for a given instrument position. For shoulder elevation ("Coord y"), differences between violin positions A1 and B1 as well as B2 are highly significant ($N = 60$, $p < 0.001$, $r^2 = 0.456$), and the difference between A1 and instrument positions A2 and Free are non-significant. R^2 for this model explains 45% of shoulder elevation variance.

TABLE 3 Correlation analysis between biomechanical data and Reference Angle α as well as data for shoulder elevation data *p < 0.05, **p < 0.01, and ***p < 0.001.

Instrument position	N	Biomechanical parameter	Reference Angle α		Shoulder protraction ("Coord x")		Shoulder elevation ("Coord y")	
			r	p	r	p	r	p
A1	90	Passive Supination 250 g	−0.469	<0.001 (***)	0.029	0.783	−0.320	<0.05 (*)
	90	Passive Supination 500 g	−0.490	<0.001 (***)	0.040	0.710	−0.268	<0.05 (*)
A2	90	Passive Supination 250 g	−0.525	<0.001 (***)	0.020	0.850	−0.287	<0.01 (**)
	90	Passive Supination 500 g	−0.529	<0.001 (***)	−0.060	0.573	−0.206	0.051
B1	90	Passive Supination 250 g	−0.365	<0.001 (***)	0.076	0.474	−0.302	<0.01 (**)
	90	Passive Supination 500 g	−0.349	<0.01 (**)	0.022	0.838	−0.060	0.573
B2	90	Passive Supination 250 g	−0.384	<0.001 (***)	0.112	0.294	−0.326	<0.01 (**)
	90	Passive Supination 500 g	−0.400	<0.001 (***)	0.090	0.398	−0.154	0.147
Free	90	Passive Supination 250 g	−0.257	<0.05 (*)	−0.027	0.803	−0.032	0.765
	90	Passive Supination 500 g	−0.313	<0.01 (**)	−0.123	0.249	0.144	0.175
Overall	450	Passive Supination 250 g	−0.307	<0.001 (***)	0.021	0.655	−0.194	<0.001 (***)
	450	Passive Supination 500 g	−0.321	<0.001 (***)	−0.011	0.821	−0.075	0.112

TABLE 4 Descriptive statistics for Reference Angle α (elbow compensation movement for the entire 16-s tune.

Instrument position	N	Mean	Min.	Max.	SD
By instrument position and for sixth hand position (Figure 7)					
A1	60	25.64	22.0	32.4	2.476
A2	60	22.86	19.1	29.4	2.110
B1	60	23.39	18.7	32.0	2.729
B2	60	19.78	15.4	28.7	2.646
Free	60	20.68	15.1	28.4	2.831
Overall mean for all instrument and hand positions (dashed line --- in Figures 7, 8)					
Overall mean	450	21.38	12.0	32.0	3.779
By instrument position and second hand position (Figure 8)					
A1	30	23.25	19.7	29.6	2.325
A2	30	21.35	16.7	27.4	2.356
B1	30	18.68	13.4	26.2	2.729
B2	30	16.27	11.7	22.7	2.688
Free	30	16.48	11.6	23.4	2.946

For second hand position, multiple regression analysis for shoulder protraction ("Coord x") shows highly significant differences between violin position A1 and all other instrument positions ($N = 30$, $p < 0.001$, $r^2 = 0.400$), explaining 40% of shoulder protraction variance. For shoulder elevation ("Coord y"), significance levels are reached for instrument position B1 ($N = 30$, $p < 0.01$, $r^2 = 0.189$) as well as B2 and Free ($N = 30$, $p < 0.05$, $r^2 = 0.189$). The difference between instrument position A1 and A2 is non-significant (see Supplementary Table S9).

For sixth hand position, a *post hoc* multiple comparison of means (Scheffé) shows that for shoulder protraction ("Coord x"), mean values between single instrument positions differ highly significantly between each other ($p < 001$) and significantly between instrument positions B1 and B2 ($p < 0.05$) as well as B2 and Free ($p < 0.010$). The difference between instrument position B1 and Free is non-significant.

For shoulder elevation ("Coord y"), highly significant differences between single instrument positions are observed for A1 and B1 as well as B2, B1, and A1, B1 and A1 as well as Free and B2 and A1 and Free ($p < 0.001$). The differences between A2 and B1 as well as B2 and A2 B2 reach the next-highest significance levels ($p < 0.010$). The remaining comparisons are non-significant. For further reference, please refer to Supplementary Table S10.

For second hand position, the same comparison of means for shoulder protraction ("Coord x") shows highly significant differences for A1 and B1 as well as B2, A2 and B2 and B2 and Free ($p < 0.001$). Comparisons between A1 and A2 as well as Free, A2 and B1 as well as A1 and Free reach the next-highest significance levels ($p < 0.010$). The remaining comparisons are non-significant.

For shoulder elevation ("Coord y"), highly significant differences are observed in two cases: B1 and Free and B2 and Free ($p < 0.001$). The difference between A2 and Free reaches the next-highest significance levels ($p < 0.010$). The remaining comparisons are non-significant. For further reference, please refer to Supplementary Table S10.

TABLE 5 Descriptive statistics for shoulder compensation movements by hand and instrument position and compared with the overall mean of values for protraction (“Coord x”) and elevation (“Coord y”).

Instrument position	*N*	Mean	Min.	Max.	*SD*
Sixth position, shoulder protraction (“Coord x”)					
A1	300	21.8	6.4	37.8	7.539
A2	300	14.0	4.0	25.8	5.750
B1	300	8.6	1.0	18.0	4.512
B2	300	4.7	−0.3	14.6	3.521
Free	300	9.1	−3.1	25.3	6.736
Sixth position, shoulder elevation (“Coord y”)					
A1	300	5.8	0.0	13.3	2.998
A2	300	4.7	0.5	10.8	2.608
B1	300	2.4	−1.2	6.8	2.156
B2	300	2.3	−0.8	9.7	2.048
Free	300	5.7	−1.0	17.5	4.568
Overall mean for all instrument and hand positions					
Shoulder protraction overall (“Coord x”)	450	11.9	−3.7	37.3	8.331
Shoulder elevation overall (“Coord y”)	450	3.9	−1.8	15.3	3.219
Second position, shoulder protraction (“Coord x”)					
A1	150	13.0	3.5	29.8	6.262
A2	150	8.1	−1.0	18.7	4.276
B1	150	3.9	−2.5	10.6	3.060
B2	150	1.8	−5.0	7.2	2.795
Free	150	7.7	−4.4	22.0	6.272
Second position, shoulder elevation (“Coord y”)					
A1	150	3.5	0.6	17.2	3.178
A2	150	2.5	−0.2	6.2	1.757
B1	150	1.7	−3.2	6.1	2.031
B2	150	1.8	−1.5	7.2	2.367
Free	150	5.1	−2.0	13.8	3.531

4.3. Results for specific use of the fourth fingers

4.3.1. Influence of the fourth fingers on elbow/upper arm compensation movements (“Reference Angle α”) by hand and instrument position

For the specific time segments pertaining to fourth finger normal and fourth finger high, results follow the same pattern as for the over 16 s-tune (see section 4.1), in that the highest values for “Reference Angle α” are reported for violin position A1 compared to all other instrument positions and for both hand positions and the gradation between the instrument positions is identical, though at higher levels (see Table 6 below):

Multiple regression analysis for “Reference Angle α” in the specific moments when the fourth fingers play shows highly significant differences between violin position A1 and all other instrument positions for time segments for fourth finger normal ($N = 90$, $p < 0.001$, $r^2 = 0.329$) and fourth finger high ($N = 90$, $p < 0.001$, $r^2 = 0.324$), thereby explaining 33 and 32% of elbow/upper arm compensation movement variance when considering all hand positions for a given instrument position.

Results for sixth hand position shows highly significant differences between A1 and all other instrument positions, both for fourth finger normal ($N = 60$, $p < 0.001$, $r^2 = 0.393$) and fourth finger high ($N = 60$, $p < 0.001$, $r^2 = 0.395$), thereby explaining between 39 and 40% of elbow/upper arm compensation movement variance when considering all measurements in sixth position for a given instrument position.

Results for second hand position are comparable to the abovementioned categories for time segments for fourth finger normal ($N = 30$, $p < 0.001$, $r^2 = 0.506$) and fourth finger high ($N = 30$, $p < 0.001$, $r^2 = 0.476$) except for A2 ($p < 0.01$), R^2 thereby explaining between 47 and 50% of elbow/upper arm compensation movement variance when considering all measurements in second position for a given instrument position (see Supplementary Table S11).

A *post hoc* multiple comparison of means (Scheffé) shows that, for the specific time segments of the normal and high fourth finger for all hand positions united ($N = 450$), mean values between single instrument positions for the entire tune differ highly significantly among each other ($p < 0.001$) except for A2 to B1 and B2 to Free (non-significant). The same pattern applies to the sequences played in sixth hand position and the time segments where the normal and the high fourth finger are played. For further reference, please refer to Supplementary Table S12.

For the normal fourth finger played in second hand position, the comparison of means shows the following pattern of differences between instrument positions:

Within the “A-type” instrument positions, A1 differs highly significantly from all other positions ($p < 0.001$) except for A2 (non-significant). Position A2 differs highly significantly from positions B2 and Free ($p < 0.001$), significantly from B1 ($p < 0.05$), and not from A1 (non-significant).

Within the “B-type” instrument positions, B1 differs highly significantly from A1 ($p < 0.001$) and significantly from A2 and B2 ($p < 0.05$) but not from Free (non-significant). B2 differs highly significantly from positions A1 and A2 ($p < 0.001$), significantly from B1 ($p < 0.05$), and not from position Free (non-significant). Instrument position Free differs highly significantly from positions A1 and A2 ($p < 0.001$) and not from B1 ($p < 0.05$) and B2 (non-significant). For further reference, please refer to Supplementary Table S12.

For the high fourth finger played in second hand position, the comparison of means shows the following pattern of differences between instrument positions:

TABLE 6 Descriptive statistics for Reference Angle α (elbow/upper arm) compensation movement for the specific time segments when the fourth fingers are played.

Fourth fingers for Instrument and sixth hand position (Figure 7)					
Fourth finger normal (time segments "a," sec. 2.000–3.995 and 10.000–11.995)	*N*	Mean	Min	Max	*SD*
A1	60	26.26	22.7	33.0	2.421
A2	60	23.34	19.6	29.7	2.087
B1	60	24.23	19.6	33.2	2.793
B2	60	20.44	16.0	29.8	2.722
Free	60	21.36	15.6	29.0	2.876
Fourth finger high (time segment "b," sec. 14.000–15.995)					
A1	60	26.62	22.8	33.7	2.509
A2	60	23.54	19.6	29.7	2.033
B1	60	24.61	19.8	34.0	2.816
B2	60	20.81	16.3	29.6	2.591
Free	60	21.78	16.1	29.2	2.805
Overall mean for all instrument and hand positions (dashed line --- in Figures 7, 8)					
Fourth finger normal (time segments "a")	450	21.91	12.0	33.0	3.865
Fourth finger high (time segment "b")	450	22.28	12.0	34.0	3.806
Fourth fingers for instrument and second hand position (Figure 8)					
Fourth finger normal (time segments "a")					
A1	30	23.46	19.9	29.6	2.337
A2	30	21.55	16.9	27.8	2.368
B1	30	19.01	13.4	26.7	2.798
B2	30	16.58	11.6	23.5	2.839
Free	30	16.86	11.9	23.6	3.005
Fourth finger high (time segment "b")					
A1	30	23.72	20.2	31.0	2.427
A2	30	21.68	18.0	27.8	2.285
B1	30	19.64	14.6	29.9	3.060
B2	30	17.08	12.5	23.0	2.568
Free	30	17.40	12.0	23.6	3.059

Within the "A-type" instrument positions, A1 differs highly significantly from all other positions ($p < 0.001$) except for A2 (non-significant). Position A2 differs highly significantly from positions B2 and Free ($p < 0.001$), while for all other position differences are non-significant.

Within the "B-type" instrument positions, B1 differs highly significantly from A1 ($p < 0.001$) and significantly from B2 and Free ($p < 0.05$) but not from A2 (non-significant). B2 differs highly significantly from positions A1 and A2 ($p < 0.001$), significantly from B1 ($p < 0.05$), and not from position Free (non-significant). Instrument position Free differs highly significantly from positions A1 and A2 ($p < 0.001$), significantly from B1 ($p < 0.05$), and not from position B2 (non-significant). For further reference, please refer to Supplementary Table S12.

4.3.2. Influence of the fourth fingers on shoulder compensation movements ("Coord x"/"Coord y") by hand and instrument position

Data for shoulder compensation movements focusing on the points in time when the fourth finger is played show a comparable pattern as reported in section 4.2.2: Values for instrument position A1 are highest and B2 lowest, and the gradation of values between instrument positions is identical. Compared with the overall means for the respective hand positions (grey shaded area in Supplementary Table S13), data suggests that instrument positions with a smaller angle degree for LoAx-CSP and LatAx-HP, as well as the "Free" position are linked to higher values for shoulder protraction and elevation throughout all points in time observed than for instrument position with a larger angle for LoAx-CSP and LatAx-HP.

Further details regarding the influence of the hand position on the degree of shoulder protraction and elevation can be found in the Supplementary Tables S13–S15.

4.4. Correlation analyses for target parameters

4.4.1. Correlation between shoulder motion data and elbow/upper arm compensation movement

The linear relationship between "Coord x" (shoulder protraction) and "Reference Angle α", as well as between "Coord y "(shoulder elevation) and "Reference Angle α" was assessed by computing Pearson's *r* correlation coefficient for all five instrument positions, both hand positions and all three time points under test.

Instrument position Free yields significant positive correlations between "Coord x" and "Reference Angle α" for all observations. Among the correlations between "Coord y" and "Reference Angle α," two out of six are significant. Positive correlations between "Coord x" and "Reference Angle α" are also observed for instrument position A2 at the beginning of the tune for sixth hand position (r = 0.304, $p = 0.018$), second hand position (r = 0.372, $p = 0.043$) as well as for second hand position fourth finger normal (r = 0.361, $p = 0.050$) and fourth finger high (r = 0.363, $p = 0.049$). A further significant correlation is reported for instrument position B2 for sixth hand position at the beginning of the tune (r = 0.268, $p = 0.038$).

For further details, please refer to Supplementary Table S16.

4.4.2. Correlation between biomechanical parameters and elbow/upper arm compensation movement

The linear relationship between the biomechanical parameters and "Reference Angle α" was assessed by computing Pearson's *r* correlation coefficient for all five instrument positions, both hand positions, and all three time points under test.

For "Passive Supination 250 g" and "Passive Supination 500 g", nine out of 10 statistically significant, negative correlations with "Reference Angle α" are reported for the entire 16-s tune (the correlation for instrument position Free in second hand position is non-significant). This also applies to the normal fourth finger in the case of correlations between "Passive Supination 250 g" and "Reference Angle α". Correlations between "Passive Supination 500g" and "Reference Angle α" yield eight out of 10 statistically significant, negative correlations (the instrument positions Free and B1 in second hand position are non-significant). For the high fourth finger, seven out of 10 statistically significant, negative correlations with "Reference Angle α" are reported both for "Passive Supination 250 g" and "Passive Supination 500 g" (instrument positions B1, B2 and Free in second hand position are non-significant).

