

Continuation tapping to triggered melodies: motor resonance effects of melodic motion

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Abstract Common Coding theory predicts that perceived action should resonate in produced action to which it bears some resemblance. Here we show that the qualities of motion commonly attributed to melodies are instantiated in motor plans that control timed movements. Participants attempted to tap a steady beat. Each tap triggered a sounded tone, and successive tones were systematically varied in pitch to form short melodies. Tapping behavior was monitored with motion capture. Although instructed to ignore them, triggered tones systematically affected timing and finger movement. When slower melodic motion was implied by a contour change or a smaller pitch displacement, the interval-tap interval (ITI) was longer. When faster melodic motion was implied by a preserved pitch contour or a larger pitch displacement, ITI was shorter. Kinematic recordings suggested that ITI Error arose from an initial failure to disambiguate perception (i.e., velocity implied by melodic motion) from action (i.e., finger velocity [FV]). Early in the tap trajectory, slower FV was associated with longer ITI and faster FV was associated with shorter ITI. These associations were reversed near mid-trajectory, suggesting a transition from execution of motor planning to online control (Glover et al. in *Exp Brain Res* 154:103–108, 2004).

Keywords Melodic motion · Continuation tapping

Introduction

William James (1890) famously stated that “every representation of a movement awakens in some degree the action that is its object.” This idea has since been demonstrated at the structural level in monkeys and humans (Rizzolatti and Craighero 2004), where it has been shown that perception and production of an action activate common brain areas. At the human behavioral level, evidence that perceptual and motor representations of action share a common code is found in at least two types of studies. First, Viviani and colleagues showed that perception may be biased by “production-based knowledge” (Hommel et al. 2001). For example, when drawing a curved trajectory such as a figure-eight, individuals slow down at the more curved parts and speed up at the straighter parts even when instructed not to (Lacquiniti et al. 1983; Viviani and McCollum 1983). Likewise, they expect that a dot tracing the same trajectory on a screen will have precisely the same varying velocity profile (Viviani and Stucchi 1992). Second, *motor resonance* effects show that perceived action modulates a response action to which it bears some resemblance, such as viewing a rotating object while rotating a knob (Zwaan and Taylor 2006: exp. 1). Both types of effects are thought to be automatic, arising from “representational overlap” between perceived and planned actions (Prinz et al. 2009).

Here we investigate motor resonance effects of *melodic motion*. The attribution of motional qualities to melodies is widespread (Shove and Repp 1995) although not universal (Zbikowski 1998), and at least as old as the earliest surviving music theoretical treatises from Ancient Greece (Barker 1989). Today, Western musicians and academics commonly describe relations between successive melodic tones using spatial metaphors, such as *pitch contour* to

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67 describe the unfolding pattern of upward and downward
68 changes in *pitch height* (i.e., frequency) and *pitch distance*
69 to describe magnitude of frequency change between tones.

70 Listeners are more sensitive to relations between tones
71 such as pitch contour and pitch distance than they are to
72 absolute pitch height of individual tones, and this sensi-
73 tivity is automatic and may be independent of musical
74 training (Trainor et al. 2002; Fujioka et al. 2004). Evidence
75 that these pitch relations are coded as “action” is found in
76 neuroimaging studies showing that passive listening elicits
77 activity in motor centers of the brains of musicians (for a
78 review, see Zatorre et al. 2007). More striking are the same
79 findings in non-musicians (Baumann et al. 2007; Chapin
80 et al. 2010; Lee et al. 2011), since such activity may not
81 reflect the covert simulation of those actions that may give
82 rise to the sounds (e.g., on a musical instrument), but
83 instead may reflect the perceived action of *the melody*
84 *itself*. Further evidence that melodic sequences may be
85 represented as action in non-musicians is found in the
86 activation of common networks by auditory spatial and
87 pitch-varying sequences (Zatorre et al. 1999). Finally,
88 Griffiths et al. (1999) found nearly identical networks of
89 regions subserving pitch and timing analysis of melodic
90 sequences, implying a representation that is driven by
91 auditory “events” rather than the integration of separate
92 perceptual features.

93 What gives rise to the perception of melodic motion? An
94 early proposal from Truslit (1938) echoed James in sug-
95 gesting that melodies elicit in the listener “a *corresponding*
96 *motion experience*” (cf. Repp 1993, emphasis added) that
97 is ultimately largely inhibited. Truslit’s notion that
98 unfolding relations between discrete pitches are automati-
99 cally and covertly simulated or mapped onto continuous
100 motion of the body seems intuitive. Consider, for example,
101 the common experience of an urge to sway one’s head with
102 an overheard melody, which may be suppressed while
103 standing in line at the supermarket.

104 According to Common Coding theory, action-oriented
105 perceptual representations of music should elicit motor
106 resonance effects (Leman 2009). This has been shown for
107 tones as a stimulus–response compatibility effect between
108 the pitch height of a target tone and the spatial position of
109 the keys on the response apparatus. Using a QWERTY
110 keyboard, Rusconi et al. (2006) found that responses to a
111 “higher” target tone (i.e., a tone of greater frequency) were
112 faster and more accurate when the correct response key
113 was higher on the keyboard (number 6) than when it was
114 lower (space bar). This was the case both when pitch height
115 was task-relevant (exp. 1) and task-irrelevant (exp. 2) and
116 for both musically untrained and trained participants.

