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Momentum in Music: Musical Succession as Physical Motion

Timothy L. Hubbard
Arizona State University

A melodic line involves a note of a given pitch and duration, followed by another note of a given pitch and duration, and so on, but we often perceive such musical succession in time as movement in space (e.g., melodic contours ascend or descend, etc.), and concepts related to motion have been used to describe and understand musical experience. Johnson and Larson (2003) suggested musical motion is analogous to motion of physical objects, and Larson (2012) discussed musical forces analogous to the forces that operate on physical objects. In this review, one such musical force, musical inertia, is compared with momentum-like effects that occur in other (nonmusical) domains. Although musical inertia was previously suggested to be analogous to representational momentum, these two effects operate on different time-scales, and it is proposed that musical representation might exhibit behavioral momentum or psychological momentum or might exhibit a unique form of musical momentum. Such a musical momentum would reflect dynamic mental representation and properties of the functional architecture of music representation; be related to auditory stream segregation, perceptual grouping, and auditory kappa and tau effects; and reflect naive beliefs regarding force. Possible musical analogues of the components of momentum (mass, velocity) are considered.

Keywords: momentum-like effect, musical forces, musical inertia, musical motion, representational momentum

Metaphors involving motion have shaped discussion and understanding of music for millennia. Rothfarb (2001, p. 927) points out that "ever since ancient times authors have identified motion as a functional aspect of music." Perhaps the most famous example is the so-called "music of the spheres" in which Kepler in *Harmonices Mundi* attempted to connect planetary motion with numerical ratios of musical intervals (Balbi, 2008). St. Augustine in *Da Musica* defined music as "scientia bene modulani," which translates as "knowledge of correct movement" (MacInnis, 2015), and Rameau's *Treatise on Harmony* refers to "collisions" of sounds (Christiansen, 2004). More recently, Shove and Repp (1995) concluded music can represent natural forms of motion, Clarke (2001, 2005) concluded the relationship between music and motion provides an important part of music's impact and meaning, Eitan and Granot (2006) considered how music was associated with bodily movement, and Phillips-Silver (2009) concluded a link between music and movement was pervasive in human experience. Consistent with this, Larson (2012) suggested an important metaphor in our conceptualization of music is "Musical Succession is Physical Motion." Indeed, Larson (2012, p. 50) noted "it is hard to imagine a term that describes physical motion that has not been, or could not be, applied to music," and he provided many examples of spatial and motion metaphors in music (e.g., melodies moving by steps or leaps, melodic contours ascending or descending, presence of passing and leading tones; see also Johnson & Larson, 2003).

The purpose here is to review data and theories regarding whether the mental representation of music embodies a dynamic of motion. Production of music typically requires motion of some sort (e.g., vibration of a string, reed, or drumhead; changing configurations of open [not pressed] and closed [pressed] keys on a musical instrument, etc.), and so in a trivial sense, music arises from motion. However, music and motion are complex concepts, and not every type of motion is necessarily a potential source of music. Rather than reviewing the relationship between music and motion in general, the goal here is simpler: to consider the relationship between music and a single consequence of motion, momentum. It is suggested that the mental representation of music exhibits momentum-like effects that share many properties with momentum-like effects in other domains of perception, cognition, and behavior. Part 1 explores the notion of musical motion and considers Larson's discussion of musical forces in general and musical inertia in particular. Part 2 reviews information on different (nonmusical) momentum-like effects and considers whether musical inertia is consistent with these effects. Part 3 examines implications and consequences of musical momentum, and considers dynamic representation and functional architecture, an emphasis on extrapolation across time, auditory streaming and perceptual grouping, auditory kappa and tau effects, naive physics of forces, and which aspects of music might map on to different components of momentum. Part 4 provides a brief summary and conclusions.

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Correspondence concerning this article should be addressed to Timothy L. Hubbard, Department of Psychology, Arizona State University, Tempe AZ 8528. E-mail: timothyleehubbard@gmail.com

Part 1: Music and Motion

It has long been thought that music is related to motion (for reviews, see Eitan & Granot, 2006; Phillips-Silver, 2009; Rothfarb, 2001; Shove & Repp, 1995). Motion of a physical object results from physical forces, and the existence of analogous musical forces associated with musical succession in Western tonal music was proposed by Larson (2004, 2012; Larson & van Handel, 2005). In Part 1, the idea of musical forces, and the properties of a specific musical force—musical inertia—are considered.

Musical Succession and Physical Motion

What is it that “moves” in music? Indeed, the idea of musical motion is something of a puzzle, in that unless the source of the music (e.g., performer, loudspeaker) is physically moving, the music per se does not actually physically move (see Larson, 2012; Zuckerkandl, 1956). A melodic line typically consists of the presentation of a (stationary) tone of a given pitch and duration followed by the presentation of another (stationary) tone of a given pitch and duration, and so on, and yet we often perceive such musical succession in time as a type of motion in space (e.g., melodic lines rise or fall, intervals move by steps or leaps, etc.). Johnson and Larson (2003; Larson, 2012) suggest that an observer can be conceptualized as moving through time (a “moving observer” or “time’s landscape” metaphor) or that time can be conceptualized as moving past an observer (a “moving time” metaphor), and these mappings of space to time are listed in Table 1. Furthermore, Johnson and Larson suggest that we seem to spatialize movement through or by time as movement through space (and this spatialization of time is especially relevant in music, see Morgan, 1980). Thus, our concept of musical succession is influenced by our experience of the movement of physical objects through space. Motion of physical objects provides a metaphor for understanding, representing, and experiencing music, and musical succession is perceived to exhibit or be susceptible to forces analogous to those that operate on the movement of physical objects in space.

We can consider the metaphor of musical succession as physical motion in more detail, and a comparison of musical succession and physical motion suggested by Johnson and Larson (2003; Larson, 2012) is shown in Table 2. The left column lists the relevant properties of physical motion, and the right column lists the corresponding properties of musical succession. Musical events are analogous to physical objects, and musical succession is analogous to physical motion. Both physical motion and musical succession are defined by the rate of change (e.g., velocity, tempo). Both physical motion and musical succession take place within a larger spatiotemporal framework in which past and future are viewed as behind and in front of, respectively, the observer, and in which physical motion and musical succession can be viewed as a passage or trajectory through that spatiotemporal framework. Both physical motion and musical succession have a starting point and an ending point; along the trajectory between these points there can be a temporary cessation or rest, and portions of that trajectory can be repeated. The most important similarity for current purposes, and the one focused on in the remainder of this article, is the last one, between musical forces and physical forces. Physical motion is influenced by physical forces, and by analogy, musical motion is influenced by musical forces. Indeed, for Larson, and as suggested earlier, musical forces are a critical aspect of our understanding, representation, and experience of music.

Table 1
Comparison of Space and Time

Space	Time
Different locations on a path	Different moments in time
Motion of the observer	“Passage” of time
Motion of objects past the observer	“Passage” of time
Distance moved by the observer	Amount of time “passed”
Location of the observer	The present
Space in front of the observer	The future
Space behind the observer	The past

Note. Adapted from “‘Something in the way she moves’ - Metaphors of musical motion” by M. Johnson and S. Larson, 2003, *Metaphor and Symbol*, *18*, 63–84. Copyright 2003 by Taylor & Francis. Adapted with permission.

Table 2
Comparison of Physical Motion and Musical Succession

Physical motion	Musical succession
Physical object	Musical event
Physical motion	Musical motion
Velocity	Tempo
Location of the observer	Present musical event
Objects in front of the observer	Future musical event
Objects behind the observer	Past musical event
Path of motion	Musical passage
Beginning/ending of physical motion	Beginning/ending of musical passage
Temporary cessation of motion	Rest, caesura
Repeated motion along a path	Recapitulation, repeat
Physical forces	Musical forces

Note. Adapted from “‘Something in the way she moves’ - Metaphors of musical motion” by M. Johnson and S. Larson, 2003, *Metaphor and Symbol*, *18*, 63–84. Copyright 2003 by Taylor & Francis. Adapted with permission.