For Passive Thumb Abduction and Reference Angle α, four out of five positive correlations are reported for sixth hand position for the entire 16-s tune and the specific use of the normal and high fourth finger (the instrument position Free is non-significant). An additional positive correlation is reported for second hand position in instrument position A1 for the high fourth finger. For "Finger Length Difference 3-5", no significant correlations with "Reference Angle α" are reported. For further details, please refer to Supplementary Table S17.

4.4.3. Correlation between biomechanical parameters and shoulder motion data

The linear relationship between "Coord x" (shoulder protraction) and the biomechanical parameters, as well as between "Coord y" (shoulder elevation) and the biomechanical parameters, was assessed by computing Pearson's *r* correlation coefficient for all five instrument positions, both hand positions and all three time points under test.

A negative correlation between "Coord x" and biomechanical parameter "Passive supination 250 g" is reported for instrument position B2, sixth hand position for the beginning of tune (r = −0.268, $p = 0.038$).

Negative correlations for "Coord y" and biomechanical parameter "Passive supination 250 g" are reported for instrument position A1, sixth position for the beginning of the tune (r = −0.348, $p = 0.006$), instrument position A2, sixth position for the beginning of the tune (r = −0.334, $p = 0.009$), fourth finger normal (r = −0.290, $p = 0.025$) and fourth finger high (r = −0.267, $p = 0.039$), instrument position B1, sixth position for the beginning of the tune (r = −0.380, $p = 0.003$) and second position for the beginning of the tune (r = −0.368, $p = 0.045$) and instrument position B2, sixth position for the beginning of the tune (r = −0.289, p = 0.025), fourth finger normal (r = −0.334, p = 0.009) and fourth finger high (r = −0.290, $p = 0.024$).

5. Discussion

5.1. Analysis of the data

The spectrum of recommendations on appropriate instrument positioning put forward by teaching traditions over the last four centuries remains very broad and partly contradictory. It could be considered a co-factor contributing to the high incidence of musculoskeletal complaints to this day. Therefore, this study investigated the effects of position changes in a violin's sideward orientation (LoAx-CSP) and inclination (LatAx-HP) on the extent of compensatory movements of the left upper extremity: Using pre-defined violin positions while playing a standardized 16-s tune, the hypothesis was confirmed that a reduction of LoAx-CSP and LatAx-HP by 30° (i.e., within a common inter-/intraindividual range of variability, including the individuals' habitual, "free" position without the support of the experimental set-up) significantly and independently increased the magnitude of compensatory movement of the left elbow and upper arm ("Reference Angle α") and left shoulder (protraction, "Coord x"/ elevation, "Coord y").

As reported for the parameters in this publication, the same observation has already been made at the objective level of muscle activation and the subjective level of perceived effort. Those published results confirm comparable patterns of changes of muscle activation and subjectively perceived muscular effort in the five instrument positions under test (Hildebrandt et al., 2021). This applies particularly to the pectoralis major muscle, which is significantly involved in the compensatory movement of the left upper arm and elbow in front of the trunk. Changing LatAx-HP from 50° to 20° (i.e., changing from position "2" to "1") and LoAx-CSP from 50° to 20° (i.e., changing from position "B" to "A," see Table 1 above) not only increased the level of muscle activation and subjectively felt effort; it also increased the extent of the compensatory movements of both the elbow/upper arm and the shoulder. These results are confirmed at all three levels investigated in the data presented in this paper: The instrument positioning (i.e., positions A1 through Free), hand positioning (i.e., sixth and second hand position), and finger positioning with a focal point lying on the fourth fingers as a special point of interest and relevance for violin performance.

In longer and more complex real-life endurance challenges (including co-factors such as the chin-and shoulder rests), the patterns and degrees of compensatory movements and the resulting effort levels are likely to be either more pronounced or variegated than would be the case in the short tunes tested in a laboratory environment. Results for the correlation between shoulder motion data and elbow/upper arm compensation movement (see section 4.4.1) could indicate that players find ways how to adapt their playing position. This adaptive process appears to lead to different combinations of compensation patterns and may benefit them when playing in a normal environment. This aspect, however, requires further investigation.

Previous studies have pointed to the specific role of the muscles associated to the shoulder girdle triggering compensatory movements (Steinmetz et al., 2008; Steinmetz, 2016; Möller et al., 2018). It appears that the more proximal arm muscles play a critical role in muscular workload in violin playing [i.e., through limited isometric endurance during longer tasks with likely critically reduced blood and O_2-supply (Hollmann and Strüder, 2009)], while more distal tasks appear to be more dynamic and involve only shorter isometric components. While previous research focuses predominantly on muscle activation levels and variability while violinists perform tasks on their own instrument (see Background section), results linked to this body of research (Hildebrandt et al., 2021) offer insight into muscle activation levels in relation to positional effects generated by standardized instrument positions. In this study, the selection of muscles and respective electrode placement mirrors other focal points in research, such as the role of the pectoralis major muscle in violin performance. By means of the 2D video motion analysis, data indirectly linked to functional aspects of the trapezius as well as the levator scapulae muscle, which are often in focus in case of task-specific health issues (Chan et al., 2000; Spahn et al., 2001; Berque and Gray, 2002; Hildebrandt and Nübling, 2004; Wagner, 2005; Chi et al., 2020; Gembris et al., 2020; Mann et al., 2021), were obtained. In line with this paper's finding on movement patterns of the left upper extremity, results for muscle activation levels suggest that, in addition to muscles focused on in other studies, the pectoralis major muscle should be equally considered when either identifying possible causes for task-specific health issues or when advising performers in view of the prevention thereof. Thus, this study's results re-confirm and extend our knowledge regarding high-stress risks in the shoulder girdle, such as playing-related health disorders, including musculo-fascial overload and shoulder impingement syndromes. The number of studies dedicated to electromyographic (EMG) measurements of violinists is growing and examines a broad spectrum of relevant aspects, such as the influence of ergonomics, anthropometrics and repertoire (Philipson et al., 1990; Cattarello et al., 2017, 2018; Kok et al., 2019; Chi et al., 2020; Mann et al., 2021), the comparison between muscle activation levels in healthy violinists and those reporting task-specific health problems (Spahn et al., 2001; Berque and Gray, 2002; Hildebrandt and Nübling, 2004), muscular variability, endurance and fatigue aspects of violin performance (Wagner, 2005; Gembris et al., 2020). In contrast, research on the comparison between subjectively perceived effort levels and objective data on muscle activation when playing the violin appears to be scarcer (Chan et al., 2000; Hildebrandt et al., 2021).

This study's sub-hypothesis ("the lower the passive supination ability and passive thumb spreading and the shorter the length of the little finger in comparison relative to the middle finger, the more compensation movements of the upper extremity") was confirmed for passive supination, not confirmed for passive thumb spreading and not confirmed the length of the little finger in comparison relative to the middle finger. The results on the influence of these biomechanical factors on compensation movements show that supination ability correlates negatively with the extent of elbow/ upper arm compensatory movements in all instrument positions, hand positions, and positions of the fourth fingers. Especially the fourth finger on the violin's lowest string, this indicates the relevance of passive supination for the fingers' reach: a reduced degree of supination ability seems to provoke increased elbow or upper arm movements in front of the trunk, thereby affecting proximal structures such as the shoulder girdle and its musculature.

The ability to spread the thumb also appears to be relevant for the fingers' reach when playing the instrument. In contrast to our sub-hypothesis, it seems to allow a higher degree of compensation movements of elbow/upper arm, and shoulder but does not reach a significant level when correlated with the player's usual instrument position ("Free"). However, significance levels of the compensation movements in the standardized test positions A1 through B2 increase with specific playing requirements during the tune (i.e., the use of the fourth finger in higher hand positions). The ability to spread the thumb cannot be clearly captured as enabling or disabling the fingers range based on data collected in this study. Also, the contradictory fact that correlations between passive thumb abduction and elbow/upper arm compensation are positive while the same biomechanical parameter correlated with data for shoulder elevation would lead to isolated cases of negative correlation calls for further investigations.

A surprising fact is that a small fifth finger (i.e., the fourth finger in violin playing), which is set back more clearly relative to the third finger, does not show any significant correlation with compensatory movements of elbow/arm and shoulder. One explanation for this could be that the differences measured in millimeters for the fifth finger are too small to trigger/elicit significantly different levels of compensation movements, which would occur in the finger stretching out along its longitudinal axis when approaching the string diagonally. Another explanation could be that players with relatively short fifth fingers are already accustomed to applying a combination of compensation movement patterns relevant for successfully performing in a given instrument or hand position before starting to play. A sub-analysis of existing data or future studies will become necessary to further clarify this aspect.

Taken together, the present results suggest that differences in effort between typical violin positions can be captured not only by objective EMG measurements and subjective BORG assessments (Hildebrandt et al., 2021), but also in the extent of compensatory movements of the elbow, upper arm and shoulder. Based on the results, a recommendation could be issued that violin position A1, in which both LoAX-CSP and LatAX-HP angles are decreased, seems significantly disadvantageous in terms of the overall effort required, and should be assumed for a limited time only. This aspect becomes particularly relevant when focusing on historically informed performance practices, where instrument positions resembling A1 are assumed (Rônez-Kubitschek, 2012). As such, results from this body of research may contribute to the choice of individually beneficial instrument positioning based on objective findings and creating choices along a spectrum of options. Results also add to the growing body of research aiming to understand the interdependency between violin performance and playing technique, relevant muscles involved, and contributing factors for developing task-specific health problems in this musician population.

An interesting detail is that, in contrast to the results for EMG and Borg measurements in the same five instrument positions (Hildebrandt et al., 2021), the extended fourth finger provokes only minimally more compensatory movements of the elbow/upper arm than the normal fourth finger. Furthermore, the more inclined instrument position (A2) seems to restrict the compensatory protraction movement of the shoulder, but at the same time, provokes more compensatory movements of the elbow and arm.

As expected, more compensatory movements occur synchronously with specific technical requirements of playing (e.g., performing in a high hand position or using the fourth finger). On one hand, this fact could be considered as an indication for a targeted and dynamic repositioning of the instrument in view of adding to the ease of performing pieces with an increased use of high registers and fourth finger, which is often the case in highly virtuosic and therefore challenging compositions. On the other hand, these findings may contribute to the individualized choice and adaptation of ergonomic aids and concepts of rest during training to prevent task-specific health issues.

5.2. Limitations of the study

The experimental setting for the assessment of violin positions A1-B2 excluded the supporting of the instrument by means of the active use of the arm, head, or shoulder, but did include the effort required to raise the arm. The latter's effect on arm and shoulder compensatory movements was not quantified in terms of its contribution to compensatory movements varying between A1-B2. Better separation between violin support and actual playing is a challenge for future studies. However, a significant proportion of the variance in arm and shoulder compensation movements was due to the positions under test. It can be expected that during prolonged static tasks as observable in a real-life environment, the overall effects of LoAx-CSP and LatAx-HP on the target parameters examined are likely to become more pronounced, and that smaller ergonomic disadvantages may also become more apparent in the degree of compensation movements. In this respect, future studies should not only record longer phases of playing (as they are common in orchestral playing, for example) but should also take a higher-resolution approach by examining the effects of smaller angular deviations from A1 (10 or 20 instead of 30°) in comparative tests.

A general limitation of the present study is that the participants played on the two lower strings, with neither vibrato, hand position shifts or changes in the position of the thumb, elbow, and head. These factors might contribute to subtle postural adjustments while playing and add to the improvement of comfort and possibly skill. In the actual practice of violin teaching and playing, the individual violin position is chosen as an individually preferred combination of the instrument's inclination and sideward orientation, as mirrored in the standardized violin positions investigated in this study. Also, a performer's learning biography and performance preferences should be viewed as a dynamic transition along the spectrum covered by these standardized positions. Further variations within these standardized violin positions had to be excluded in the context of this study to provide a solid scientific basis.

Possibly, more importantly, the exclusion of the use of the bow and its weight when running the tests may have influenced the position and comfort of the left arm in a currently undefined way: The length of the right arm, the point of contact with the strings, and its influence on the left arm and hand adjustments to dynamics, sound quality, bow speed, etc. were not required. Therefore, a note should be added to the data presented that further testing should be devoted to more complex conditions involving bowing tasks and switching between additional strings, hand or finger positions, and consideration of anthropometric characteristics (Ackermann and Adams, 2003; Wagner, 2005; Wagner, 2012). Future studies will also aim to expand the technological possibilities of generating shoulder motion data in analogy to the 3D motion capture system used to collect data for "Reference Anlge α" to exclude potential inter-rater variability common for analogue evaluation methods and as applied to shoulder motion data collection for "Coord x" and "Coord y".

5.3. Translational aspects

Throughout the centuries-long tradition of violin playing and teaching, a wide range of recommendations and traditions regarding instrument positioning have been propagated by violin pedagogues (Flesch, 1978; Galamian, 1983; Rostal, 1993; Rônez-Kubitschek, 2012) and first scientific approaches (Szende and Nemessury, 1971). Each recommendation issued by a respective school (e.g., German, Italian, and French; Rônez-Kubitschek, 2012) influences the sidewards orientation of the instrument (LoAx-CSP) and the inclination of the instrument (LatAx-HP). Despite the limitations mentioned above, the present study provides further insights into the possible effects of violin positioning on parameters relevant to musicians' health. The final choice of instrument positioning remains a decision that the violinist makes with a teacher or therapist. However, when a violin position is needed that involves a lower degree of shoulder and arm compensatory movement or muscle activation, data can provide initial steps towards more targeted decision-making. This could, for example, prove useful when recovering from a task-specific injury or in case of limited supination ability.

In addition, the data may help to maintain (proximal) muscle activation at a lower level and thus extend the duration of the performance before the onset of muscle effort at higher levels. This aspect can be important in performance contexts such as when playing in an orchestra: The violin sometimes needs to be held and supported for several hours, with trade-offs between sitting position, the ergonomic challenges of making music together with a stand partner and ensuring contact with, section leaders and the conductor. For players in the context of historically informed performance practice, the choice of positioning may be adapted to the requirements of a particular musical structure, e.g., high registers and the number of hand position changes.

It may also be that the instrument does not necessarily need to be played in the objectively easiest position, given a violinist's expressive quality or a subjectively perceived optimum. Some violinists may choose to play in a position that involves slightly greater compensatory movement and muscle activation if it benefits the level of expression or provides a temporary sense of greater stability to master a passage in performance. However, health issues may need to be addressed depending on how long this condition lasts.