Musical Forces

Larson (2004, 2012; Larson & van Handel, 2005) identified three forces that are experienced in Western tonal music: *musical gravity* (i.e., the tendency of a note above a stable reference or platform to descend), *musical magnetism* (i.e., the tendency of an unstable note to move toward the closest stable pitch), and *musical inertia* (i.e., the tendency of pitches or rhythms to continue in their current pattern). Different musical forces can have effects individually or in concert (e.g., musical inertia can act alone or combine with musical gravity, musical magnetism, or other potential musical forces). Larson considers musical forces analogous to physical forces and to have influences on the representation of music analogous to the influences of physical forces on physical objects. He considers musical gravity analogous to representational gravity (i.e., a bias in the represented location of an object that is in the direction of implied gravitational attraction; Hubbard, 1997; Zago, 2017), musical magnetism analogous to the landmark attraction effect (i.e., the estimated distance from a target to a landmark is less than the estimated distance from that landmark to that target, Bryant & Subbiah, 1994), and musical inertia analogous to representational momentum (i.e., a bias in represented location of an object in the direction of anticipated motion of that object, Freyd & Finke, 1984). Interestingly, Larson suggests expressive meaning in music is in part an emergent property of such forces, and this is consistent with proposals regarding effects of analogous dynamics on visual aesthetics (e.g., Arnheim, 1974, 1988; Freyd, 1993).

Larson (2012, pp. 1–2) points out that "we not only *speak* about music as if it was shaped by musical analogs of physical gravity, magnetism, and inertia, but we actually *experience* it [music] in terms of 'musical forces'" (emphasis in original), and this has implications for whether musical forces should be considered as "merely" metaphorical. These implications are based on a distinction that Larson makes between "thinking about music" and "thinking in music," with the former involving nonmusical symbols (e.g., words, gestures) and the latter involving auditory imagery (which Larson refers to as *auralizing*) in which pitches and durations are subjectively experienced in the absence of the corresponding auditory stimulus. Although it is clear that reference to forces in thinking about music (e.g., in analysis or linguistic description) is metaphorical, it is less clear that reference to forces in thinking in music (e.g., in auditory imagery) is also metaphorical. Larson (2012, p. 1) proposes "our experience of physical motion shapes our experience of musical motion in specific and quantifiable ways," but he is careful to stress that musical forces are metaphorical and not literal properties of sounds in the way that, for example, frequency and duration are literal properties of sounds.[1] Even so, a comparison of musical inertia with representational momentum (see below) suggests that musical inertia (or a momentum-like effect) is not simply a metaphor, but is an integral part of the functional architecture of the representation of music.

Evidence for Musical Inertia

Larson (2004, 2012; Larson & van Handel, 2005) discusses findings consistent with the idea of musical inertia and that are based on a variety of methodologies, including studies of composition and improvisation, experiments on melodic fragment completion, and comparisons of data from experiments with human participants with computer models incorporating the idea of musical inertia. Larson also points out that musical inertia is not a completely new idea, but is similar to good continuation described in Meyer (1956, 1973), a central part of Jones's (1981, 1982) expectancy model, similar to von Hippel's (2002) notion of step inertia (i.e., a tendency for semitone or whole tone steps to continue in the same direction), and a special case of Narmour's (1990, 1992) implication-realization model in which listeners expect an interval smaller than a tritone to be followed by intervals of similar size and direction. Also, it is possible that the medium of auditory imagery might exhibit analogues of such forces within the functional architecture of mental representation (Hubbard, 2017a); such a notion parallels an earlier suggestion of Hubbard (2006a), who proposed that representational momentum was a predictable consequence of second-order isomorphism in the functional architecture of mental representation underlying mental rotation.[2] If musical inertia is similar to other momentum-like processes, then any apparent momentum-like properties might not be metaphorical, but might instead reflect properties of the representation.

There are numerous findings that are not discussed by Larson (2012) but that are also consistent with the idea of musical inertia. For example, if an unexpected silent gap appears in a familiar melody, participants often report spontaneous auditory imagery of a continuation of the melody, and such imagery is accompanied by activation in auditory association cortex (Kraemer, Macrae, Green, & Kelley, 2005). If participants listen to a familiar music CD, they often report anticipatory auditory imagery of the upcoming track during the silence between tracks, and such imagery is accompanied by activation in auditory cortex (Leaver, van Lare, Zielinski, Halpern, & Rauschecker, 2009). Imagining a continuation of a musical scale after hearing the initial notes of that scale, or the absence of an expected note, results in emitted potentials highly similar to evoked potentials for perceived notes (Janata, 2001). In general, auditory imagery involves expectancies and preserves much of the structural and temporal information of the referent auditory stimulus (Hubbard, 2010, 2013a, 2013b, 2017a), and for musical stimuli, such information could support potential musical inertia (or momentum-like effects). Relatedly, the persistence of various forms of involuntary auditory musical imagery such as earworms (e.g., Williams, 2015), musical hallucinations (e.g., Keshavan, David, Steingard, & Lishman, 1992), and musical obses-

[1] Larson's (2012) theory is based on an analysis of Western tonal music, and the extent to which the musical forces he identifies are experienced in non-Western music has not been examined. Even so, a number of predictions might be made. Larson suggests that musical inertia should be less dependent upon learning or enculturation than is musical gravity or musical magnetism, and this predicts that musical inertia is likely to be found in other tonal systems. Also, given that physical gravity and physical inertia are invariant forces that do not depend upon the specific type of object being acted upon, it could be predicted that analogues of gravity and inertia effects within a given tonal or harmonic framework would not depend upon specifics of the tonal system. Indeed, the idea that physical forces are invariant would predict that analogous musical forces should be found in all musical systems (e.g., given that the function of a drone in an Indian raga establishes the harmonic base or tonality of a musical piece [Jairazbhoy, 1971], it could be predicted that musical magnetism toward the pitch of the drone would occur).

[2] In Shepard's (1981) notion of second-order isomorphism, transformations in a distal stimulus (e.g., as a physical object rotated) are mirrored by transformations in the proximal stimulus (e.g., the image on the retina) and in the mental representation of the distal stimulus (e.g., visual imagery). For example, an object rotating from orientation A to orientation C would pass through an intermediate orientation B, and this reflects a constraint on physical rotation. Similarly, the mental representation of an object that rotates from orientation A to orientation C must pass through an intermediate orientation B (Cooper, 1975, 1976), and this reflects a constraint on mental transformation (Shepard, 1981). The mental transformation is thus a functional analogue of the physical transformation, that is, mental rotation is second-order isomorphic to physical rotation. Although Shepard's discussion of second-order isomorphism focused on preservation of spatial information (e.g., passing through intermediate orientations), the idea of second-order isomorphism is consistent with preservation of information involving invariant physical principles. For example, a physical object that rotates from orientation A to orientation C must also possess momentum, and this reflects a constraint on physical transformation. The mental representation of an object that rotates from orientation A to orientation C (e.g., the inducing stimuli in Freyd & Finke, 1984) would thus exhibit a functional analogue of momentum, that is, representational momentum (Hubbard, 2006a). Also, and of particular relevance to the notion of musical momentum, a second-order isomorphism preserves temporal information as well as spatial information (e.g., a physical object rotating at a constant velocity will take longer to rotate from orientation A to orientation C than to rotate from orientation A to an intermediate orientation B).

sion (e.g., Taylor et al., 2014), are also consistent with the idea of musical inertia.

Findings involving sensorimotor synchronization, in which a specific behavior is temporally correlated (i.e., rhythmically entrained) with an external (referent) event (for review, see London, 2012; Repp, 2005; Repp & Su, 2013), are also consistent with the idea of musical inertia. A well-studied example of sensorimotor synchronization involves tapping a finger with the beat of a metronome, and other examples include walking, visual tracking, dance, and musical ensemble performance. Sensorimotor synchronization occurs at multiple time-scales (e.g., in dance, arm movements and body sway often occur at different periodicities; Toiviainen, Luck, & Thompson, 2010) and in several species (e.g., social chorusing in nonhuman animals [Greenfield, 1994; Phillips-Silver, Aktipis, & Bryant, 2010]; body movements to music or metronomes in parrots [Schachner, Brady, Pepperberg, & Hauser, 2009], bonobos [Large & Gray, 2015], horses [Bregman, Iversen, Lichman, Reinhart, & Patel, 2012], and California sea lions [Cook, Rouse, Wilson, & Reichmuth, 2013]). Such synchronization includes not just timing, but also perception of accented and unaccented beats (e.g., Brochard, Abecasis, Potter, Ragot, & Drake, 2003; Grahn & Rowe, 2009), and is more effective for more periodic rhythms (e.g., Dalla Bella, Białuńska, & Sowiński, 2013). A key aspect of sensorimotor synchronization is that the rhythmic pattern of the referent stimulus must be extrapolated into the future in order for synchronization to occur; such an extrapolation is consistent with musical inertia.