As all participants were young, healthy students who had no musculoskeletal complaints at the time of measurement, the results may be insufficiently representative of a population with a high prevalence of musculoskeletal complaints due to compensatory movements, such as for example orchestral players (Berque and Gray, 2002; Steinmetz et al., 2008; Vinci et al., 2015; Kochem and Silva, 2017). A more detailed picture of the causative factors for these complaints could also include other influences, such as individual patterns of posture and movement and practice habits, including approaches to taking breaks during practicing and working. Similarly, despite initial encouraging results and observations based on this study (Hollmann and Strüder, 2009; Hildebrandt et al., 2021; Newly Developed Multi Adaptable Chin Rest, Model Zuerich, 2017), further research should be conducted to assess the transferability of this study's findings to classroom, counseling, and therapy settings in terms of their validity. Gender effects and an even broader focus on anthropometric co-factors (Ackermann and Adams, 2003; Wagner, 2005; Wagner, 2012) should also be considered in future studies.

6. Conclusion

The central finding of this study is that when the sideward orientation of the instrument (LoAx-CSP angle) and the inclination of the instrument (LatAx-HP angle) are decreased by 30°, the compensatory movements of the violinist's left elbow/upper arm and shoulder increase highly significantly and independently of each other and are additionally increased by biomechanical factors such as reduced supination ability and increased thumb spreading ability. Furthermore, there is an increase in compensatory movements in synchrony with playing technique requirements such as higher positions and the use of the little finger. Since the present tests were relatively short (16 s. each), more significant effects are likely to be expected in the case of longer-lasting professional tasks, even with smaller changes in angle. Although these findings are preliminary, they can serve as indications for favorable instrument positions and training concepts. It should be kept in mind that compensatory movements result from a highly complex interplay between individual elements of violin posture, the various temporally coordinated movement demands of the left and right hands and general expressive intentions.

Data availability statement

The datasets presented in this article are not readily available because parts of data sets currently in evaluation process for further publications. Requests to access the datasets should be directed to oliver.margulies@zhdk.ch.

Ethics statement

The studies involving human participants were reviewed and approved by Canton of Zürich Ethics Committee (Project number: KEK-ZH-Nr. 2014-0008). The patients/participants provided their written informed consent to participate in this study.

Author contributions

HH: grant applicant and project leader, overall management, and specialist supervision of all project phases. OM: project co-leader, organization, practical and specialist supervision of all project phases, and preparation of data for analysis. MN and WV: methodology, data collection, data analysis, and data interpretation. WH: consultation on functional anatomical biomechanical matters, data analysis and interpretation, and specialist supervision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1017039/full#supplementary-material

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What a difference a syllable makes—Rhythmic reading of poetry

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In reading conventional poems aloud, the rhythmic experience is coupled with the projection of meter, enabling the prediction of subsequent input. However, it is unclear how top-down and bottom-up processes interact. If the rhythmicity in reading loud is governed by the top-down prediction of metric patterns of weak and strong stress, these should be projected also onto a randomly included, lexically meaningless syllable. If bottom-up information such as the phonetic quality of consecutive syllables plays a functional role in establishing a structured rhythm, the occurrence of the lexically meaningless syllable should affect reading and the number of these syllables in a metrical line should modulate this effect. To investigate this, we manipulated poems by replacing regular syllables at random positions with the syllable "tack". Participants were instructed to read the poems aloud and their voice was recorded during the reading. At the syllable level, we calculated the syllable onset interval (SOI) as a measure of articulation duration, as well as the mean syllable intensity. Both measures were supposed to operationalize how strongly a syllable was stressed. Results show that the average articulation duration of metrically strong regular syllables was longer than for weak syllables. This effect disappeared for "tacks". Syllable intensities, on the other hand, captured metrical stress of "tacks" as well, but only for musically active participants. Additionally, we calculated the normalized pairwise variability index (nPVI) for each line as an indicator for rhythmic contrast, i.e., the alternation between long and short, as well as louder and quieter syllables, to estimate the influence of "tacks" on reading rhythm. For SOI the nPVI revealed a clear negative effect: When "tacks" occurred, lines appeared to be read less altering, and this effect was proportional to the number of tacks per line. For intensity, however, the nPVI did not capture significant effects. Results suggests that top-down prediction does not always suffice to maintain a rhythmic gestalt across a series of syllables that carry little bottom-up prosodic information. Instead, the constant integration of sufficiently varying bottom-up information appears necessary to maintain a stable metrical pattern prediction.

KEYWORDS

syllables, meter, reading, rhythm, poetry, top-down, bottom-up

1. Introduction

Regarding rhythm and timing, oral reading of unfamiliar conventional poetic language can be challenging at times as it includes, e.g., processing of an infrequent or irregular syntax, adjusting atypical phrase boundaries, or retrieval and prediction of stress and accent cues, etc (see Attridge, 1995; Hanauer, 2001; Carper and Attridge, 2003; Yaron, 2008). Thus, stress expectation management (Schmidt-Kassow, 2007; Schmidt-Kassow and Kotz, 2009a,b) may deviate gradually from lexical information, when the poem's metrical grid and its rhythmic *gestalt* and melodic contour (see Schrott and Jacobs, 2011; Morgan et al., 2019; Scharinger et al., 2022) suggests so. Suprasegmental cues from preceding text material might even amplify this effect (compare Brown et al., 2015).

Metrically regular and rhymed language (MRRL) tends to be rhythmized differently compared to normal text/prose reading (Menninghaus and Blohm, 2020; de Arruda et al., 2022). For example, in both, silent and oral reading of MRRL, syllables play a central role as units of pronunciation (see Breen and Clifton, 2011, 2013; Breen, 2014, 2018; Beck and Konieczny, 2021). In oral reading, this is reflected in the systematic variation of syllable onset intervals (SOIs). Also, intensities for strong and weak syllables have been found to alter according to the respective meter (Fitzroy and Breen, 2020). Reading MRRL is thus characterized by pronounced articulatory gestures provoking a differential lengthening/shortening and intensifying of the smallest unit of speech, the syllable, hence causing an emphasized alternating stress distribution. The resulting phenomenon, that readers often quickly extract a beat from MRRL, and thereby project a meter onto upcoming lines, is an astonishing aspect of online processing during MRRL-reading. However, there has been little debate on the functional role of a specific composition of syllabic and phonemic material for establishing MRRL beat and meter.

To illustrate this phenomenon: After just a few words of reading this very sentence, you may have noticed that you have already started to establish a rhythmic pattern. You may have also automatically anticipated and predicted the upcoming stress distribution. And, right now, you are even reading the following sequence of *tack tack tack* as if they were real words. You probably have projected an alternating *strong-weak-(less) strong* stress onto them. Here, the *tack tack tack* sequence occurred as a one-time incident. But when reading longer texts containing more tacks and hence overall fewer prosodic cues, it can become difficult to update the stress expectation management during reading, even when the text imposes a concerted corset of meter and rhythm. Such is the case in conventionally metered and rhymed poetry:

As fragile as this breath could be
it flows tack tack – from A to C
and onwards, though tack tack tack see
this glimpse of whispers "*tack tack tack*".

As fragile as this breath could be
it flows as air – from A to C
and onwards, though you cannot see
this glimpse of whispers "*to be free*".

As can be seen from this example,[1] other factors also contribute to the experience that poems bear musical quality (Blohm et al., 2021). Amongst them are melodic qualia (Menninghaus et al., 2018), the rhyme as a salient, verse-defining feature (e.g., Carminati et al., 2006; Wagner and McCurdy, 2010; Fechino et al., 2020) or alliterations (Lea et al., 2008). For all of these, as well as for meter, one structural principle of the MRRL is particularly noteworthy, namely *repetition* (compare Tierney et al., 2018a,b, 2021). It is only through the principle of structured repetition that all the rhythmic effects of the factors mentioned come to bear. In particular, this also applies to the perception and establishment of the metrical grid most frequently found in the poetic verses of a poem, resulting in a poem appearing to be iambic or trochaic in conception.

Based on findings by Woodrow (1909) on non-speech sounds and there tendency to be grouped either iambically or trochaically depending on duration or intensity, Hayes (1985, 1995) formulated the Iambic-Trochaic-Law (ITL) for speech-segments, according to which syllables that differ in intensity tend to be grouped as diads with initial prominence. In contrast, they are grouped into diads with final prominence if they differ in duration. However, there is more to it. When readers group a stream of stressed and unstressed syllables into metrical units that follow the principle of structured repetition, then whether it is perceived as trochaic or iambic depends on the factor that is held constant. For example, if only intensity is varied while syllable duration is constant, alternating segments are grouped trochaic (Hay and Diehl, 1999, 2007). What's more, if perception is biased by an iambic or trochaic prime, the processing of successive segments can accordingly be affected (Fiveash et al., 2021), and this has supposedly biological underpinnings operating on abstract laws (compare Tabas et al., 2020). Additional factors that contribute to the realization of stress are pitch, spectral tilt, and in general, all shifts in vowel and/or consonant quality, resulting from adjusted articulatory gestures, e.g., vowel reduction or deletion, but also strengthening, gemination, or aspiration (compare Tilsen, 2019; Gordon and van der Hulst, 2020) – all mostly highly correlative of each other. Our study focuses on duration and intensity, which may well be considered the two most distinctive general features of emphasis. Other factors mentioned above are outside the scope of this paper.

For metrically regular, rhymed language (MRRL), a stronger and more systematic rhythmicity has been postulated (see Cummins and Port, 1998; Bröggelwirth, 2007). Testing the ITL for German language, Wagner (2010) examined the reading of poetry (trochaic, iambic, dactylic and "lied") by comparing two groups, professional actors vs. non-professional jazz-choir singers. Results showed a clear durational contrast for iambs vs. trochees, with more pronounced lengthening of stressed syllables in iambs for both groups. However, subsequent analyses of phase relations suggests that independent of meter, a ratio of 3:2 (stressed:unstressed) was preferred. The author points out, that this pattern was more present in singers than in actors and concludes that the professional level of experience and the accompanying recitative expertise modulate the timing when rhythmizing MRRL. In addition, the data suggested that unstressed feet are more salient in iambic units than in trochaic ones. However, although for MRRL a more binary stance for stressing might hold true, a later comparison with prose (Wagner, 2012) revealed durational similarities, e.g., lengthening of the stressed syllable in iambs was found there, too. Still to date, the characteristics of the ITL are not yet sufficiently understood and most studies are based on decision-making or tapping experiments, mostly focusing on the perceptual mode (auditory channel), but rarely using oral production (for an overview see Wagner, 2022). For example, Wagner (2022) draws the attention to the specific functional relationship of prominence, i.e., salience, and duration, which he proposes do not necessarily "go hand in hand" (*ibid*., 269), and that both, speech production and speech perception need to be investigated. Although not MRRL was examined, but recorded (*bába bába bába*) and perceived (*ba ga ba ga ba ga*) sequences, his research findings suggest that listeners process words on the basis of two orthogonal dimensions, namely *duration* and *grouping*, of the respective auditory signal. Its interpretation is thus assumed to be understood as a relative relation of the two dimensions. The author concludes that "intensity and duration are generally poor cues for the distinction between iambs and trochees, but excellent cues for grouping and prominence" (*ibid*., 282). Wagner's results highlight a key problem common for much of the literature related to ITL, namely the mixing of the physical properties of the sound signal itself with the cognitive phenomenon of projecting a derived abstract meter onto an incoming auditory signal and hence processing further input accordingly.

1 Written by the first author.

For example, using an EEG oddball paradigm, Henrich and Scharinger (2022) had participants listening passively to pseudoword sequences while watching a silent movie. Pseudowords consisted of the disyllabic pattern *gugu* and were manipulated in pitch, however, not in duration or intensity, and also differed in foot (iambic/trochaic) or/and position of omission. Results showed that for iambs, omission of the second position led to stronger MMNs amplitudes compared to the first position omission, which was in line with their hypothesis. This pattern was correspondingly reversed for trochees. The omission on the strongly stressed first syllable of a trochee led to earlier MMNs than the weakly stressed first syllable of an iamb. For iambs, MMNs were even stronger when the strong syllable was omitted. This most likely can be explained by linking predictive processing of the (omitted) sound event (compare Tal et al., 2017) with the fact that for differentiation of events (i.e., by duration, intensity or pitch), an anticipated more salient event should be more crucial than the less salient one, presumabely always in relation to potentially preceding or subsequent silent pauses. Henrich and Scharinger (2022) interpret their results found for pitch in the predictive coding framework and state, that the MMNs elicited by omission mirror the "violation of a syllable-based prediction" and its prosodic quality (*ibid*, 8). They also report a significant MMN latency effect only for the first syllable, with shorter ones for trochees than iambs. They explain this effect with the ITL, which would expect higher pitch/intensities for foot beginnings and longer durations for foot endings (compare Crowhurst and Olivares, 2014; Crowhurst, 2020), as well as with the notion of possible articulatory habituation leading to a preferred trochaic patterning in German language (compare Wiese and Speyer, 2015; Wiese, 2016). However, in the described experiment by Henrich and Scharinger (2022), only pitch (see also Breen and Fitzroy, 2021) was under investigation but not intensity or duration.

Therefore, one of the leading questions of our study is, whether theoretical implications of the ITL, i.e., potential articulatory constraints such as intensity or duration, would nevertheless be applied to *tacks* during reading metrically regular, rhymed language (MRRL) aloud, which should actually all be stressed due to their onomatopoetic quality stemming from "ticktack" (tick-tock), which symbolizes the beat/ticking of a clock, as well as the "ck"-ending, which in German has a voiceless, short and hard *k*-sound. This also seems to add on the urge to stress the syllable by explicitly voicing the single vowel "a." However, tack is no word by itself, yet it resembles characteristics of a word, but it does not carry individual semantic meaning. Importantly, in the rhythmic form of a poem *tacks* must be read partially unstressed according to the respective "governing" metrical grid of the poem conceptualized either iambically or trochaically. As a preliminary assumption regarding ITL, readers then should have already derived an abstract representation of the primary metrical unit - either iambic or trochaic - after reading just a few *tack*-less poem verses, and we should find *tacks* to differ accordingly in duration or in intensity. Hence, our focus was, firstly, on examining direct output of rhythmic MRRL-speech sounds, and secondly, online handling of MRRL-rhythm including violations of – as we would call it – *sound-scape/acoustical matrix* during oral reading. To our knowledge, no other study has tackled this specific problem yet. And, referring to the above described experimental results, another important question is to what extend results in relation to ITL might be confounded by effects of predictive processing shaped by an abstract metrical grid vs. the pure phonemic MRRL-material.

In other words, we were additionally interested in whether the *tack*-manipulations of the contrastive and consecutive order (Nolan and Jeon, 2014) of time-, respectively, pattern-bound MRRL-sounds could affect suspected top-down/bottom-up processes behind oral reading and might affect an assumed predictive processing of the main metrical figure, which has to be maintained and updated constantly throughout reading a poem in order to keep "the beat." The principles of the predictive coding theory (PCT), (compare Rao and Ballard, 1999; Friston, 2008, 2010; Clark, 2013) have recently been applied to the processing and production of acoustic signals and transferred to the field of music (Koelsch et al., 2019; Vuust et al., 2022). For example, Vuust et al. (2022) had introduced the predictive coding of music model (PCM), whereby processing of music (perception, action, emotion, and learning) are postulated "recursive Bayesian processes, by which the brain attempts to minimize prediction error" (*ibid*., 289). Since processing music and language share circuits and overlap in brain mechanisms (see Fiveash et al., 2021), it is obvious to assume processes of predictive coding also for the processing of language, and especially of conventional poetic language. Thus, one can propose PCT/PCM as a theoretical framework in which possible interfering effects of *tacks* on establishing a certain meter – by perceiving a specific salience pattern in sounds, leading even to temporal beat distribution – can be discussed.