Properties of Musical Inertia

Larson (2012) claimed that musical inertia is stronger than musical gravity or musical magnetism but can act in combination with those or other potential musical forces, is less dependent upon learning or enculturation than is musical gravity or musical magnetism, and influences the strength of melodic pattern completion and the relative frequencies of different continuations to a given melodic stem. In addition to Larson's claims, there have been attempts to relate properties of perceived motion in music to motion of the human body (e.g., the ritardando at the end of a musical phrase parallels the slowing of a runner at the end of a run, Friberg & Sundberg, 1999; but see Honing, 2003; an infant's interpretation of an ambiguous rhythm as a function of "bouncing," Phillips-Silver & Trainor, 2005). Relatedly, Todd (1999; Todd & Lee, 2015) suggested that motion is essential in perception of music, and that perception of motion in music results from vestibulomotor mechanisms and an audio-visuomotor mechanism that modulate gesture and locomotion, respectively. Motion in music might be more akin to apparent motion than to physical motion (cf. Gjerdingen, 1994), and this is consistent with speculation of Munger, Solberg, and Horrocks (1999) that representational momentum for implied motion (involving visual targets composed of separate and discrete inducing stimuli analogous to the separate and discrete musical notes of a target melody) involves filling in the steps between inducing stimuli.

The most important property of musical inertia is contained within its definition: Musical inertia is the tendency of pitches or rhythms to continue in the currently perceived pattern. The idea of a continuation implies an extrapolation in musical pitch (or auditory frequency) space and an extrapolation forward in time. Studies of representational momentum for motion of a pitch in auditory frequency space or for motion of a sound source in physical space (discussed below) indicate the importance of a spatial dimension. Interestingly, and consistent with the importance of a temporal dimension, Larson (2012, p. 163) explicitly suggests that "aspects of rhythm and meter may be seen as derived from our experiences of analogous physical motions and physical forces," and the potential importance of rhythm and meter (i.e., of temporal information) is consistent with the emphasis on rhythm and periodicity in studies of sensorimotor synchronization discussed earlier. Larson's notions are similar to those in the dynamic attending theory of Jones and colleagues (Barnes & Jones, 2000; Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999), in which listeners presented with an auditory sequence extract regularities from the first events in the sequence and use this information to anticipate subsequent events in the sequence. Indeed, extraction and anticipation in dynamic attending theory give rise to specific rhythmic expectations that appear highly similar to those suggested by musical inertia and a momentum-like effect for rhythmic patterns.

The importance of rhythm and meter (i.e., of temporal information) in musical inertia is consistent with the emphasis on temporal information as a key part of a dynamic representational momentum in Freyd (1987), and is also consistent with the importance of temporal information in momentum-like effects more generally. Larson (2012, p. 179) quotes Hatten (2004, p. 124), who suggested "meter and tonality each afford analogies to gravitation or dynamic vectoral space, making possible the experience of embodied motions subject to dynamics and constraints comparable to those affecting the body in a natural environment." The idea of "dynamic vectoral space" is consistent with the spatiotemporal framework suggested by Johnson and Larson (2003; Larson, 2012) for musical motion and with suggestions regarding how dynamics such as representational momentum might be instantiated in spatiotemporal networks within mental representation (e.g., Erlhagen & Jancke, 2004; Hubbard, 1995c; Müsseler, Stork, & Kerzel, 2002). Also, the idea that meter and tonality are subject to dynamics and constraints comparable to dynamics and constraints affecting the body in a natural environment is consistent with findings that patterns of bodily movement influence how an ambiguous rhythm is interpreted (e.g., Phillips-Silver, 2009; Phillips-Silver & Trainor, 2005) and with calls for a more embodied approach to music cognition (e.g., Cox, 2016; Leman, 2007; Leman & Maes, 2014).

Part 2: Musical Inertia and Momentum-Like Effects

Part 1 discussed the existence of perceived musical forces and suggested how one such force, musical inertia, is related to a metaphor based on the motion of physical objects in space. Part 2 describes several momentum-like effects associated with changes in (nonmusical) objects, actions, and behaviors, and considers the similarity of musical inertia to these momentum-like effects.

Musical Inertia and Representational Momentum

Larson (2012, p. 218) stated "representational momentum appears analogous to musical inertia in a number of ways," and this suggests the possibility that musical inertia might reflect a special case of representational momentum involving perceived motion in a musical stimulus. Accordingly, properties of representational momentum, and whether those properties are similar to properties of musical inertia, are considered.

Representational Momentum. As noted earlier, memory for the final location of a moving target is displaced slightly forward in the direction of that target's motion (i.e., a target is remembered as having traveled slightly farther than it actually traveled), and this is referred to as *representational momentum* (for reviews, see Hubbard, 1995c, 2005, 2014). Several properties of representational momentum are relevant to a comparison with musical inertia. Representational momentum is increased with increases in target velocity (Hubbard, 2005, 2014). Representational momentum is larger for horizontal motion than for vertical motion, and for vertical motion, larger for descending motion than for ascending motion (Hubbard, 1990; Hubbard & Bharucha, 1988), and representational momentum is larger for receding motion than for approaching motion (Hubbard, 1996; Nagai, Kazai, & Yagi, 2002). Representational momentum depends upon a target maintaining a consistent identity (Kelly & Freyd, 1987) and is influenced by the semantic content of that identity (e.g., representational momentum for an ambiguous ascending shape is larger if that shape is labeled "rocket" than if that shape is labeled "steeple," Reed & Vinson, 1996). Representational momentum is influenced by expectations regarding the future behavior of the target (e.g., if a change in direction of target motion is anticipated, representational momentum is in the direction of anticipated, rather than actual, target motion [Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991]). These properties are consistent with the possibility of a continuation of perceived patterns of pitch or rhythm, and thus consistent with the possibility of musical inertia.

Music is usually experienced as an auditory stimulus. Although the majority of research on representational momentum involved visual stimuli, several studies examined momentum-like effects for a pitch moving in auditory frequency space or for the location of a moving sound source. Memory for the final pitch of an ascending or descending set of tones is displaced in the direction of pitch motion and exhibits effects of velocity and direction consistent with those found for visual stimuli (e.g., Freyd, Kelly, & DeKay, 1990; Hubbard, 1995a; Kelly & Freyd, 1987). Memory for the final pitch in a periodic cycle of ascending and descending tones is displaced backward if the final pitch is the highest or lowest pitch in the cycle (i.e., if direction of pitch motion was about to reverse) and forward if the final pitch is not the highest or lowest in the cycle (Johnston & Jones, 2006), and this parallels findings from studies with visual stimuli that exhibit periodic motion (Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991). However, memory for the final pitch of a set of tones involving highly schematic musical intervals (a sequence involving a tonic, fifth, and octave), but in which the final pitch is mistuned flat or sharp, is displaced toward a correctly tuned interval rather than in the direction of pitch motion (Hubbard, 1993); this indicates that musical schemata can modulate momentum-like effects. Also, memory for the location of a moving sound source is displaced in the direction of motion (Getzmann, 2005; Getzmann & Lewald, 2007, 2009; Getzmann, Lewald, & Guski, 2004; Schmiedchen, Freigang, Rübsamen, & Richter, 2013).

Comparisons of musical inertia and representational momentum. Larson (2012) suggested that several variables including velocity, acceleration and deceleration, direction of motion, semantic/conceptual knowledge, perceived weight, and apparent friction have similar effects on musical inertia and on representational momentum. Consistent with this, Eitan and Granot (2006) found that the magnitude of downward bodily motion associated with descending pitch was larger than the magnitude of upward bodily motion associated with ascending pitch, and this parallels findings that representational momentum is larger for descending visual targets than for ascending visual targets (Hubbard, 1990; Hubbard & Bharucha, 1988). As noted earlier, Larson (2004, 2012; Larson & van Handel, 2005) suggested one of the properties of musical forces is that the influence of such forces can be combined (e.g., musical inertia can combine with musical gravity or musical magnetism), and this is consistent with demonstrations that representational momentum can combine with representational gravity (Hubbard, 1990, 1997), representational friction (Hubbard, 1995b, 1998), and the landmark attraction effect (Hubbard & Ruppel, 1999). Additionally, Larson and van Handel (2005) found that musical gravity was weaker than musical inertia, and this is consistent with findings that displacements attributed to representational gravity are smaller than displacements attributed to representational momentum (e.g., Hubbard, 1990; Hubbard & Bharucha, 1988; Motes, Hubbard, Courtney, & Rypma, 2008).

There are at least two differences between musical inertia and representational momentum. One difference is that the notion of musical inertia is broader than the notion of representational momentum. Physical inertia involves the tendency for an object in motion to remain in motion and for an object at rest to remain at rest. As an object at rest has zero momentum (as momentum = mass × velocity, and an object at rest has zero velocity), a nonzero momentum is possible only for objects in motion; thus, musical inertia could potentially exist in the presence or absence of musical motion, whereas representational momentum would exist only for representations of objects in motion.[3] Even so, it is difficult to conceive how music would not be perceived to exhibit motion, as even a simple isochronous sequence leads to expectation of continuation (e.g., Large & Jones, 1999). Given that musical inertia is defined as a continuation of a previous pattern of pitches or rhythms (which implies motion), effects previously attributed to musical inertia should perhaps be attributed to musical momentum. A second difference is that the time-scales of musical inertia and of representational momentum are different. Representational momentum occurs on a time-scale of hundreds of milliseconds, whereas musical inertia involves stimuli of varying lengths and multiple time-scales (cf., phase correction and period correction in sensorimotor synchronization, Repp, 2005; body movement during dance, Toiviainen et al., 2010). Even though musical inertia and representational momentum share many properties, it seems unlikely that musical inertia results from or is an example of representational momentum for musical stimuli.

Larson's (2012) discussion of musical inertia focuses on vertical and horizontal aspects of music, that is, on changes in pitch height (vertical axis) of notes across time (horizontal axis) or on rhythms

[3] Such a discussion could be misread as suggesting that momentum is just a special case of inertia in which velocity is nonzero. However, physics views momentum and inertia as fundamentally different qualities. Momentum is the product of an object's mass and velocity, whereas inertia refers to how much external force must be applied to the object to change the state of motion or rest of the object. Momentum is thus intrinsic to an object, whereas inertia is not intrinsic to an object.

that unfold across time (horizontal axis). However, a third spatial dimension, depth, is relevant to comparison of musical inertia and representational momentum (cf. moving observer and moving time metaphors in Johnson & Larson, 2003). Increases or decreases in the loudness of a sound source are often perceived as an approaching or receding, respectively, of that sound source (e.g., Rosenblum, Carello, & Pastore, 1987). The change in loudness of a stimulus increasing in acoustic intensity is perceived as greater than the change in loudness of a stimulus decreasing in acoustic intensity by the same amount (Neuhoff, 1998; Olsen, Stevens, & Tardieu, 2010; Seifritz et al., 2002). The larger perceived change in intensity in an approaching stimulus is linked to underestimation in time-to-contact (Schiff & Oldak, 1990; Shaw, McGowan, & Turvey, 1991) and to forward displacement of the location of the sound source (Neuhoff, 2001), and this is consistent with findings regarding visual time-to-contact and representational momentum for the location of a sound source (as forward displacement of an approaching sound source would decrease the time-to-contact of that sound source). Importantly, other theories of dynamic musical structure discussed below (e.g., Huron, 2006; Meyer, 1956, 1973; Narmour, 1990, 1992) do not predict momentum-like effects for changes in acoustic intensity.

Varieties of Momentum-Like Experience

Representational momentum is one of at least five different types of momentum-like effect, with the four other types consisting of operational momentum, attentional momentum, behavioral momentum, and psychological momentum (see Hubbard, 2014, 2015a, 2015b). These five types of momentum-like effect form two natural groupings, one of which involves perceptual time-scales and the other of which involves longer time-scales. As noted earlier, musical inertia generally seems to operate on a different time-scale than does representational momentum and appears more compatible with momentum-like processes that operate on a longer time-scale.

Perceptual time-scale. Forms of momentum at the perceptual time-scale include representational momentum, operational momentum, and attentional momentum (see Hubbard, 2014). As noted earlier, representational momentum refers to a tendency to remember a moving target as having traveled further in the direction of motion than that target actually traveled. Operational momentum involves a similar bias in the estimation of quantity; more specifically, if participants make a speeded judgment of quantity, they usually overestimate the sum of an addition and underestimate the difference of a subtraction (e.g., Knops, Zitzmann, & McCrink, 2013; McCrink, Dehaene, & Dehaene-Lambertz, 2007). It is as if the estimated answer is displaced along a (mental) number line in the direction of the arithmetic operation. Attentional momentum involves the cost involved with changing the direction of a shift of attention. For example, if two stimuli are equally distant from the focus of attention, but one is along the path of the current movement of attention and one is not, an observer will be slower to detect the stimulus that is not along the current path of the movement of attention, and this difference has been attributed to the cost of stopping movement of attention in one direction and beginning movement of attention in a different direction (e.g., Pratt, Spalek, & Bradshaw, 1999; Spalek & Hammad, 2004). Representational momentum and attentional momentum each arise within a few hundred milliseconds and then decline, and operational momentum can be hypothesized to exhibit a similar time-scale.

Longer time-scale. Forms of momentum-like experience that occur at a longer time-scale (minutes, hours, days, or longer) include behavioral momentum and psychological momentum (see Hubbard, 2015a). Behavioral momentum involves a continuation of a previously learned behavior (Nevin, Mandell, & Atak, 1983). The theory behind behavioral momentum suggests that just as a physical body continues in motion until acted upon by an outside force, ongoing behavior maintained by constant reinforcement continues at a steady rate until acted upon by an external variable (i.e., acted upon by a different reinforcer or the original reinforcer is removed). Studies of behavioral momentum typically focus on animal learning (e.g., Nevin, Tota, Torquato, & Shull, 1990; Podlesnik & Shahan, 2009) or on behavior analysis and treatment of developmentally delayed or psychopathological behaviors in humans (e.g., Belfiore, Basile, & Lee, 2008; Dube, Ahearn, Lionello-DeNolf, & McIlvane, 2009). Psychological momentum involves the perception of whether a given behavior or outcome can be more or less easily achieved as a function of the outcome of previous behaviors or outcomes (Iso-Ahola & Dotson, 2014, 2016). This is typically studied in the domain of sport competition (e.g., an individual or team is perceived as having or not having momentum in a game or contest; Briki, den Hartigh, Markman, & Gernigon, 2014; Gernigon, Briki, & Eykens, 2010), although nonsport examples can be found (e.g., choosing financial investments, Antonacci, 2015; Hendricks, Patel, & Zeckhauser, 1993; gambling, Arkes, 2011; completing domestic or academic tasks, Markman & Guenther, 2007).

Comparisons across momentum-like effects. A comparison of properties of different momentum-like effects is given in Table 3. Properties of representational momentum suggested by Freyd (1987) are listed in the left column, and although Freyd only addressed representational momentum, many of these properties can also be hypothesized to hold for operational momentum and attentional momentum (Hubbard, 2014, 2015b). Properties of behavioral momentum and psychological momentum suggested by Hubbard (2015a) are listed in the middle column. There is considerable overlap between properties of representational momentum (and presumably other perceptual time-scale momentum-like effects) listed in the left column and properties of behavioral momentum and psychological momentum (longer time-scale momentum effects) listed in the middle column, as representational momentum, behavioral momentum, and psychological momentum all involve continuation of target behavior, are disrupted by incoherence or interruption, do not involve guessing, do not stem solely from sensory processes, are resistant to change, are decreased over relatively extended durations, and involve many types of continuous transformation or change; indeed, the primary difference appears to be the time-scale within which each momentum-like effect occurs (Hubbard, 2015a, 2015b). These similarities are consistent with the hypothesis of a more general (high-level or top-down) mechanism that extrapolates momentum-like effects at a variety of time-scales (cf. Jordan, 2013).