However, as debated in Engel et al. (2001) the classical dichotomy between top-down and bottom-up cannot be maintained (compare for music Pando-Naude et al., 2021; see also discussion Pourtois et al., 2008), which is relevant specifically to a cognitivist approach. Regarding the phenomenon of rhythm perception and beat induction (Honing, 2012, 2018) and applying it to metrically regular, rhymed language (MRRL), top-down hence may be captured best as a genre-driven stress expectation management on higher levels based on concrete sets of representative, albeit abstract units (Tabas et al., 2020), such as iambs or trochees. However, it is questionable, to which extend this is a conscious, internally generated, rather controlled act during online oral reading, potentially modulated by musical proficiency, and to which extend it is only existent and/or manipulable through interaction with the exogenous MRRL-input (i.e., bottom-up realization). Although the presented experiment only indirectly contributes to shed light on the assumed "interactive, bidirectional information exchange between levels of internal hierarchical systems" serving "to reconcile incoming information with internally generated predictions" (Rauss and Pourtois, 2013), it may well give insight on a syllabic-conceptual "threshold" in MRRL-reading, with respect to the actual oral output of the processing of multiple successive (presumably precision-weighted) "prediction errors," elicited by a number of tacks, against a presumed strong "default" of prediction, i.e., either the iambic or the trochaic unit. This notion is captured by Vuust et al. (2022) formulation, that "prediction errors are useful only when things are predictable" (*ibid*., 289; compare also Ficco et al., 2021; Trapp et al., 2021).

In this context, an additional research question was whether musical proficiency can be a moderating factor or not for picking up a poem's rhythmic figuration (compare Blohm et al., 2021, 2022) and "defend" the updating and maintaining of its main metrical grid against potential *tack*-interferences during oral MRRL-reading. Although we did not distinguish between basic auditory skills and musical expertise (for a discussion see Mankel and Bidelman, 2018; Tierney et al., 2021), the assumption holds that musically proficient readers have a prediction advantage because of precise timing due to musical practice and auditory training and thus also in anticipating speech-bound (MRRL) pauses (compare Patel, 2012, 2014; Turk and Shattuck-Hufnagel, 2014; MacIntyre and Scott, 2022). This should influence the application of durational and intensity patterns of syllables positively, which are the smallest unit of speech and most distinct rhythmic entity during oral reading of conventional poetry.

To sum up, we expect musically trained readers to extract a poem's "beat" induced by the MRRL sound-gestalt easier than musically inactive readers, in accordance with the definitions given in Ravignani and Madison

(2017) and Beck and Konieczny (2021). This in turn, should influence the temporal ratio, i.e., quasi-isochronicity (compare also Kotz et al., 2018; Ravignani et al., 2018; Aubanel and Schwartz, 2020), with which musical active readers encounter *tacks* during oral reading, differently so compared to inactive readers. Specifically, we use the SOI as well as mean intensity, to investigate rhythmic contrasts during MRRL reading, with a special focus on syllables which where substituted by the non-sensical syllable *tack*.

Additionally, we analyzed the rhythmicity of entire lines. The normalized pairwise variability index (nPVI) is a measure that provides an aggregated value of rhythmicity, and is often used in music analysis (Patel and Daniele, 2003; London and Jones, 2011). We used this measure to estimate the amount of rhythmic variation in each line. The nPVI can be computed from both SOIs and syllable intensities. Pairwise variability means that strong variations between adjacent syllables leads to high nPVI scores. Both the iambic and the trochaic should result in elevated nPVIs, because both imply an alternating pattern of stresses.

Our hypotheses for SOI and intensities were:

For regular syllables:

H1: Reading patterns resemble speaking patterns (Gagl et al., 2022), where stressed syllables are often longer and louder than unstressed syllables (for English see Carter and Clopper, 2002). We therefor expect SOIs to be longer, and intensities to be higher for strong syllables than for weak syllables (simple stress hypothesis).

H2: When poems are read aloud, "acoustic" sequences must be produced from the "silent" text material. If the acoustic signal is generated along the lines of how it is decoded, then properties established by basic iambic-trochaic-law effects in perception (Hayes, 1985, 1995) should also apply to oral production. We hence expect syllable strength to be expressed more by *intensity* differences in trochaic meter, and more by SOI differences in iambic meter (ITL hypothesis).

H3: Metric grids consist of syllables clustered into metrical units. In the iambic grid, these units are comprised of dyads of an unstressed syllable followed by a stressed syllable, and vice versa in trochaic grids, where a stressed syllable is followed by an unstressed one. When metrical units are produced as pronunciation units, we expect an increased likelihood of separating pauses, resulting in prolonged syllables onset intervals for the final syllable in the unit. The *metrical unit hypothesis* hence predicts an *interaction of meter and stress*: In iambic meter, the stressed syllable becomes lengthened even more, whereas in trochaic meter, it is the unstressed syllable that is lengthened (metrical unit hypothesis).

H4a: According to the OPERA hypothesis (Patel, 2011, 2012, 2014), years of training in musical skills should be associated with an improvement in temporal precision. We therefore expect musicality to be a modulating factor, particularly for SOIs, such that the effect of stress on SOIs should be more pronounced for musically active readers.

H4b: To compensate the lack of temporal precision, musically inactive readers might prefer intensity to express stress, such that the effect of stress on intensity should be more pronounced for musically inactive readers.

H4c: On the other hand, musically inactive readers might be less effective in expressing stress *in general*, such that the effect of stress on intensity should be less pronounced for musically inactive readers.

For tacks:

H5: When top-down processing prevails in the absence of distinctive bottom-up information on tacks, iambic and the trochaic speaking patterns should be projected onto tack syllables, such that SOIs and intensities for "tacks" should reflect the stress pattern of the metrical grid, as they do for regular syllables.

H6: If bottom-up processing prevails over top-down processing, "tacks" should be leveled out, i.e. they should be pronounced more similarly to each other, resulting in similar SOIs and intensities, regardless of stress.

H7: The syllable "tack" itself has a tendency to be pronounced as stressed, due to its phonetic properties. If top-town predictions are projected onto tacks, readers might therefor experience a conflict whenever the metrical grid suggests tacks to be unstressed. This interference can result in "paradoxical" SOI lengthening for weak tacks.

H8: Corresponding to H2, we expect that stress is expressed more via intensity differences in trochaic poems, and more by SOI differences in iambic poems. This should also apply to tack-syllables, such that the effect of stress on intensity should be greater in trochaic poems, whereas the effect of SOIs should be greater in iambic poems. This hypothesis amounts to a comparison between two two-way interactions (stress × meter, for intensity and SOI).

H9: Rhythmic reading requires the permanent alignment of bottom-up and top-down information to ensure the maintenance of the metric grid. Because tacks lack distinctive bottom-up information about stress, the top-down projection of a metrical grid could fade away with an increasing number of tacks in the same verse, and it should become increasingly difficult to maintain the metrical grid. That would be reflected in an interaction of *stress* and *tack index/tacks per line*.

H10a,b,c: Consistent with H4a for regular syllables, we expect that musically active readers will be better at maintaining the metrical grid, even in the absence of supporting bottom-up information. For tack-syllables, we also expect interactions between *musical* and *stress* corresponding to H4a, b, and c.

H11: We expect musically active participants also to be less affected particularly when they encounter multiple tacks within a line. This

> predicts an interaction of *musical*, *stress*, and *tack index*/*tacks per line*.

Hypotheses for rhythmicity, aggregated per line:

> *H12*: If syllable-*stress* is reflected in SOIs and intensities varying between strong or weak syllables, we also expect to find line-based nPVI effects for SOIs and intensities for predictors that show a modulating effect on/interaction with stress, such as meter and musicality. If confirmed, the nPVI would thus provide a simpler aggregated measure – allowing for models with fewer predictors – that could still capture these effects.

2. Materials and methods

2.1. Participants

In total, 17 participants (11 women, 6 men; *M* age = 29.53; *SD* age = 13.37, range: 20–69 years) took part in the reading experiment, all were native speakers of German. In exchange, subjects received course credits or could sign up for a raffle. All participants gave written consent before the experiment started and the study was conducted in accordance with the "Ethical Principles for Medical Research Involving Human Subjects" (Declaration of Helsinki, 1964). Data of four participants had to be excluded because of technical mistakes during data collection. The remaining data of 13 participants (8 female, 5 male; *M* age = 31.85; *SD* age = 14.58, range: 21–69 years) were used for the analysis.

2.2. Stimuli

A total of 18 conventional poems were used as stimuli, of which one half was iambic and the other half trochaic. The original poems were manipulated by substituting single syllables with a "tack"-syllable. "Tacks" were placed at random positions and occurred in random number within a line. Except for one poem (D1, line two), lines which included tacks started earliest at the third verse. They could represent single syllabled words ("tack") as well as multiple syllabled words (e.g., "tacktack"). The decision to use "tack" as the substituting syllable was based on two factors: (1) its percussive characteristic, for it is often used in music rehearsals to illustrate a piece's rhythm, and (2) because it is the second syllable of "ticktack" (tick-tock), a word which commonly denotes a ticking sound, often used to illustrate, e.g., the ticking of a clock and thus suitable for temporal assignment.

2.3. Questionnaires

In an attempt to investigate possible relations to reading habits or to musical proficiency, further data was collected. *Reading habit questionnaire*: A questionnaire was developed to measure reading habits and their potential correlation with the overall reading performance of individuals. The following data were collected: Demographic data (age, gender, educational level), reading habits I (categories, e.g., newspaper, novels, etc.), reading habits II (percentage of reading/writing, analog vs. digital, and reading time spend with category), reading habits III (actual familial reading habits and during childhood, reading to other people privately/professionally), speaking/writing development, speaking habits, L2 languages, language (therapy) experiences, speaking anomalies (e.g., mumbling), and auditive habits (volume setting tendencies, i.e., loud/silent, music listening preferences). *MusA*. A short Questionnaire to Assess Musical Activity (Fernholz et al., 2018), which investigates music preferences as well as musical activity. After analyzing the two questionnaires for possible correlations between musicality and reading habits first, only factor *musical* was integrated in later analysis.

2.4. Recordings

For audio recordings, we used Sennheiser headset PC 8 USB with a frequency response of 42–17.000 Hz and Praat recording software (version 6.0.41; Boersma, 2001). Also, video-recordings (full body) were carried out with Sony video camera DCR-SR72.

2.5. Procedure

The study was conducted in the lab of the Center for Cognitive Science at the University of Freiburg. The experimental session started with reading a short info sheet about the procedure of the experiment. Next, participants had to fill out the questionnaires, which roughly took 10 min to complete. Participants then were instructed to place themselves in an upright position in front of the video camera. To ensure a fixed body position, participants had to locate both their forefeet close to a Gaffa tape line that was glued to the floor. After that, the experimenter positioned the headset on the participant's head and made sure that the microphone was placed properly, with a maximum distance of 2 cm to the participants' lips. Then the height of the video camera was adjusted, and image capture was focused. The last part of the set-up was a quick mic and recording test. Finally, stimuli-texts were handed over to the participant, with graphics turned upside-down to make sure that no time was given to reflect on genre ahead of reading. Before the reading of the stimuli was recorded, participants were asked to read aloud and according to one out of three conditions, *rhythmically*, to read in line with a beat (*tactus*), or *no instruction*. Then the Praat recording button was pressed and subjects were ordered to turn around the stimuli sheets and to start read. On average, recordings took roughly 10-15 min.

2.6. Data analysis

In a first step, a syllable table was prepared listing all syllable tokens chronologically for each poem, such that each row represented one syllable token. Further information for each syllable was assigned, e.g., the poem and the word the syllable belongs to, and the numeric index of a syllable in a word, line, and poem, etc. In another step, a subset from the recorded audio files was chosen, namely the poems "Im Grase" by Justinus Kerner (*A1*, 273 syllables), "Die Gunst des Augenblicks" by Friedrich Schiller (*D2*, 270 syllables), "Reiselied" by Hugo von Hofmannsthal (*C2* with 76 syllables; partly catalectic), "Mittag" by Theodor Fontane (*D1*, 68 syllables), "Das Sonett" by Johann Wolfgang von Goethe (*E1*, 154 syllables) and "Herbst" by Theodor Storm (*F2*, 150 syllables; this stimulus had been reduced by omitting stanzas 6 and 7). Stimuli *A1*, *D1*, *E1* were categorized iambic and *C2*, *D2*, and *F2* trochaic. For this reduced subset, all recorded sound files were separated per poem using Praat Software (version 6.0.53; Boersma and Weenink, 2018) and saved in *.wav* format. Then, for each *.wav* file a separate *.txt* format file with the corresponding stimuli text was generated, per poem and per participant. Next, we obtained automatically annotated Praat TextGrids with words and phones segmented and labeled, by applying WebMAUS Basic from BAS Web Services Version 3.1 (Schiel, 1999; Kisler et al., 2017) and by running the *.wav* and *.txt* files pairwise, as instructed. Using again Praat Software, the resulting TextGrids were inspected. If positioning of a boundary or an interval was imprecise, annotation of initial or final phones of the word was manually corrected. We added another tier for the boundaries for syllables. After annotation for all TextGrids was completed, praat scripts for duration and intensity (Reetz, 2020) were applied to perform computations for all labeled intervals to obtain the necessary data points for analysis. For duration, we used the output provided by the script for the variables for file index, label, i.e., either phon, syllable, word or line, corresponding to the annotation described above, and, starting points for each as well as duration for each. For intensity, the scripts' output used were the values for mean-dB.

All resulting files were read into R. Additionally, the questionnaire data were transferred to Excel and also read into R. The data frames for syllable durations and intensities were then joined with the syllable table and with a subset of the merged questionnaire data. Four variables were added: (*i.*) *meter*, i.e., whether a poem was categorized iambic or trochaic, (*ii*) *stress*, meaning the predicted stressing of syllables according to the metrical grid. Two poets coded this variable by annotating *s* for strong and *w* for weak syllables, which led to almost strictly binary patterns with only a few exceptions per poem. Additionally (*iii*), *instruction*, encoding whether the poems should be read rhythmically (*rhythmic*), in line with a - individually induced and projected - beat (*on beat*, "im Takt"), or whether no instruction was given at all (*no instruction*). Next (iv.) the variable *musical* was derived from the answers given for questions 4 and 8 of the MusA questionnaire. First, participants were asked whether or not they had ever been musically active in their lives, i.e., by playing an instrument or by singing, and if so at what age and how many hours per week. If they answered "no," they were annotated as not active. Otherwise, subjects were then asked: *In the last 12 months, how often have you been musically active?* One of following answer options could be checked for a) instrument as well as for b) singing: *Not at all*, *once a month or less*, *2–3 times a month*, *1 time per week*, *2–3 times per week*, *4–6 times per week*, *daily*. Answers of both parts (instrument + singing) were combined, i.e., when at least one answer in both parts was different from *Not at all*, the participant was coded as musical: *active*, otherwise *not active*. This resulted in six participants being categorized as *active*, and seven participants as *not active*.