Table 3
Comparison of Representational Momentum, Behavioral Momentum and Psychological Momentum, and Music Representation

RM	BM and PM	Music representation
Target motion continues	Learned behaviors continue	Pitch and rhythm patterns continue
Depends upon coherent direction of motion	Disrupted if task is interrupted	Earworms disrupted by other sounds
Differs from guessing	Involves learned behaviors	Involves previous exposure to music of a culture
Does not stem from sensory processes	Does not stem from sensory processes	Does not stem from sensory processes
Impervious to practice or error feedback	Continued use of previously successful strategies	Importance of schemata; slow change in composition and performance practices
Occurs very rapidly	Occurs minutes, hours, or more after learning	Occurs minutes, hours, or more after learning
Increases over short durations and then decreases with extended durations	Decreases with extended durations	Decreases with extended durations
Attached to a represented object, not to an abstract frame	Involves continuation of a specific behavior	Involves continuation of a specific musical stimulus
Include non-rigid transformations	Involves many different types of behaviors	Involves many different types of musical stimuli

Note. RM = representational momentum; BM and PM = behavioral momentum and psychological momentum.

Musical Inertia, Behavioral Momentum, and Psychological Momentum

The right column of Table 3 lists properties of music representation, and if these are compared with properties of behavioral momentum and psychological momentum listed in the middle column, several similarities can be seen. In behavioral momentum and psychological momentum, learned behaviors continue; in music representation, a familiar piece of music continues (e.g., anticipatory auditory imagery [Kraemer et al., 2005; Leaver et al., 2009]). Behavioral momentum and psychological momentum are disrupted if the task is interrupted; similarly, earworms are disrupted by other sounds (e.g., Hyman et al., 2013). Behavioral momentum and psychological momentum involve learned behavior; understanding of key and tonality are learned (e.g., Castellano, Bharucha, & Krumhansl, 1984; Tillmann, Bharucha, & Bigand, 2000). Neither learned behavior nor music representation results from purely sensory processes. In behavioral momentum and psychological momentum, a successful strategy or technique continues to be used; analogously, musical stimuli are experienced through musical schemata (e.g., Dowling, 1978; Gjerdingen, 1990; Krumhansl, 1990), and changes in compositional and performance practices occur relatively slowly. Also, behavioral momentum, psychological momentum, and musical inertia are decreased with extended duration, involve a specific stimulus or behavior, and involve many different types of stimulus or behavior.

The similarities of properties of music representation and properties of behavioral momentum and psychological momentum suggest that effects attributed to musical inertia might actually reflect a momentum-like effect similar to behavioral momentum or psychological momentum, or perhaps even be a special case of behavioral momentum or psychological momentum. Such a musical momentum would be similar to musical inertia in that it involves a continuation of patterns of pitches and rhythms, but it is broader than musical inertia in that it relates this continuation to extrapolation in nonmusical stimuli. Interestingly, the role of physical forces in mental representation of musical stimuli is both broader and narrower than the role of analogous forces in mental representation of nonmusical stimuli. As noted earlier, musical inertia is broader than momentum-like phenomena in that inertia also involves the behavior of stimuli at rest. However, musical gravity seems narrower than representational gravity in that Larson (2012, p. 2) defines musical gravity as “the tendency of notes above a stable reference platform to descend,” but Hubbard and Ruppel (2013) found evidence of representational gravity in memory for the initial pitch of an ascending or descending tone sequence in the absence of an obvious reference or platform. It is possible that knowledge or experience of music (within a given compositional system) provides a framework (e.g., schema) through which effects of dynamics based on physical forces such as momentum and gravity are modulated.

Although discussion of musical inertia usually focuses on findings involving a longer time-scale more similar to that of behavioral momentum or psychological momentum than the perceptual time-scale of representational momentum, there are other findings that suggest musical expectation can occur on the perceptual time-scale. For example, harmonic priming (Bharucha & Stoeckig, 1986; Bigand, Poulin, Tillmann, Madurell, & D’Adamo, 2003; Justus & Bharucha, 2001) and differences in ERPs to musical stimuli (e.g., Besson & Faïta, 1995; Daltrozzo & Schön, 2009; Paraskevopoulos, Kuchenbuch, Herholz, & Pantev, 2012) show effects of expectations on a time-scale similar to that of representational momentum. It is possible that a single inertia-like or momentum-like mechanism might account for different examples of musical inertia or momentum-like effects in music cognition (cf. a single mechanism might result in momentum-like processes at different time-scales, e.g., Hubbard, 2015a, 2015b; Jordan, 2013). Alternatively, it is possible that different examples of musical inertia or momentum-like effects in music cognition result from different mechanisms. However, even if multiple mechanisms are eventually documented, a more general musical momentum at the level of computational theory (in the sense of Marr, 1982) might still exist (cf. discussion of a computational theory of representational momentum in Hubbard, 2005). The remainder of this article explores the implications and consequences of such a musical momentum.

Part 3: Implications and Consequences of a Musical Momentum

Part 2 discussed musical inertia and different types of momentum-like effects and suggested that properties of longer time-scale momentum-like effects (behavioral momentum and psychological momentum) are similar to properties of musical inertia. Part 3 considers whether musical inertia should be reconceived as a momentum-like effect, and implications and consequences of such a musical momentum are considered.

Dynamic Representation

If musical stimuli exhibit a form of momentum-like effect, then the mental representation of those stimuli should be dynamic. However, there are several models within music cognition literature that involve dynamic musical structure but do not specify momentum-like effects per se. These models, like the momentum-based approach suggested here, focus on expectation. Meyer (1956, 1973) suggested music representation involves expectations based on low-level percepts (e.g., Gestalt principles) and higher-level learning and memory. Jones (1981, 1982) suggested a time-based attentional trajectory and the use of cognitive anchor points. Narmour (1990, 1992) suggested specific musical intervals set up expectations (i.e., implications) regarding what would most likely follow that interval (i.e., realization). Margulis (2003) extended Narmour's model by including more global expectations at a variety of time-scales as well as the local expectations addressed by Narmour. Huron (2006) described five processes (imagination, tension, prediction, reaction, appraisal) involved in expectation in music (and other) cognition. These models involve the tension or difference between the current percept and what is expected, although they do not always specify a mechanism by which represented information can bridge the gap between what is perceived and what is expected. Interestingly, momentum-like processes have been proposed to bridge just such a gap (Hubbard, 2005, 2006a, 2014, 2015a, 2015b), and so momentum-like processes are compatible with and might provide potential mechanisms for some of these models.

One model of dynamic representation that explicitly involves momentum-like effects is Freyd (1987), who suggested two criteria for dynamic mental representation. If mental representations of musical stimuli are dynamic and involve momentum-like effects, then those representations should meet those criteria. The first criterion is that a dynamic representation should represent time intrinsically, and this requires that temporal information in the representation be directional and continuous. Musical materials fulfill the requirements of directionality and continuity, as melody unfolds in a specific direction (forward in time), and between any two points in time (e.g., phrase beginnings or endings, different portions of a beat, etc.), an intermediate point exists. The second criterion is that time is a necessary aspect of the representation; that is, if temporal information were removed from the representation, then the representation would no longer preserve the same meaning. Musical materials fulfill this criterion, as temporal information is critical for several aspects of music (e.g., cadences, voice leading), and removal of this information (e.g., if all notes occurred simultaneously) would affect musical experience and meaning. Although Freyd focused solely on representational momentum, behavioral momentum and psychological momentum also meet these criteria (Hubbard, 2015a). Given the similarity of momentum-like effects in music to behavioral momentum and psychological momentum noted earlier, a form of musical momentum based on dynamic representation involving momentum-like effects appears plausible.

Previous models of dynamic musical structure do not explicitly include the intrinsic and necessary representation of temporal information that Freyd (1987) suggested results in representational momentum and Hubbard (2015a) suggested might result in behavioral momentum and psychological momentum. Therefore, a momentum-based idea of dynamic representation of music differs from other ideas regarding dynamic representation of music, and this provides a basis for predictions about which types of musical expectations might result in a momentum-like effect: Musical expectations that involve directionality and continuity of temporal information should result in momentum-like effects, whereas musical expectations that do not involve directionality and continuity of temporal information should not result in momentum-like effects. Thus, it can be predicted that if a consistent direction of change (i.e., motion) is not clear, then a momentum-like effect should not occur (e.g., a sequence of random pitches would not exhibit a momentum-like effect; cf. Johnston & Jones, 2006; Kelly & Freyd, 1987). Similarly, if the underlying dimension is not continuous, then a momentum-like effect should not occur (e.g., modulation between discrete and separate keys should not exhibit a momentum-like effect). Although a lack of directionality or continuity would not result in extrapolation of a momentum-like effect, some other type of expectation might nonetheless be present.

If momentum-like effects in music reflect a dynamic aspect of the mental representation, then musical momentum would be an intrinsic part of the representation and not a separate and abstract understanding or interpretation. Indeed, Larson (2012, p. 78) suggested "We cannot clearly separate our understanding and conceptualization of music from our experience of it. We do not merely experience a musical work and *then* understand it . . . rather, our understanding is woven into the fabric of our experience. . . . Thus the way we *experience* a piece of music will depend importantly on how we *understand* it" (emphasis in original). Similar to how representational momentum (and perhaps other momentum-like effects) might reflect properties of the functional architecture of mental representation (e.g., second-order isomorphism, Hubbard, 2006a), musical momentum might also reflect properties of the functional architecture of mental representation. For example, a musical stimulus could be viewed as tracing a trajectory through a representational space involving spatiotemporal information (cf. Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999), and musical momentum would involve extrapolation of a trajectory isomorphic to a forward continuation of a physical object moving along a spatiotemporal trajectory. Such a view is consistent with Larson's (2004, 2012; Larson & van Handel, 2005) views regarding the relationships between physical forces and musical forces and between physical objects and musical events.

Emphasis on Effects Across Time

Although momentum-like effects involve continuation in both space and time, representational momentum, operational momentum, and attentional momentum seem to emphasize (and be experienced as) effects primarily across space (Hubbard, 2014), and behavioral momentum and psychological momentum seem to emphasize (and be experienced as) effects primarily across time (Hubbard, 2015a). Given that a potential musical momentum generally appears more similar to behavioral momentum and psychological momentum than to representational momentum, this would suggest that any potential musical momentum would primarily involve effects across time. Such a notion is consistent with metaphors of "moving time" and "time's landscape" in Johnson and Larson (2003), Larson's (2012) emphasis on contributions of rhythm and meter to the experience of musical forces, observations that music generally unfolds across time rather than across space, and the stress on temporal correlation in sensorimotor synchronization. An emphasis on temporal information is consistent with the theory of dynamic mental representation and momentum-like effects (e.g., Freyd, 1987; Hubbard, 2015a) and with theories of dynamic attending and entrainment (e.g., Barnes & Jones, 2000). Also, a musical momentum that emphasized effects across time would be a critical component of the perceptual organization of musical stimuli, and evidence of this can be seen in studies of auditory streaming and perceptual grouping.

Auditory Streaming and Perceptual Grouping

The possibility of musical momentum has implications for perceptual grouping of musical stimuli, and this can be seen most clearly in the literature on streaming effects in auditory scene analysis (for review, Bregman, 1990). For example, successive notes separated by a small pitch step are perceived to be in the same auditory stream, whereas successive notes separated by a large pitch leap are perceived to be in different auditory streams (e.g., Miller & Heise, 1950; van Noorden, 1975). Similarly, recognition of melodies that have distractor tones interleaved with tones of the melody is easier if there is a larger separation in pitch between distractor tones and tones of the melody (e.g., Dowling, 1973). These patterns are consistent with musical momentum, as a greater difference between successive notes (in pitch, timbre, loudness, etc.) is more likely to result from a new or different sound source than from a continuation of the same sound source. Even so, not all streaming effects are consistent with musical momentum. For example, an auditory stimulus consisting of two alternating groups of pitches at a slower tempo is likely to be perceived as a single stream, but at a faster tempo is likely to be perceived as two streams (e.g., Bregman & Campbell, 1971). However, a faster tempo could be predicted to result in a single larger momentum-like effect rather than in separate momenta for different parts of the stimulus. Although inertia- or momentum-like effects are consistent with many grouping principles, they are not consistent with all such principles.

Momentum-like effects might be able to account for (or at least are consistent with) findings regarding perceptual grouping in some dichotic listening studies. For example, in Deutsch's (1975) scale illusion, different musical tones are presented to each ear of a listener; the physical stimulus involves relatively large differences between subsequent tones presented to a given ear, but the percept reflects a reinterpretation of the stimulus in which the changes between notes presented to a given ear are relatively small (see Figure 1). Although the scale illusion is typically attributed to grouping by similarity (or proximity) of auditory frequency rather than by spatial location (cf. figural goodness in Deutsch & Feroe, 1981), preference for smaller changes between successive pitches is consistent with a momentum-like effect.[4] Relatedly, Hubbard (2011, 2017b) pointed out several similarities of the consequences of Gestalt grouping principles and the consequences of representational momentum, and he suggested representational momentum was a new category of Gestalt principle; such an argument could

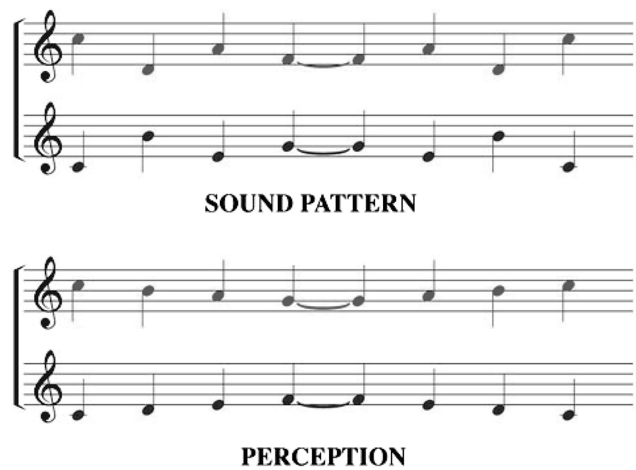

Figure 1. An illustration of the scale illusion. Listeners are presented with the stimulus in the top panel (sound pattern, with the notes in the top staff presented to the right ear and the notes in the bottom staff presented to the left ear), and their reported perception is shown in the bottom panel (perception, with the notes in the top staff reported at the right ear and the notes in the bottom staff reported at the left ear). Adapted from *Musical illusions and paradoxes* by D. Deutsch, 1995, La Jolla, CA: Philomel Records, Inc. Copyright 1995 by Philomel Records, Inc. Adapted with permission.

potentially apply to musical momentum (and other momentum-like effects). Also, findings involving the scale illusion (and auditory stream segregation in general) are consistent with the dynamic attending theory of Jones and colleagues (Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999), and differences between the physical stimulus and the perceived stimulus reveal constraints on the implied trajectory through space and time.

Auditory Kappa and Tau Effects

The idea of momentum implies movement along a trajectory through space and time, and this is related to the kappa and tau effects. In the visual domain, it has long been known that changes in stimulus spacing affect judgment of timing, and this has been

[4] The perceived reversal of pitch motion occurring midway through the scale illusion stimulus is consistent with findings that different auditory streams do not usually cross (Tougas & Bregman, 1985), and this might initially be seen as inconsistent with a momentum-like effect (which might be suggested to predict a single direction of motion for each stream). However, if participants perceive each stream to contain a different auditory object, then this reversal is consistent with momentum-like effects in which a visual object approaches a barrier and is expected to bounce off (i.e., not cross) the barrier (Hubbard & Bharucha, 1988). More specifically, forward displacement decreases as the object approaches a barrier, and at the moment of contact, displacement is actually backward (i.e., in the direction of the anticipated [future] motion). Consistent with this, Johnston and Jones (2006) found that when just a single auditory stream consisting of a set of oscillating pitches is presented, forward displacement occurs when the final pitch is between the highest and lowest pitches, but backward displacement occurs when the final pitch is the highest or lowest (and a reversal of motion is expected). Thus, if a change (reversal) is expected, momentum-like effects would be in the direction of that change; it is not the case that momentum effects must necessarily be in the direction of current motion.

referred to as a *kappa effect* (e.g., Cohen, Hansel, & Sylvester, 1953; Price-Williams, 1954). Similarly, changes in stimulus timing affect judgment of spacing, and this has been referred to as a *tau effect* (e.g., Geldreich, 1934; Helson & King, 1931). Henry and McAuley (2009; Henry, McAuley, & Zaleha, 2009) examined auditory versions of the kappa and tau effects in which three pitches at different locations in auditory pitch space were sequentially presented through headphones (giving rise to apparent motion in pitch space). The auditory kappa and tau effects were larger with faster pitch velocities, and descending pitch motion led to a larger tau effect than did ascending pitch motion; these patterns are similar to those in studies of representational momentum for auditory stimuli (e.g., Freyd, Kelly, & DeKay, 1990; Hubbard, 1995a), and this suggests such effects might be based upon a representation that extrapolated movement in a trajectory across time and pitch space. Indeed, the auditory motion hypothesis (Jones, 1976; Jones & Yee, 1993; MacKenzie, 2007) suggests interactions between perceived pitch and perceived duration in the auditory kappa and tau effects result from a pitch-time trajectory (cf. Jones, Kidd, & Wetzel, 1981) that emphasizes motion-like properties (e.g., momentum). The auditory kappa effect is influenced by intensities of the tones, with larger differences in intensities resulting in longer estimates of time (Alards-Tomalin, Leboe-McGowan, & Mondor, 2013), and this is consistent with changes in loudness being perceived as motion in depth and greater differences in loudness suggesting longer traveled distances.