From here on, all statistical analyzes were performed using the software R (version 4.1.1; R Core Team, 2020). We calculated mixed-effects regression models using the lmer function from the lme4 package (version 1.1–27.1; Bates et al., 2015). For all calculations, including nPVIs (adapted from http://cspeech.ucd.ie/Fred/nPVI.php), we used function *contrSum* for sum-coding from the car package (Fox and Weisberg, 2019). In sum-coding, the intercept represents the grand mean. Hence, the estimate difference between two conditions of a binary factor is two the times the estimate β. For estimating the p-values we used the function tab_model from the sjplot package (R package version 2.8.12, Lüdecke, 2022), using method *Satterthwaite* for estimating the degrees of freedom. Cohen's d was estimated using the function lmd.score from the EMAtools package (version 0.1.4, Kleiman, 2021). We report Cohen's $d > 0.1$.

We analyzed the data on two distinct levels, the syllable level (1) and the line level (2). All data, were the SOI exceeded 2000 ms, were eliminated. The data set yielded an average of 981 syllables per participant and, overall, 120 lines per participant.

2.6.1. Syllable level

Level 1 investigated rhythmic signatures at the syllable level. Two subsets were created, one including only regular syllables and the other including only tack-syllables. The reason the data set was split this way was to generate a clean baseline for regular syllables so that the variance of the data patterns of the tacks could be compared to it.

For each response variable, two identical models were fitted. The first model fit was used to identify outliers in the residuals using the function boxplot() with range 1.5: only data where the residual did not exceed 1.5 times the inter-quartile range from the box were included in the data set that entered the second model fit, which is the one reported here.

2.6.1.1. Syllable onset interval

Duration was sub-leveled into *syllable duration* (syllable onset to offset) and duration of the SOI, i.e., the beginning of the onset of a syllable until the onset of the succeeding syllable. We only report SOI, because this measure integrates speaking pauses (rests) and thus reflects rhythmicity better than the mere syllable duration. Pauses at the end of each line were excluded. Thus, in the SOI model fit for regular syllables, the dependent variable was *SOI*, the fixed effects predictors used were *stress*, *musical* and *meter*. *Participant* and *syllable* were included as random factors. For participant, the random intercept and the random slope for *stress* were included. Only the random intercept was included for *syllable*.

The structure of the model for tacks was almost the same, except that the variable for the index number of a tack within a line (*tack index*) was added as fixed effect predictor, and logically, *syllable* as random intercept was excluded for this model fit.

2.6.1.2. Mean intensity

We used the same model fit described above, but the dependent variable was changed to mean intensity (*i_mean*).

2.6.2. Line level

Level 2 examined rhythmic signatures at the line level. Specifically, we were interested in the rhythmic contrasts between adjacent syllables. These could be based on the durations or intensities of syllables, which both could be indicating stress.

Grabe and Low (2002) had introduced the nPVI as a measure of the variability of successive syllabic durations, in their work this was based on vowel length. In an modified adaption, Patel and Daniele (2003) had used it to compare French and English speech rhythms with rhythms in respective musical compositions. Here, we used the normalized nPVI index as an indicator for rhythmic variation within lines, based on the version presented by Cummins (n.d.)[2], which calculates the nPVI for a sequence of syllable onsets:

$$nPVI = 100\left[\sum_{k=1}^{m-1}\left|\frac{d_k - d_{k+1}}{\left(d_k - d_{k+1}\right)/2}\right| / \left(m-1\right)\right]$$

2 https://cspeech.ucd.ie/Fred/nPVI.php

Next, an aggregated data frame for lines was produced from the syllable data frame, using the nPVI as the aggregation function over syllable SOIs (*npvi_soi*) and intensities (*npvi_i_mean*) for each line. We added the running line number for each poem (*line*), and the maximum number of syllables per line (*n_sylls*). This dataframe also contained the binary variable *tack line* indicating whether a "tack" was in a line or not, as well as the numerical variable *tacks per line* representing the number of tacks within a line. Furthermore, the binary variable *musical*, i.e., whether the participant was musically active or not, was added. For the analysis, the numeric variables *tack*, *line*, and *n_sylls* where centered, using the scale-function from the Base-R package, respectively named *tack_C*, *line_c*, and *n_sylls_C*. The variables *meter*, *musical*, and *instruction* where coded as factors.

For the line level, we will only report general model fits, which means that no distinct subsets for tack-lines and non-tack-lines were used for the data analysis. Instead, we introduced the variable *tack line* to indicate whether at least one tack syllable was present in the line.

2.6.3. Normalized pairwise variability index for syllable onset intervals

For the dependent variable (*npvi_soi*) two identical models were fitted. The predictor models consisted of the fixed effects predictors *tack line*, *musical* and *meter*. The variables *participant* and *poem* were included as random intercepts. In addition to the random intercept for participant, the random slope for *tack line* was included. Again, we first identified outliers in the residuals using the function boxplot() with range 1.5. In the successive model fit, only data where the residual did not exceed 1.5 times the inter-quartile range from the box were included in the data set. We only report the second model fit here. In a second version of this model the binary variable *tack line* was replaced by the continuous variable *tacks per line* as a fixed effect predictor. Accordingly, in addition to the random intercept for participant, the random slope for *tacks per line* was included.

2.6.4. Normalized pairwise variability index for intensities

The procedure for fitting the model was the same as just described for nPVI duration, except that the dependent variable was exchanged, i.e., *npvi_i_mean* was inserted instead.

Please note that in the further course, we will use the term "inactive" for the "not-active" level of the between-subject factor "musical" to ensure improved readability of the text.

3. Results

3.1. Syllable level

3.1.1. Syllable onset interval

The model fit for SOIs for regular syllables (Table 1 and see Figure 1A) revealed a significant main effect for *stress* ($p < 0.001$), i.e., on average the SOI for a strong syllable was spoken 41.08 ms ($\cong 2 \times \beta$, *Cohen's* $|d| = 4.77$) longer than for a weak syllable. A significant two-way interaction with *musical* was found for *stress* ($p = 0.025$), meaning that for musically active readers, the average SOI for a strong syllable was an

TABLE 1 Syllable onset intervals and mean intensity for regular syllables.

Predictors	SOI for regular syllables					Mean intensity for regular syllables				
	β	*ste*	*df*	*t*	*p*	*β*	*ste*	*df*	*t*	*p*
Intercept	254.16	6.77	31.81	37.52	**<0.001**	65.72	0.94	11.39	69.86	**<0.001**
Stress [strong]	20.54	1.71	23.98	11.99	**<0.001**	0.37	0.12	16.53	3.09	**0.007**
Musical [active]	3.31	5.63	15.30	0.59	0.566	−0.67	0.93	11.00	−0.72	0.489
Meter [iambic]	2.13	0.86	26969.86	2.48	**0.013**	−0.08	0.05	7876.23	−1.78	0.075
Stress [strong] * musical [active]	3.63	1.39	10.37	2.61	**0.025**	−0.01	0.11	10.97	−0.13	0.896
Stress [strong] * meter [iambic]	−0.12	0.85	27020.09	−0.14	0.890	0.09	0.04	7960.20	2.03	**0.043**
Musical [active] * meter [iambic]	−0.70	0.51	30000.07	−1.35	0.176	−0.06	0.03	9842.80	−2.03	**0.042**
Stress [strong] * musical [active] * meter [iambic]	0.06	0.51	30019.13	0.11	0.911	−0.02	0.03	9843.20	−0.74	0.458
Random effects										
σ^2	2623.56					8.31				
τ_{00}	5982.17 $_{corrected.syllable}$					6.29 $_{corrected.syllable}$				
	406.63 $_{vpnum.x}$					11.23 $_{vpnum.x}$				
τ_{11}	21.53 $_{vpnum.x.stress\ [S.strong]}$					0.14 $_{vpnum.x.stress\ [S.strong]}$				
ρ_{01}	0.81 $_{vpnum.x}$					−0.02 $_{vpnum.x}$				
ICC	0.71					0.68				
N	13 $_{vpnum.x}$					13 $_{vpnum.x}$				
	431 $_{corrected.syllable}$					431 $_{corrected.syllable}$				
Observations	10,024					10,306				
Marginal R^2/Conditional R^2	0.046/0.723					0.023/0.687				
AIC	109016.742					52376.487				

Bold values indicate statistical significance.

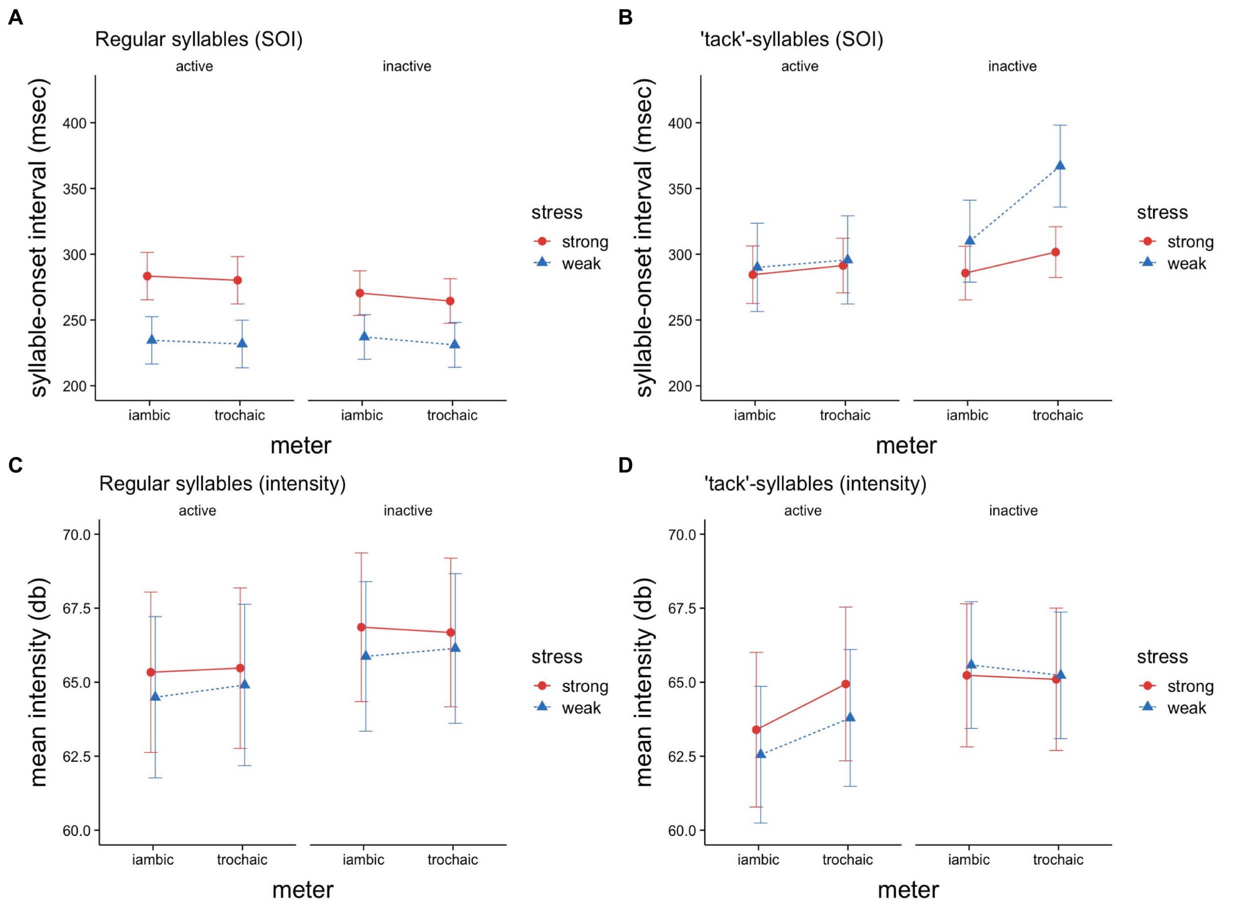

FIGURE 1
Syllable-onset intervals **(A,B)** and syllable intensities **(C,D)** for *regular syllables* **(A,C)** and *'tack'-syllables* **(B,D)**, as a function of stress (strong vs. weak), meter (iambic vs. trochaic), and musical activity (active vs. not active). The whiskers depict 95% confidence intervals.

additional 7.26 ms ($|d|=1.58$) longer. The model also revealed a significant main effect for *meter* ($p=0.013$), indicating that SOIs in poems with iambic patterns were on average 4.26 ms longer, meaning that iambic poems were on average read slower than trochaic poems.

For tack syllables, *stress* appeared to have an effect, but the effect was not significant ($p=0.079$). Surprisingly, speaking time for SOIs for weak tack syllables was on average 19.7 ms longer than for strong tack-syllables ($|d|=0.51$). The analysis (Table 2) revealed a significant main effect for *meter* ($p=0.001$), i.e., SOIs were 29.22 ms ($|d|=0.15$) longer in poems with trochaic patterning. A main effect was also found for the *tack index* ($p<0.001$), i.e., the index for the particular "tack" within a line. It shows that, on average, each increment of a tack syllable within a line increases the SOI by 15.84 ms ($|d|=0.18$). In addition, the model yielded a significant two-way-interaction for *musical* with *meter* ($p=0.003$), indicating that musically active subjects' SOIs were on average 26.02 ms longer in iambic poems than in trochaic ($|d|=0.13$). Although no main effect was found for *musical*, the analysis suggests a two-way-interaction of *stress* and *musical* ($p=0.066$, $|d|=0.53$), which is based on a three-way interaction with *meter* ($p=0.007$). Figure 1B illustrates this result. While musically active readers seem to make an almost negligible distinction between strongly and weakly stressed tack-syllables, regardless of meter, musically inactive readers show a different pattern. In both iambic and trochaic poems, they exhibit longer SOIs for the weakly stressed syllables, an effect that is more pronounced in trochaic poems.

On top of the main effect found for *tack index*, the model shows a reliable two-way interaction of *musical* and *tack index* ($p=0.016$), as shown in Figure 2A. This indicates that the positive main effect for *tack index* was mainly due to the musically inactive readers, where each additional tack in a line increased the main effect of SOI by 4.7 ms, while for musically active participants it was decreased by the same amount.

In the analysis, *stress* appeared to interact with *meter* and *tack index*, however, the effect turned out not to be significant ($p=0.075$). Also, no two-way-interactions were found for *stress* and *meter* or for *stress* and *tack index*.