Naïve Physics of Forces

Many individuals who are untutored in physics exhibit beliefs regarding the operation of physical forces that are incorrect, and study of these beliefs (and the differences between these beliefs and the actual operation of physical forces) is referred to as *naïve physics*. Representational momentum for a visual target is often consistent with naïve physics rather than with objective physical principles (e.g., Freyd & Jones, 1994; Hubbard, 2013c; Kozhevnikov & Hegarty, 2001). Larson (2012) suggests that just as many individuals misunderstand the operation of physical forces, so too do some musicians misunderstand the operation of musical forces. Therefore, if effects attributed to musical inertia are momentum-like effects, then it should be possible to find effects consistent with a naïve view of momentum within discussions of music; indeed, Larson provides an analysis of the writings of two prominent music theorists that he suggests supports his claim that misconceptions regarding the operation of musical forces parallel misconceptions regarding the operation of physical forces reported in studies of naïve physics.[5] Relatedly, one idea from naïve physics that has been studied in the literature on momentum-like effects is belief in an impetus principle (e.g., Hubbard, 2004; Markman & Guenther, 2007); although the musical analogue of "impetus" is not clear (e.g., would an increase in perceived impetus involve an increase in accent, overall loudness, tempo, or other parameter?), it could be predicted that a musical stimulus with greater impetus might exhibit stronger musical inertia or momentum-like effects than would a musical stimulus with less impetus.

Components of Momentum

Honing (2003) pointed out that theories positing motion of the human body as a basis for perceived motion in music did not specify the analogues of mass and speed (velocity) that would be necessary for solving mechanical equations related to motion. Consideration of music as potentially involving momentum-like effects is relevant to this issue. Physical momentum is the product of an object's mass and velocity; if musical stimuli exhibit a momentum-like effect, then it should be possible to identify analogues of mass and of velocity in (the representations of) musical stimuli. As musical inertia appears more similar to behavioral momentum and psychological momentum, and as analogues of mass and velocity for behavioral momentum and psychological momentum have been suggested in the literature, these analogues are noted for comparison.

Musical mass. In behavioral momentum (e.g., Nevin, 1988, 2012), the behavioral analogue of mass is the resistance of the behavior to change. The greater the resistance to change, the greater the behavioral mass. In psychological momentum (e.g., Markman & Guenther, 2007), the psychological analogue of mass is the importance of the goal or task. The more important a goal or task is considered to be, the greater the psychological mass of that goal or task. The example Markman and Guenther (2007) provide is that a sports team who defeated a major rival in an important game is thought to have more momentum going into their next game than would a sports team who defeated a nonrival.[6] One possibility for a musical analogue of resistance to change or of the importance of the goal or task is the strength and stability of a tonal center. In other words, a potential equivalent of mass or weight for a musical stimulus might be the strength and stability of the tonal center of that stimulus. All other factors being equal, music with a strong and stable tonality and key would possess more musical mass, and would be predicted to exhibit a stronger momentum-like effect. Relatedly, although general effects of the strength and stability of a tonal center on representation of a melodic line might be observed, more specific effects of the strength and stability of

[5] The two theorists that Larson (2012) discusses are Jérôme-Joseph Momigny and Leonard B. Meyer. Larson cites a passage from Momigny (1806; cited in Lerdahl, 2001) that confuses physical attraction and physical inertia, mistakenly attributes an effect of distance to inertia, and assumes that only one force operates at a time. Larson cites passages from Meyer (1956, 1973) that conflate inertial tendencies and magnetic tendency toward a goal, erroneously suggest musical inertia evaporates when a goal is attained, and also imply musical motion can be explained in terms of a single principle (of good continuation).

[6] Studies of representational momentum suggest that (implied) objective mass per se does not influence the magnitude of a momentum-like effect; rather, effects of mass seem to be subjectively experienced as effects of weight (Hubbard, 1997). Although mass and weight are theoretically separable, effects of mass are typically experienced as weight because mass and weight are not phenomenally distinguishable within a constant gravitational field (such as that experienced on the surface of the Earth). Such a notion is consistent with contemporary ideas regarding the importance of embodiment on cognitive processing (e.g., Barsalou, 2008; Cox, 2016; Gibbs, 2005; Leman, 2007). Also, it is not entirely clear that a distinction should be made between behavioral mass (weight) and psychological mass (weight), and it might be that behavioral mass (weight) and psychological mass (weight) are the same entity or quality but with different names given by different groups of researchers (an analogous notion holds for behavioral velocity and psychological velocity).

a tonal center on the representation of individual notes might also be observed, but the latter might be more akin to an effect of musical magnetism than to an effect of musical inertia per se.

The strength and stability of a tonal center is a relatively high-level concept (as is the importance of defeating a rival in an athletic or other competition), but it is possible that lower-level auditory information (e.g., pitch, location, loudness) might be associated with (or analogous to) mass. For example, a given piece of music might be perceived as more massive if that music is generally lower in pitch. Larger musical instruments (e.g., tuba, trombone) typically produce lower pitches than do smaller musical instruments (e.g., flute, piccolo), and it seems plausible that the relationship between an instrument's size and the pitch produced by that instrument might exist for other types of objects as well. Another possibility is that a given piece of music might be perceived as more massive if that music seems to originate from lower in the picture plane. Larger objects are typically lower in the picture plane than are smaller objects (e.g., Arnheim, 1974; Winner, Dion, Rosenblatt, & Gardner, 1987), and lower pitches and higher pitches are typically associated with lower locations and higher locations in the picture plane, respectively (e.g., Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006). Finally, a given piece of music might be perceived as more massive if that piece of music is louder. Indeed, the loudness of a sound is often colloquially referred to as "volume," a term that has clear connotations regarding size (which correlates with mass). These possibilities are speculative, of course, but suggest possible avenues for future research.

Musical velocity. In behavioral momentum (e.g., Nevin, 1988, 2012), the behavioral analogue of velocity is response rate. In psychological momentum (e.g., Markman & Guenther, 2007), the psychological analogue of velocity is not as clearly defined, but seems to reflect either response rate or reinforcement rate (which, of course, are often correlated). The higher the response rate (or the reinforcement rate), the greater the behavioral momentum or psychological momentum. One obvious possibility for a musical analogue of velocity is tempo. Just as velocity of a physical object determines (in part) the momentum of that object, so too might the tempo of a musical event determine (in part) the momentum of that musical event. This is consistent with suggestions by Johnson and Larson (2003; Larson, 2012) that a musical event is analogous to a physical object and that physical velocity is analogous to tempo (see Table 2). Both tempo and response rate are typically defined as the number of events (e.g., musical beats, operant responses) per unit of time. Music with a faster tempo would possess a higher musical velocity, and would thus be predicted to exhibit a larger momentum-like effect. However, music can have a subjective speed that is not necessarily identical with the tempo of the tactus (e.g., Boltz, 2011; London, 2011; Madison & Paulin, 2010), and it is not clear whether velocity should reflect the notated tempo or the perceived tempo. A related possibility for a musical analogue of velocity is inter-onset-interval (IOI), the latency between the onsets of temporally adjacent events (e.g., adjacent notes). Many of the arguments for tempo might be applied to IOI.