As the graphical representation suggests (Figure 2A), the overall results are due to a specific pattern: For musically inactive readers the SOIs tend to be longer overall for the tack syllables coded "weak" compared to the tack syllables coded "strong," independent of meter. Musically active readers, on the other hand, show a different pattern for iambic vs. trochaic. Here, we find shorter SOIs for the weakly stressed tacks in iambic poems compared to the strongly stressed ones found with a larger tack index, and vice versa, longer SOIs with a larger tack index for the weakly stressed tacks compared to the strongly stressed ones in trochaic poems. As the graph also illustrates, the pattern for trochaic poems for musically active readers is particularly interesting, as SOIs for weak syllables are shorter than for strong syllables with a smaller tack index, but with a larger tack index the pattern reverses, and SOIs for strong syllables are even shorter than with the smaller tack index, and SOIs for weak syllables become noticeably longer. To analyze whether

TABLE 2 Syllable onset intervals and mean intensity for variable *tack* syllables.

Predictors	SOI for tacks					Mean intensity for tacks				
	β	*ste*	*df*	*t*	*p*	*β*	*ste*	*df*	*t*	*p*
Intercept	286.85	9.46	37.04	30.32	**<0.001**	66.57	0.86	11.67	77.70	**<0.001**
Stress [strong]	−9.85	5.53	72.98	−1.78	0.079	0.66	0.17	131.27	3.79	**<0.001**
Musical [active]	−3.14	9.46	37.04	−0.33	0.742	0.36	0.86	11.67	0.42	0.683
Meter [iambic]	−14.61	4.40	5806.16	−3.32	**0.001**	−0.17	0.16	2062.01	−1.03	0.303
Tack index	7.92	1.95	5811.09	4.06	**<0.001**	−1.01	0.07	2061.68	−14.13	**<0.001**
Stress [strong] * musical [active]	10.33	5.53	72.98	1.87	0.066	0.28	0.17	131.27	1.60	0.112
Stress [strong] * meter [iambic]	−2.19	4.40	5805.03	−0.50	0.619	−0.21	0.16	2061.31	−1.31	0.189
Musical [active] * meter [iambic]	13.01	4.40	5806.16	2.96	**0.003**	−0.34	0.16	2062.01	−2.08	**0.038**
Stress [strong] * tack index	−1.25	1.95	5812.40	−0.64	0.521	−0.23	0.07	2061.89	−3.18	**0.002**
Musical [active] * tack index	−4.70	1.95	5811.09	−2.41	**0.016**	−0.56	0.07	2061.68	−7.86	**<0.001**
Meter [iambic] * tack index	1.89	1.95	5807.74	0.97	0.333	−0.06	0.07	2061.80	−0.82	0.414
Stress [strong] * musical [active] * meter [iambic]	−11.86	4.40	5805.03	−2.69	**0.007**	−0.24	0.16	2061.31	−1.46	0.145
Stress [strong] * musical [active] * tack index	−0.18	1.95	5812.40	−0.09	0.928	0.01	0.07	2061.89	0.20	0.839
Stress [strong] * meter [iambic] * tack index	3.47	1.95	5806.66	1.78	0.075	0.07	0.07	2061.17	1.00	0.320
Musical [active] * meter [iambic] * tack index	−2.64	1.95	5807.74	−1.36	0.175	−0.04	0.07	2061.80	−0.49	0.623
Stress [strong] * musical [active] * meter [iambic] * tack index	3.17	1.95	5806.66	1.62	0.104	0.11	0.07	2061.17	1.51	0.132
Random effects										
σ^2	6803.36					9.26				
τ_{00}	905.91 $_{\text{vpnum.x}}$					9.15 $_{\text{vpnum.x}}$				
τ_{11}	144.96 $_{\text{vpnum.x.stress [S.strong]}}$					0.05 $_{\text{vpnum.x.stress [S.strong]}}$				
ρ_{01}	−0.72 $_{\text{vpnum.x}}$					0.80 $_{\text{vpnum.x}}$				
ICC	0.13					0.50				
N	13 $_{\text{vpnum.x}}$					13 $_{\text{vpnum.x}}$				
Observations	2059					2099				
Marginal R^2/Conditional R^2	0.100/0.220					0.108/0.552				
AIC	24033.687					10766.851				

Bold values indicate statistical significance.

the effect of tack index with regard to the specific pattern for musically active readers, is statistically tenable, we additionally computed a model for musically active readers only. The model revealed a significant three-way-interaction of *stress*, *meter*, and *tack index* ($t = 2.673$, $p = 0.008$).

3.1.2. Mean intensity

For regular syllables, the analysis (Table 1) reveals a significant effect for *stress* ($p = 0.007$). As shown in Figure 1C, the pronunciation of stressed syllables was on average 0.74 dB ($|d| = 1.52$) louder than that of weak syllables. The model suggests an effect for *meter*, i.e., the mean intensity was increased by about 0.16 dB in trochaic poems, however, the effect was not significant ($p = 0.075$). The model also yielded a significant two-way-interaction between *stress* and *meter* ($p = 0.043$), indicating that in iambic poems, strong syllables were spoken 0.18 dB louder than weak syllables. Noticeably, the mean intensity differs less between strong vs. weak syllables in trochaic poems. Although no main effect for *musical* ($|d| = 0.43$) was found, there is a significant two-way-interaction of *musical* with *meter* ($p = 0.042$), showing that musically active readers read less intensively overall in iambic compared to trochaic poems.

The analysis for tacks (Table 2) shows a main effect for variable *stress* ($p < 0.001$), indicating that stressed tack-syllables were overall about 1.32 dB ($|d| = 0.66$) more pronounced. Figure 1D illustrates that this effect was established by a particular pattern: mean intensities for musically active readers were elevated for stressed syllables compared to unstressed syllables and, notably, correspondingly for both iambic and trochaic poems. Conversely, mean intensities for musically inactive readers show no contrast between stressed and unstressed syllables, and likewise, for both meters. The model also yielded a main effect for *tack index* ($p < 0.001$), showing that each increment of a tack syllable within a line decreases intensity by 2.02 dB ($|d| = 0.62$). Furthermore, we found a significant two-way interaction of *stress* with *tack index* ($p = 0.002$, $|d| = 0.14$), such that the effect was even more pronounced for strong syllables, with an additional average decrease of 0.46 dB (see Figure 2B). As can also be seen in the graph, although no main effect was found for *musical* ($|d| = 0.25$),

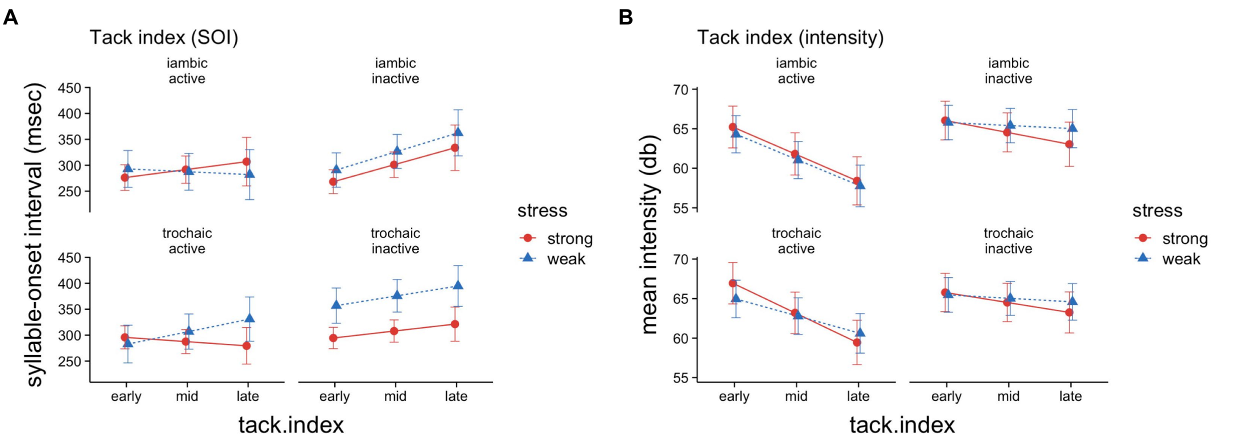

FIGURE 2
Syllable-onset intervals **(A)** and syllable intensities **(B)** for *tack* syllables, as a function of stress (strong vs. weak), meter (iambic vs. trochaic), musical activity (active vs. not active), and tack index (small ~0, mid, large ~5). The whiskers depict 95% confidence intervals.

TABLE 3 Combined table for nPVI SOI and nPVI mean intensity for lines with and without tacks.

Predictors	nPVI syllable onset duration (SOI)					nPVI mean intensity				
	β	*ste*	*df*	*t*	*p*	*β*	*ste*	*df*	*t*	*p*
Intercept	51.93	1.65	4.65	31.52	**<0.001**	5.31	0.25	13.90	21.06	**<0.001**
Tack in line [F]	2.58	0.43	647.92	6.01	**<0.001**	−0.10	0.11	11.03	−0.88	0.398
Musical [active]	−0.18	0.61	11.12	−0.30	0.768	0.17	0.21	11.01	0.81	0.433
Meter [iambic]	0.46	1.59	4.06	0.29	0.788	0.29	0.15	4.13	1.93	0.124
Tack in line [F] * musical [active]	1.04	0.43	647.28	2.43	**0.015**	−0.23	0.11	11.03	−2.05	0.065
Tack in line [F] * meter [iambic]	−0.22	0.43	1537.34	−0.51	0.610	−0.08	0.05	1524.42	−1.80	0.072
Musical [active] * meter [iambic]	0.86	0.43	1537.09	2.00	**0.045**	−0.04	0.05	1524.17	−0.80	0.425
Tack in line [F] * musical [active] * meter [iambic]	0.07	0.43	1537.15	0.17	0.864	0.03	0.05	1524.17	0.58	0.564
Random effects										
σ^2	281.64					3.22				
τ_{00}	2.44 $_{participant}$					0.54 $_{participant}$				
	13.72 $_{poem}$					0.12 $_{poem}$				
τ_{11}	0.01 $_{participant.tack\_line [S.FALSE]}$					0.13 $_{participant.tack\_line [S.FALSE]}$				
ρ_{01}	1.00 $_{participant}$					0.18 $_{participant}$				
ICC						0.20				
N	13 $_{participant}$					13 $_{participant}$				
	6 $_{poem}$					6 $_{poem}$				
Observations	1,560					1,558				
Marginal R^2/Conditional R^2	0.029/NA					0.042/0.230				
AIC	13260.898					6354.937				

Bold values indicate statistical significance.

there was a significant two-way-interaction with *tack index* ($p<0.001$, $|d|=0.35$), i.e., the more tacks occurred earlier in the line, the higher the overall mean intensities for musically inactive readers. Interestingly, the model also yielded a significant two-way-interaction between *musical* and *meter* ($p=0.038$), revealing that with a higher tack index, mean intensities decreased by about 0.68 dB on average for musically active readers and for iambic poems.

3.2. Line level

3.2.1. Normalized pairwise variability index for syllable onset intervals

The analysis (Table 3) of the nPVI for SOI for lines with tacks versus lines without tacks revealed a significant main effect of *tack in line* ($p<0.001$). It shows that the nPVI values as an indicator of

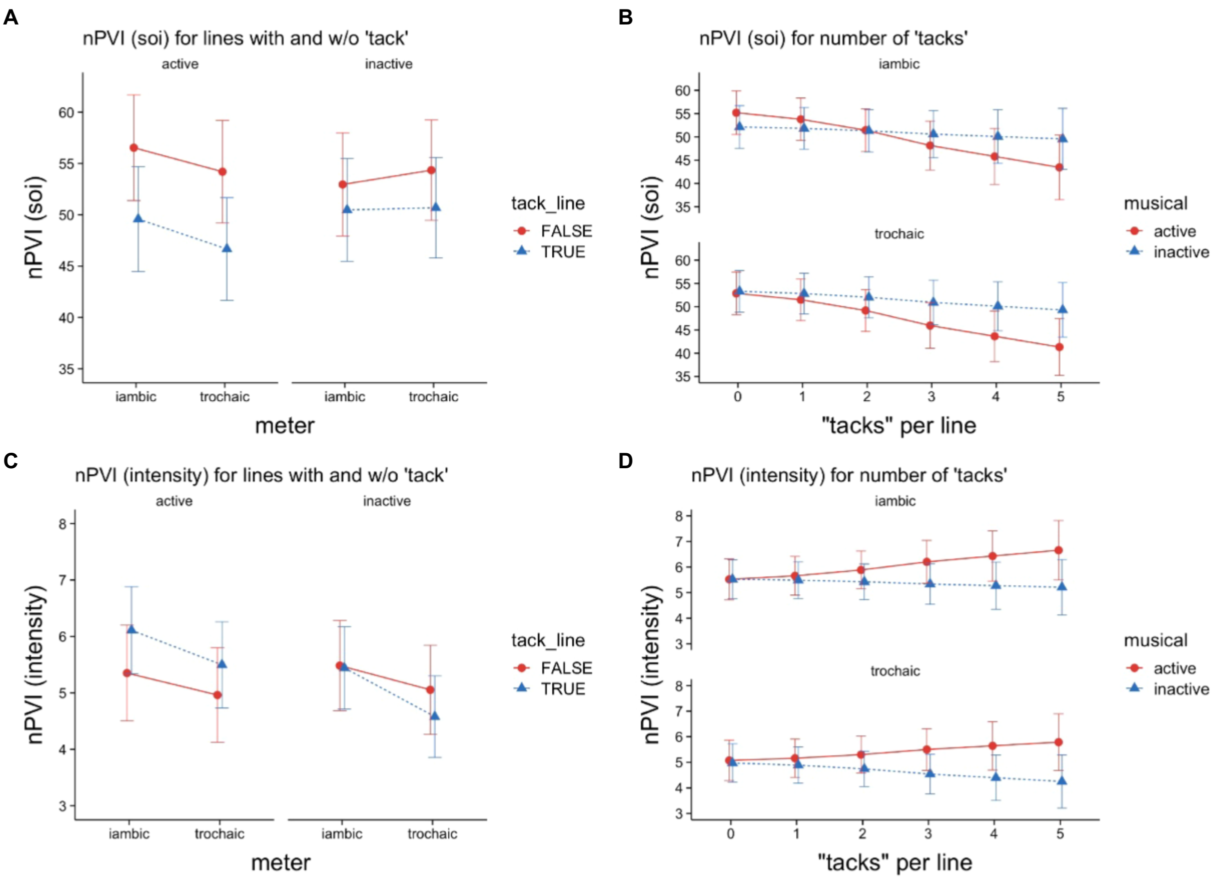

FIGURE 3
Illustration of analyses on the line level. *SOI-based nPVIs* **(A,C)** and *intensity-based nPVIs* **(B,D)**, as a function of meter (iambic vs. trochaic), musical activity (active vs. not active), and tack line [whether or not one or more tacks are present in a line **(A,B)**], or tacks per line (the number of tacks in a line), ranging from low=0 to high=5 **(B,D)**. The whiskers depict 95% confidence intervals.

rhythmic contrast for SOIs were different for lines with and without tacks, with lines without tacks having the higher value ($\beta = 2.58$, $|d| = 0.47$) compared to lines with tacks. Thus, as detailed in Figure 3A, the nPVI for SOIs for lines without tacks was more pronounced for both iambic and trochaic conceptualized poems than for lines that contained tacks. Additionally, a significant two-way interaction of *tack in line* with *musical* was found ($\beta = 1.04$, $p = 0.015$, $|d| = 0.19$). Figure 3A also illustrates that, surprisingly, the nPVI for SOIs for lines with tacks is significantly reduced for musically active readers compared to lines without tacks. On the other hand, the nPVI for SOIs for musically inactive readers does not seem to differ much for lines with or without tacks. Although there was no main effect for *musical*, the model also yielded a two-way interaction with *meter* ($\beta = 0.86$, $p = 0.045$, $|d| = 0.10$).