A less obvious possibility for a musical analogue of velocity is the strength of the musical expectations of the listeners. For example, a given piece of Western music might be in a specific key, but a listener unacquainted with the conventions of Western music would not have specific expectations regarding a return to the tonic or to other aspects of key or tonality. In this view, a listener with a stronger expectation (based on greater musical knowledge) would experience a faster musical velocity. Effects of such expectations might be reflected in chord errors in piano performance (e.g., Palmer & van de Sande, 1993, 1995), ratings of how well a tone fits a musical context (e.g., Castellano et al., 1984), melodic anchoring (e.g., Bharucha, 1984, 1996), and harmonic priming (e.g., Tillmann, Bigand, & Pineau, 1998). Interestingly, if velocity corresponded to the strength of musical expectations, then the strength of a tonal center would be important for the analogue of mass and for the analogue of velocity; in the former case, musical mass is more relevant to properties of the composition and less relevant to properties of a listener's musical knowledge, whereas in the latter case, musical velocity is more relevant to properties of a listener's musical knowledge and less relevant to properties of the composition. However, whether musical velocity is more appropriately considered as analogous to tempo, IOI, the strength of musical expectation, or some other factor remains an open question.

Independence of mass and velocity. Just as mass and velocity of a physical object are conceptually independent in Newtonian physics, Nevin (1992) suggested behavioral mass and behavioral velocity are conceptually independent in behavioral momentum, and Markman and Guenther (2007) suggested psychological mass and psychological velocity are conceptually independent in psychological momentum. If the earlier speculations that musical mass is related to the strength and stability of key and tonality, pitch, location, or loudness, and that musical velocity is related to the tempo or the strength of melodic expectation, are correct, then the analogues of mass and velocity in musical momentum are conceptually independent, as well. For example, musical mass in the form of key strength and distance from the tonal center is conceptually independent of musical velocity in the form of tempo or perceived expectation based on knowledge of that tonal structure (e.g., although a given piece of Western music might be in a specific key, a listener unacquainted with the conventions of Western music would not have specific expectations regarding return to the tonic or other aspects of that key). Of course, the trajectory of a musical passage is highly constrained by tonality or other rules, but the trajectory of behavior in behavioral momentum and psychological momentum is similarly constrained by rules (e.g., prior conditioning, beliefs, performance). Regardless, the independence of mass and velocity should be considered in any attempts to identify analogues of mass and velocity in a potential musical momentum.

Whither Musical Momentum?

There are many aspects of music representation that reflect an inertia-like or a momentum-like continuation. However, there are at least two issues that remain unresolved. One issue is whether such findings are more appropriately described as inertia or as momentum. Larson (2012) described continuation involving musical stimuli as "inertia," whereas analogous continuations involving nonmusical stimuli are usually described as "momentum." Although Larson noted similarities of musical inertia and representational momentum, he did not comment on differences between inertia and momentum. Interestingly, the idea of "continuation" in musical inertia literature connotes a more passive lack of stopping, whereas the idea of "extrapolation" in representational momentum literature connotes a more active generation of motion; it might be that use of "continuation" or "extrapolation" influences whether such anticipations are viewed as passive inertia or active momentum. As noted earlier, the apparent lack of a stationary condition in music is more consistent with momentum than with inertia, as velocity is a component of momentum but is not a component of inertia; to the extent that velocity is related to forward extrapolation (i.e., faster velocities lead to larger extrapolations), those extrapolations are momentum-like rather than inertia-like. Along these lines, momentum is an intrinsic property of the object, but inertia describes how much external force must be applied to an object in order to change its behavior; thus, momentum is more likely to be an intrinsic part of the mental representation than is inertia (see also Footnote 3).

A second issue is whether there is a uniquely musical form of momentum-like effect or if momentum-like effects observed with musical stimuli are examples of a more general form of momentum that happens to involve musical stimuli (e.g., high-level processes in Hubbard, 2006a, 2006b). Musical inertia, like sensorimotor synchronicity, occurs at a variety of time-scales (e.g., predicting the next note, predicting repetitions of rhythms or pitch sequences, Larson, 2012). Sensorimotor synchronization and dynamic attending are capable of entraining to different tempi, and so rhythmic entrainment could reflect this more general mechanism or process rather than a mechanism or process unique to music representation. More generally, it is possible that momentum-like effects in music reflect the application of more general extrapolation mechanisms and not mechanisms unique to music representation per se. Alternatively, expectation or extrapolation effects that occur with musical stimuli (or potentially music-like stimuli in sensorimotor synchronization or rhythmic entrainment) could reflect unique mechanisms, in which case musical momentum would be a new form of momentum-like effect in addition to representational, operational, attentional, behavioral, and psychological forms of momentum-like effect previously described in the literature. There are no obvious predictions regarding momentum-like effects that should (should not) occur with musical stimuli but that should not (should) occur in nonmusical stimuli, but delineating how momentum-like effects in music are similar to or different from momentum-like effects in nonmusical stimuli is an important topic for future studies.

Part 4: Summary and Conclusions

There is a long history of considering musical succession as reflecting physical motion. However, when we consider what might actually move in music, the idea of musical motion is less clear. Larson (2004, 2012; Larson & van Handel, 2005) proposed the existence of several musical forces (musical gravity, musical magnetism, musical inertia) that provide metaphors for understanding, experience, and representation of music. More specifically, observation of the forces acting on physical objects provides a metaphor for understanding the succession of notes in a musical stimulus as a type of physical motion through space. A wide range of data is consistent with the existence of musical inertia. Larson (2004, 2012; Larson & van Handel, 2005) reviewed data from studies of composition and improvisation, experiments on melodic fragment completion, and comparison of performance of human participants in experiments on music cognition with computer simulations incorporating the idea of musical forces. Additional findings consistent with the idea of musical inertia include spontaneous auditory imagery during an unexpected gap in familiar music, anticipatory auditory imagery of an upcoming song, preservation of spatial and temporal information of auditory stimuli in auditory imagery, persistence of involuntary auditory musical imagery in earworms, and sensorimotor synchronization. The idea of musical inertia is also consistent with previous notions in several music theoretic and cognitive models of music processing and attention.

The idea that the representation of a stimulus could be influenced by physical forces that operate on that referent stimulus is consistent with literatures on representational momentum and other spatial biases in which the judged (represented) location of a moving target is influenced by analogues of the physical forces that would have acted on the referent physical object (Hubbard, 1995c, 1999, 2005, 2006a). Indeed, Larson (2012) suggested that musical inertia seemed analogous to representational momentum. Although there are many similarities and parallels between musical inertia and representational momentum, the wider potential applicability of inertia (i.e., to objects at rest as well as to objects in motion), and differences in the time-scales of musical inertia and representational momentum, suggest that musical inertia is not a special case of representational momentum in which movement is within a musical stimulus. However, other momentum-like effects, namely behavioral momentum and psychological momentum, appear more consistent with the wider notion of musical inertia and operate on longer time-scales than does representational momentum. It is possible that musical inertia is a momentum-like effect that reflects an application of behavioral momentum or psychological momentum or a more general extrapolation mechanism. Alternatively, it is possible that findings attributed to musical inertia involve mechanisms unique to music, and that motion in music results in a new form of momentum-like effect.

Considering musical stimuli as exhibiting momentum-like effects has several implications and consequences for theories regarding the understanding of music in particular and cognition in general. First, momentum-like effects offer a single mechanism for a range of phenomena (e.g., auditory streaming and perceptual grouping, auditory kappa and tau effects, sensorimotor synchronization) previously accounted for by different mechanisms. Second, if music exhibits momentum-like effects, then variables shown to influence momentum-like effects in other domains (see Hubbard, 2014, 2015a, 2015b) might similarly influence the representation of music. Indeed, Larson (2012) highlighted examples of this when he discussed similarities of musical inertia and representational momentum. Third, considering the potential analogues of mass and velocity on musical stimuli could potentially offer new insights into musical cognition. Fourth, momentum-like effects in music might reflect naïve misconceptions about motion similar to those in momentum-like effects in other domains. Fifth, a consideration of momentum-like effects in music connects music with larger literatures of human perception, cognition, and behavior that report momentum-like effects. As Larson points out, momentum-like effects are part of not just our understanding, but also our experience, of music. Such effects are not limited to music, though, but occur in nearly every domain of human experience, and so it is possible that momentum-like effects in music reflect a more general extrapolation mechanism.

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