Further analysis explored the possibility that the number of tacks within a line might play a modulating role. As highlighted in Table 4, the model showed a significant main effect for the variable *tacks per line* ($\beta = -1.49$, $p < 0.001$, $|d| = 2.87$), i.e., with each additional tack more in a line, the nPVI-value decreased by 2.98. In addition, the analysis revealed a two-way interaction of *tacks per line* with *musical* ($\beta = -0.84$, $p = 0.016$, $|d| = 1.62$), meaning that the effect was even stronger for musically active readers, with an additional average decrease of 1.68. *Musical* appeared to interact with *meter*, but the effect turned out to be not significant ($\beta = 0.79$, $p = 0.065$). In Figure 3C this is graphically detailed, such that for iambic and trochaic meters, the nPVI for the SOI decreased for musically active readers with a higher number of tacks within a line. However, the graph also shows that this effect was much less pronounced for musically inactive readers in the trochaic poems and almost negligible in the iambic poems.

3.2.2. Normalized pairwise variability index for intensities

For nPVI mean intensity for lines with tacks versus lines without tacks, no main effect was found for *tack in line* (see Table 3), and although the model suggests that *tack in line* interacted with musical, the effect turned out to be not significant ($\beta = -0.23$, $p = 0.065$, $|d| = 1.23$). Additionally, *tack in line* appeared to interact with *meter*, but the effect was also not significant ($\beta = -0.08$, $p = 0.072$). Also, there was no main effect for meter. The graphical inspection (see Figure 3B) of this result shows that the nPVI for mean intensity was higher for musically active readers in both iambic and trochaic poems when the lines contained tacks. In contrast, the nPVI for mean intensity for musically inactive readers decreased for lines with tacks compared to "normal" lines.

TABLE 4 Combined table for nPVI mean intensity and nPVI SOI for tack count.

Predictors	nPVI syllable onset duration (SOI)					nPVI mean intensity				
	β	*ste*	*df*	*t*	*p*	*β*	*ste*	*df*	*t*	*p*
Intercept	51.88	1.55	4.76	33.52	**<0.001**	5.31	0.25	13.86	20.93	**<0.001**
Tacks per line	−1.49	0.30	12.17	−5.01	**<0.001**	0.04	0.08	11.15	0.53	0.609
Musical [active]	−0.18	0.61	11.12	−0.29	0.777	0.17	0.21	11.01	0.80	0.440
Meter [iambic]	0.36	1.49	4.08	0.24	0.820	0.29	0.15	4.12	1.93	0.124
Tacks per line * musical [active]	−0.84	0.30	12.02	−2.81	**0.016**	0.14	0.08	11.13	1.87	0.088
Tacks per line * meter [iambic]	0.06	0.28	1528.43	0.22	0.829	0.04	0.03	1526.47	1.39	0.164
Musical [active] * meter [iambic]	0.79	0.43	1526.24	1.85	0.065	−0.02	0.05	1524.15	−0.55	0.585
Tacks per line * musical [active] * meter [iambic]	−0.08	0.28	1526.28	−0.29	0.770	0.00	0.03	1524.18	0.02	0.984
Random effects										
σ^2	282.25					3.20				
τ_{00}	2.43 $_{participant}$					0.54 $_{participant}$				
	11.81 $_{poem}$					0.12 $_{poem}$				
τ_{11}	0.13 $_{participant.tacks\_per\_line}$					0.07 $_{participant.tacks\_per\_line}$				
ρ_{01}	−0.02 $_{participant}$					−0.17 $_{participant}$				
ICC	0.05					0.20				
N	13 $_{participant}$					13 $_{participant}$				
	6 $_{poem}$					6 $_{poem}$				
Observations	1,560					1,558				
Marginal R^2/Conditional R^2	0.025/0.073					0.040/0.236				
AIC	13268.573					6353.326				

Bold values indicate statistical significance.

No main effect was found for the number of tacks within a line (see Table 4). Again, the model suggests *tacks per line* to interact with *musical*, however, the effect turned out to be not significant ($\beta = 0.14$, $p = 0.088$, $|d| = 1.12$). Figure 3D illustrates this result, with both musically active and musically inactive readers showing a comparably high nPVI for the mean intensity at a lower number of tacks per line (<2). However, this pattern changes as the number of tacks within a line increases, for both iambic and trochaic poems. Then we find that the nPVI for mean intensity tends to be higher overall for musically active readers than for musically inactive readers.

3.2.3. Instruction

Each participant was assigned to one of three instruction groups (*no instruction*, *rhythmic*, *on beat*). In a previous analysis, we found that the *instruction* was less effective than expected, so we did not include it as a predictor in our models. However, we found that musicality was confounded with our instruction groups: Three musically active but only one inactive participant received no instruction, three active and two inactive subjects were instructed to read "rhythmically," while no active, but four inactives were instructed to read "on beat" ("im Takt"). Therefore, we fit two more models – one for SOI-based nPVIs and one for intensity based nPVIs – to reaffirm that the musicality effects were not due to the instruction assignment. In these models, we had both variables – *musical* and *instruction* – interact with the same predictors, so any effect of musicality should disappear, or at least be reduced, if it can be attributed to instruction. While instruction did seem to account for some variability in the data (see Figures 4A,C), its inclusion in the model appeared to have virtually no effect on the general effect pattern of musicality, as can be seen in Figure 4B,D, when compared to the result of the simpler model (see Figure 3B,D): The significant interaction between *musical* and *tacks per line* for nPVI (SOI) remained significant ($\beta = -1.04$, $t = -2.66$, $p = 0.008$). Also, the main effect of *tacks per line* was unaltered ($\beta = -1.55$, $t = -5.01$, $p < 0.001$). We found one difference though: While there was no main effect of *musical* in the analysis above, the model now yields this main effect ($\beta = -1.3$, $t = -2.12$, $p = 0.034$), indicating that musically active participants read less rhythmically. However, since this effect only appears after the additional inclusion of the instruction variable, it is very likely that this effect is a suppressor effect due to the confounding of the two variables.

As for *instruction* itself: There appears to be an effect of *instruction*, as the nPVI (SOI) was significantly increased when no explicit instruction was given ($\beta = 2.19$, $t = -2.82$, $p = 0.005$). For intensities, the nPVI for poems in *iambic* meter was slightly reduced when participants were instructed to read rhythmically ($\beta = 0.15$, $t = -2.36$, $p = 0.018$).

However, as shown above, these effects did not substantially alter the general pattern of effects of *musical*. We therefor conclude that the omission of the instruction predictor was justified.

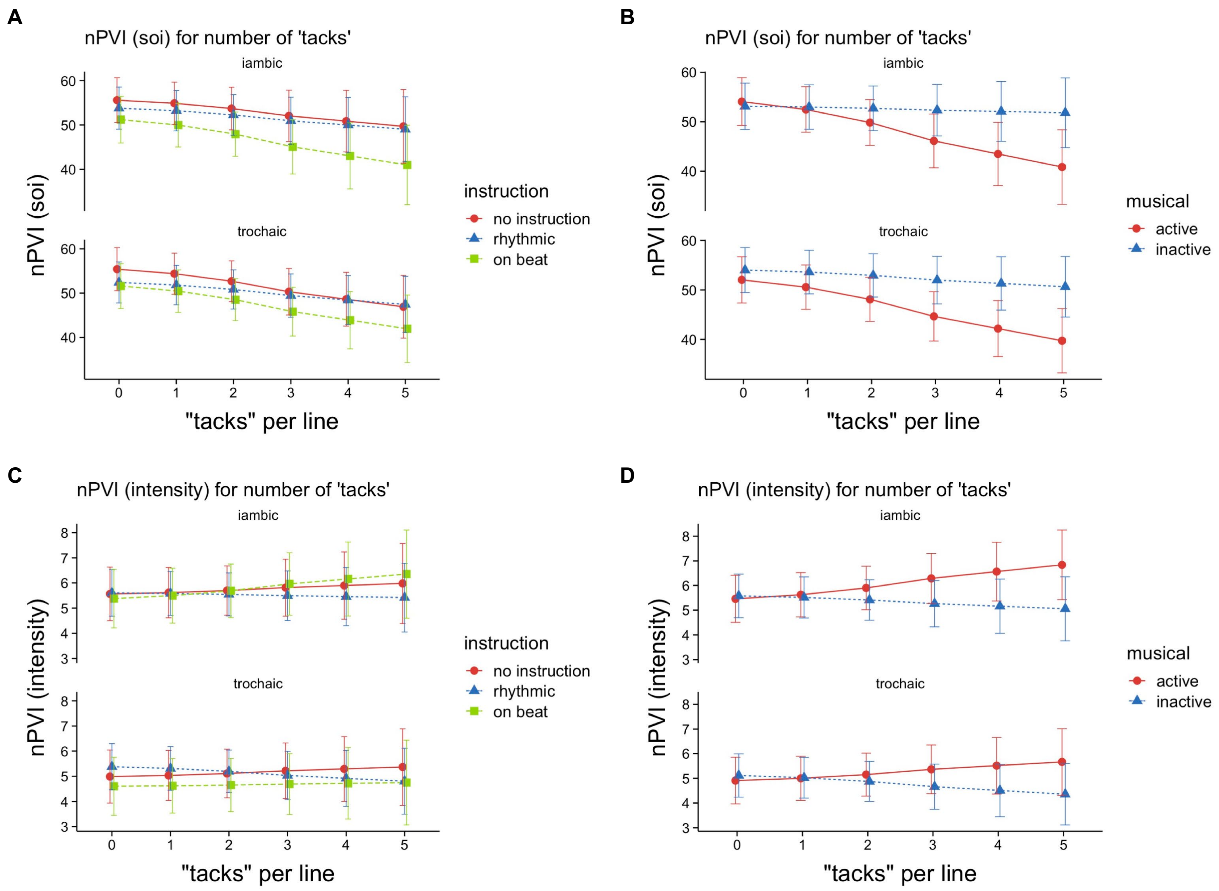

FIGURE 4
Illustration of the analysis of variable *instruction* on the line level for two models: including variable *instruction* **(A,C)** vs. including the interaction of *instruction* and *musical* **(B,D)**. *SOI-based nPVIs* **(A,B)** and *intensity-based nPVIs* **(C,D)**, as a function of meter (iambic vs. trochaic), and either instruction (no instruction vs. rhythmic vs. on beat; **A,C**) or musical activity (active vs. not active; **B,D**), and tacks per line (the number of tacks in a line, ranging from low=0 to high=5; **B,D**). The whiskers depict 95% confidence.

4. Discussion

Our goal was to investigate rhythmic patterns during oral reading of metrically regular, rhymed language (MRRL) and whether readers would realize a poem's metric conceptualization, i.e., either as iambic or trochaic, by applying duration or intensity-based syllable patterning. Furthermore, we wanted to investigate whether the integration of the semantically meaningless syllable *tack* leads to interference. The aim of this was to gain insight into the extent to which readers can maintain a governing metrical grid during oral reading. Our idea was that musically inactive individuals would be more easily irritated by *tacks* than musically trained individuals. One premise for this would be that musically active individuals are more likely than musically inactive individuals to subordinate bottom-up processing in reading MRRL to a higher-level temporal relationship, i.e., top-down processing (compare Strait et al., 2010; Zhang et al., 2015). However, we also assumed that an increasing number of tacks in a verse would make it more difficult for both groups to maintain the main metrical grid.

At the syllable level, the results found for SOIs for the regular syllables show that both groups exhibited a stress pattern that corresponded to the underlying iambic or trochaic conception of the poems (cf. Figure 1A), with longer SOIs for the stressed syllable and shorter SOIs for the weak syllable. This result is in line with our simple stress hypothesis (H1). Remarkably, the musically active group showed a more pronounced difference between strong and weak syllables. This is in line with the OPERA-hypothesis (Patel, 2011, 2012), which assigns a higher temporal precision to musically active readers, and is thus supporting H4a.

For regular syllables, the strong-weak distinction was also replicated for intensity patterns (cf. Figure 1C), consistent with H1. The stress difference found was slightly stronger in the iambic conceptualized poems though, contrary to H2. According to the iambic-trochaic law (Hayes, 1985, 1995), the perception of an aural signal should be metrically biased, in that trochaic units are associated with intensity based stress marking, and iambic units with duration based marking. If perception preferences (but see Hay and Diehl, 2007) can be transferred to reading aloud, then we should have found a greater intensity difference for strongly and weakly stressed syllables in the trochaic poems. One explanation for this result could be that readers have to be more focused in iambic meter, which is less preferred in the everyday German. Also, contrary to our expectation that musical advantage also positively affects the use of intensity to mark stress (H4c), there was no difference between musically active and inactive readers. Overall, the results for regular syllables corroborate the findings by Breen (2018) and Breen and Fitzroy (2021), showing that both, duration and intensity, are used to realize the specific poetic sound quality and metrical discrimination during oral poetry reading.

We also specifically examined how "tacks" replacing regular syllables would affect SOIs and intensities. For SOIs the insertion of tacks in verse lines resulted in a different pattern compared to regular syllables, in that the weak syllables had longer SOIs (cf. Figure 1B). Interestingly, musically active readers seemed to exhibit no effect between strong and weak tack-syllables, regardless of meter. The SOIs for musically inactive readers, on the other hand, showed a clear difference for strongly and weakly stressed tacks, however with prolonged syllable reading times for the weakly stressed tack-syllables, as predicted by H7. This effect was more pronounced in trochaic poems than in iambic ones. Thus, our "leveling" hypothesis (H6), which expected that tacks are pronounced more similar to each other, leading to similar SOIs, independent of meter, seems to hold for musically active readers only, whereas musically inactive readers seem to experience overall more interference from "tacks", resulting in lengthened SOIs of weakly stressed tack syllables. This suggests that tacks lead to a clash between top-down processing, i.e., the projection of the main metrical grid, and bottom-up processing, i.e., the assumption that tacks must be emphasized (H7). The interference is stronger in trochaic meter, where the weak syllable is the last syllable of the metrical unit. This result suggests that musically inactive readers chose to separate metrical units more strongly by pausing after a weakly stressed tack at the end of a trochaic unit. They thus appeared to have marked the boundaries of metrical units, instead of marking stress. This corresponds to H3, which was however not supported by the data for regular syllables. An alternative interpretation would be based on preference-hypothesis (Domahs et al., 2008; Wiese and Speyer, 2015), i.e., in German, a trochaic pattern is preferred, and musically inactive readers – in the absence of distinctive bottom-up information – may just locally fall back into a trochaic pattern. In other words, it could be that musically inactive readers superimpose the trochaic pattern preferred in everyday speech, even if they have globally derived the appropriate main metrical grid, e.g., iambus, and have applied it to tack-free verses before. In this case, SOIs would be still used to mark stress in iambic poems and musically inactive readers would switch to trochaic meter when they read tacks.

As illustrated (cf. Figure 2A), the SOI increased with tack index, but stronger so for musically inactive readers. For musically active readers, the tack index seems to have a complex effect on stressed and unstressed tacks. In iambic poems, the more tacks in a line, strongly stressed tack-syllables become lengthened even further, whereas weak tack-syllables become shorter with an increasing tack index. This result seems to support H10a. However, in trochaic poems, the opposite pattern emerged, which however did not amount to a significant four-way-interaction of *stress*, *musical*, *meter* and *tack index* ($p = 0.10$). Nevertheless, the three-way-interaction of stress, meter and tack index for musically active readers supports our interpretation.

The particular pattern found for musically active readers suggests that with an increasing number of tacks SOIs are used for marking the boundaries of the respective metrical unit, rather than to signal prominence for strong vs. weak tack-syllables. Thus, the iambic or trochaic stress pattern "encapsulated" in the metrical unit seems to prevail due to top-down processing of the metrically regular, rhymed language (H10).

In contrast, and interestingly so, for musically inactive readers the pattern of SOIs for tacks appears to be similar for both, iambic and trochaic poems, in that SOIs for strongly stressed tacks are shorter than for weakly stressed tacks. The consistent effect of stress suggests that metrical information is also maintained by inactive readers. The stress effect was however stronger in trochaic poems. While the tack index slowed down reading in general, it did not change this pattern of results. Therefore, the two suggested interpretations for the general effect of tacks – metrical unit vs. preference for trochaic – are valid independent of the number of tacks in a line.

In general, we find, in both groups, indicators for top-down-processing in reading tacks, however differently so. While musically active readers seem to use the "metric unit"-strategy for both, iambic and trochaic versions, musically inactive readers appear to use this strategy only in trochaic poems. In iambic poems they appear to fall back into trochaic meter, which is the dominant pattern in German.

Looking at mean intensities for tack-syllables, musically inactive readers show no difference between strong and weak tack syllables (*cf.* Figure 1D), whereas musically active readers clearly used intensity to mark prominence, as predicted in H5. The differential effect of musicality however supports H10c. Prominence marking by musically active readers was even more pronounced in trochaic poems, in support of H8.

The significant negative main effect of tack index on intensity means that tacks were generally spoken more quietly as the number of tacks increased (*cf.* Figure 2B). This could point at readers losing confidence about the metrical grid when more tacks occur in a line. For musically inactive readers, intensity decreased even more rapidly for strong syllables. Musically active readers, on the other hand, showed a different pattern for iambic and trochaic items. While they overall clearly used intensity for prominence marking, only in iambic poems did they do so for later tacks as well. This seems paradoxical, as prominence marking on tacks was overall stronger in trochaic poems, and hence seems to be easier here. However, as the corresponding results for SOIs clearly point toward the metrical unit hypothesis, where the lengthening of the unit-final syllables indicates grouping into metrical units, this effect may also be responsible for increasing intensities of unit-final syllables on later tacks (compare Wagner, 2022).

We also calculated the nPVI, aggregating neighboring syllable duration and intensity contrasts per line. The nPVI provides a simpler measure for calculating rhythmic contrasts (see H12+). Furthermore, the nPVI revealed additional properties of rhythmic processing, compared to the syllable level.

The nPVI over SOIs (*cf.* Figure 3A) revealed that oral MRRL-reading was rhythmically more pronounced in lines without tacks than in lines with at least one tack syllable. While this effect holds for both musically active and inactive readers, it was stronger for active readers. This nPVI pattern mirrors the syllable-based SOI effects of stress marking very well (*cf.* Figures 1A,B). These results clearly show that the lack of distinctive phonemic qualities in tacks disturbs the maintenance of the metric grid, which then solely depends on top-down projections.

Musically active readers also read the iambic lines more rhythmically than the trochaic lines, with or without tacks, while musically inactive readers did not show a meter effect. This pattern cannot be found in the syllable data. As trochaic patterns fit the general preference of German, this might have led musically active readers to smoother reading, as the meter is clearly identifiable. Iambic lines may require more stress distinction to be identifiable. Why we did not find this result on the syllable level, remains an open question.

Although musically active readers showed a quite steep decline of rhythmicity with high number of tacks in a line, the meter effect still prevailed (*cf.* Figure 3B). Inactives, however, showed a slower decline, and no signs of differentiation between meters whatsoever.

If tack-syllables were processed as nonsense-syllables, it might be possible that some syntactic form had been projected onto them. Thus, an alternative interpretation would hold that the effects found could be due to "surprisal" (Levy, 2008). Any results found could then have been driven by sentence processing and syntax-driven predictions related to timing. If we had replaced only a specific class of words with tacks, indeed, there could have been a learning effect, for example, if readers had realized that only nouns had been replaced. However, in our stimulus material, "tacks" substituted *different* word categories. Thus, although tacks remain unpredictable, they are likely to be perceived very quickly as placeholders, i.e., as words that fit any context. Furthermore, even if projections were occasionally possible, then presumably so only in verses including one, max. two tacks. It seems unlikely that readers were able to maintain a clear syntactic form in verses with more than two tacks, especially, since in poetry, grammatically correct syntax is often systematically broken or transformed. Therefore, we strongly assume that readers assigned less of a functionally relevant syntactic role to "tacks" during reading because of the poeticized language. Also, it is more plausible that with an increasing number of tacks within a line, syntactical processing as well as semantic comprehension become less important, whereas 'keeping the rhythm' while reading should become the main goal in order to complete the task at hand, which was to read the poem out loud.

However, another alternative and more likely interpretation would be that syntactic predictions, enabled by the meaningful regular syllables, may be a factor as important as phonetic structure for extracting, updating, and maintaining a leading metrical grid, because unlike the tack-syllables the regular syllables combine to form words and phrases. Thus, effects found for tack-syllables could also be explained by a tack induced weakening of the ongoing syntactic prediction process, disrupting the syntax-aligned metrical prediction of phrasal stress, as suggested by Hilton and Goldwater (2021). Thus, if there are fewer syntactic predictions possible, or non at all, because a line contains multiple meaningless tacks, then it is possible that there is less of a boost to metrical processing from these non-syntactic bottom-up cues, which in turn could have led readers' performance to become more dependent on the top-down projection of the main metrical grid. For this, musicians might have overall more experience in keeping the beat while maintaining a meter and simultaneously realizing a rhythm "in line" with it. This alternative interpretation is supported by the results found for the nPVI for SOIs, indicating that as the number of tacks per line increased (and thus as syntax within a line/stanza became more impoverished), there was less differentiation of meter.

For musical active readers we found a higher intensity-based nPVI for lines including tacks compared to lines without tacks. This result confirms the pattern found at the syllable level (cf. Figure 1D), and corroborates our interpretation, that musically active readers use intensity more for prominence marking in lines containing tacks. This would speak in favor of a more dominant role of top-down processing in musically active readers compared to inactives.

Although we expected for *intensity* that main effects found at the syllable level would also be visible at the line level, this was not the case. This was true for meter. On the one hand, the two-way interactions suggest that there may be a power problem. On the other hand, it would be possible that "tacks" represent syllable-like sounds which, due to their CV structure, provide little potential for intensive pronunciation anyway as well as for intensity variation: The syllable is overall short, but also the vowel is to be spoken short, and the ratio of voiceless vs. voiced phonemes is 3:1. Therefore, although a "tack" might be *perceived* as a 'syllable' which is to be stressed, it leaves little room for intensity variation in actual production. What is more, for the realization of stress and meter for tacks, it is also quite possible that pitch could be a better discrimination criterion for equal syllables, especially if 'tacks' follow each other immediately. In our study, the decision not to include pitch was based on a work by Zahner et al. (2019), who showed that although pitch contributes to the prominence, it must not necessarily add further information on the processing and vocalizing of metric information/projection. Nevertheless, a follow-up experiment should also investigate pitch (compare Breen and Fitzroy, 2021). However, the results at the syllable level show that intensity is indeed used for prominence marking, but rather by musically active readers than inactives. The syllable level thus seems to be better suited than the nPVI to investigate fine grained rhythmic and modulating (intensity) aspects of oral reading of poetry and the associated top-down and bottom-up processes.

Our findings support the notion that there is no 'cut-off' dichotomy between top-down and bottom-up processes (Rauss and Pourtois, 2013) during reading poetry aloud. In the context of the predictive model of music (Vuust et al., 2022) our results can indirectly contribute to the debate (e.g., active inference, Koelsch et al., 2019), since investigating SOIs and intensity in reciting poetry appears to be closely linked to prediction. At least for conventional poetry, the arrangement of the syllable sequences, respectively the composition of words within a line toward the stanza allows for a structured temporal distribution of their sounds. This in turn establishes a rhythm from which a "beat" can be induced, and against which a meter can be build up. Although the words and syllables of the poem are known from everyday speech (compare also Wagner, 2002, 2008), their pronunciation duration and accentuation are predicted top-down and subordinated to the selected model (e.g., choice of meter). With each stanza, reading can be further rhythmically adapted to it, i.e., 'strengthening the metric model' (Vuust et al., 2018). Specifically, for musically active readers, the patterns found in our study suggest that both SOIs and intensity are used to do so. Since musical training can improve and shape temporal precision (Danielsen et al., 2022) and metrical discrimination (Nave-Blodgett et al., 2021), it is reasonable to assume that musically active readers find it easier to quickly and accurately determine the leading meter of a poem. If their reading is oriented more toward the sound gestalt of the text and less toward comprehension, this should potentially minimize prediction errors regarding timing. The integration of multiple "tacks" however clearly led to distortions of the rhythmic reading pattern (i.e., higher prediction error) and the overall temporal distribution within the context of the line/stanza. This phenomenon shows the importance of the phonetic characteristics of a syllable for the rhythmic quality of a text. Especially in the context of reading out loud, the interaction of meter projection with the actual articulatory muscle production of the sound itself is fundamental for precise timing and hence related to predictive processes. Overall, musically active readers appeared to be better at adapting sensory input to the chosen prediction model, aka "resampling the evidence" (Vuust et al., 2018, p. 25). They presumably did so by "attenuating or suppressing precision of prediction errors" (*ibid.*) using the articulatory gestures, thus enabling sensomotoric synchronization, which, in turn, supports predictive coding.

4.1. Limitations

We coded the meter by the variable "stress" for each poem. However, there were few cases in a sequence of 3 or 4 tacks in which a tack was omitted during oral reading. For these, the manual Praat annotation could not assign which exact tack was omitted. Thus, for these few cases it could be possible that the assignment of the stress variables does not exactly match the tacks or their correct position during reading.

Another limitation of our study is that it employs only a small sample size of 17, of which 4 had to be excluded due to recording problems, leaving only 13 participants (6 musically active, 7 musically inactive) with usable data. Thus, for musicality as between-subject factor, one can criticize that a it does not provide reliable estimates. Some effects found turned out to be only marginally reliable. Hence, for these effects, evidence is inconclusive and further research is needed. However, the problem is somewhat mitigated by the fact that the amount of data points per subject is sufficiently high on the syllable level (on average, 981 syllables per participant) and with the aggregated version on the verse level (overall, 120 verse lines per participant).

In our analysis, we focused primarily on the post-hoc variable *musicality*. However, one aspect of the experimental set-up was the reading instruction (no instruction, rhythmic, on beat). Obviously, the variable *instruction* and the variable *musicality* were confounded. However, our post-hoc analysis including both, *instruction* and *musicality*, revealed – in comparison with the simpler model – that for both nPVIs (SOI and intensity) the general pattern of results for musicality was not affected by the inclusion of *instruction*, even though the two confounding variables were included in the model.

All musically active individuals in our subset were women. Therefore, our musicality variable could also be confounded by the factor gender.

One might criticize a missing control variable, since no data was collected for poem reading of non-manipulated poems, which then could have been used to compare reading for SOIs and intensity with 'tack' positions. However, we used the lines without tacks as baseline for comparison. Nevertheless, an updated version of the experiment should consider using originals, too.

5. Conclusion

At the syllable level, our results strongly suggest that both SOIs and intensities are used to mark stress differences with respect to a meter, but differently for musically active and musically inactive readers. With respect to nonsensical syllables such as tacks, musically active readers seem to maintain a prominence marking, but by using intensity. Musically inactive readers, on the other hand, experience a clash between top-down and bottom-up information. The nPVI results suggest a decrease in top-down processing for tacks, and even more so for musically active readers. However, the syllable-level results suggest that for tacks, musically active readers shift stress marking from SOI to intensities. The nPVI appears to capture metrical rhythmicity in the oral reading of conventional poetry. However, it fails to capture fine-grained processes at the syllable level.

In summary, our results suggest that the phonetic structure of syllables within the rhythmic 'gestalt' of a poem is indeed important for extracting, updating and maintaining a guiding metrical grid. We found that musically active participants tended to maintain the rhythmic structure better than inactive participants. Our findings contribute to the discussion of the iambic-trochaic law and the integration of bottom-up information in the predictive processing of language.

Data availability statement

The raw data and the R script for data analysis supporting the conclusions of this article will be made available by the authors upon email request.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JB and LK designed the experiments and contributed to data analysis and writing process. JB created the stimuli, conducted and ran the experiments. LK led the process. All authors made a substantial, direct and intellectual contribution to the article and approved the submitted version for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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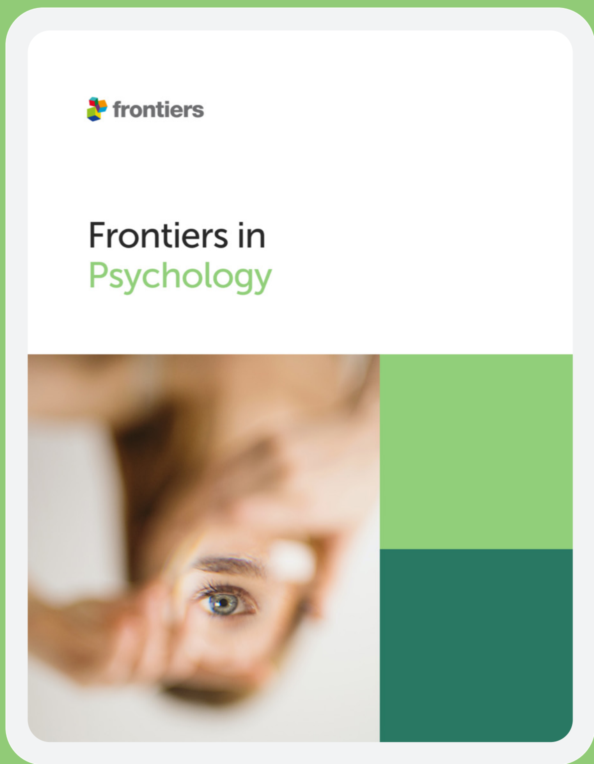

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