117 In two previous studies, we used a modification of the
118 continuation-tapping task to further investigate motor res-
119 onance effects in longer melodic sequences (Ammirante

et al. 2011; Ammirante and Thompson 2010). Non- 120
musicians first synchronized finger taps on a single key of a 121
MIDI keyboard with a pacing signal; next, the pacing 122
signal was removed and participants attempted to continue 123
to tap at the same tempo until the end of the trial. In our 124
studies, each tap in the continuation phase triggered a 125
sounded tone. The pitches of the triggered tones were 126
manipulated to form quasi-musical (Ammirante et al. 2011) 127
and musical (Ammirante and Thompson 2010) melodies. 128
Although participants were instructed to focus on tapping 129
and ignore the tones that were triggered by their taps, 130
information systematically affected timing of the taps that 131
immediately followed. Where a triggered tone implied 132
faster melodic motion, the intertap interval (ITI) that the 133
tone initiated was shorter; where a triggered tone implied 134
slower melodic motion, ITI was longer, implying that 135
melodic motion resonated in timed movements. 136

137 In particular, these data supported suggestions that pitch 137
contour and pitch distance are psychoacoustic correlates of 138
turn and displacement, respectively, in physical space. 139
Pitch perception studies suggest that, as with continuous 140
movement in physical space along a curved trajectory that 141
varies in radius of curvature (Viviani and Stucchi 1992), 142
sequences of discrete tones are perceived to (1) lose 143
momentum at a contour changing (CC) tone, such that 144
listeners expect less pitch distance should be “traversed” to 145
and from it (Guilford and Nelson 1936; Heise and Miller 146
1951), and (2) gain momentum at a contour-preserving 147
(CP) tone, such that listeners expect greater pitch distance 148
traversed (Freyd et al. 1990; Hubbard 1993, 1995; Keele 149
et al. 1987). (In the sequence C4–E4–G4–F4, the F4 is a 150
CC tone because it changes direction, while the G4 is CP 151
because it continues direction.) 152

153 Pitch-timing interactions also support momentum 153
implied by pitch contour. Boltz (1998) presented listeners 154
with isochronous melodies and manipulated the number of 155
CC tones in each melody. She found that melodies con- 156
taining more CP tones were judged to have faster tempi 157
than melodies containing more CC tones, even when there 158
was no actual difference in tempo between the melodies. 159
These findings suggest that in an isochronous sequence 160
varying in pitch height, a temporal interval completed by a 161
CP tone may be perceived to unfold more quickly than an 162
interval completed by a CC tone. Consistent with the 163
prediction that momentum implied by pitch contour should 164
induce a motor resonance effect in continuation tapping, 165
we found that an ITI initiated by a triggered tone was 166
significantly shorter for CP tones than for CC tones 167
(Ammirante and Thompson 2010; Ammirante et al. 2011). 168

169 Manipulations of pitch distance also elicit pitch-timing 169
interactions (Cohen et al. 1954; Yoblick and Salvendy 170
1970; Shigeno 1986, 1993; Crowder and Neath 1994; 171
MacKenzie 2007; Henry and McAuley 2009). In a 172

173 synchronized tapping task to a continuous pacing signal
 174 oscillating sinusoidally in pitch, McAnally (2002) found
 175 that the tendency for taps to precede each oscillation
 176 increased with pitch distance. Thus, just as greater spatial
 177 displacement of a moving body within a fixed time interval
 178 means faster motion, greater displacement of pitch at a
 179 steady rate may have implied faster melodic motion, res-
 180 onating in the production of a faster tempo. Our findings
 181 using discrete changes in pitch that were self-triggered in
 182 continuation tapping replicated McAnally's (2002) findings
 183 for continuous changes in pitch in synchronization with an
 184 external pacing signal. With pitch distance between trig-
 185 gered tones fixed within trials but varied between trials,
 186 tempo was faster with increased pitch distance (Ammirante
 187 et al. 2011). When pitch distance was varied between 0 and
 188 2 semitones within trials, ITIs were shortest when initiated
 189 by a 2-semitone increase in pitch distance and longest
 190 following a 2-semitone decrease (Ammirante and Thomp-
 191 son 2010). In sum, our previous data supported the pre-
 192 diction that, due to overlap between perceptual and motor
 193 representations of action, implied velocity of melodic
 194 motion should resonate in timed movement.

195 In the current experiment, in addition to ITI, we used
 196 kinematic measures to more directly address the motor
 197 resonance hypothesis. We again adopted the continuation-
 198 tapping paradigm and, as in Ammirante and Thompson
 199 (2010), taps triggered tones that form melodies. Tap tra-
 200 jectories were recorded with motion capture. Our goal was
 201 to test the prediction that deviations in ITI are associated
 202 with a failure to disambiguate perception (i.e., velocity
 203 implied by melodic motion) from action (i.e., finger
 204 velocity [FV]). Thus, we expected that faster melodic
 205 motion implied by CP tones and tones containing an
 206 increase in pitch distance should resonate as faster FV in
 207 the tap that follows; slower melodic motion implied by CC
 208 tones and tones containing a decrease in pitch distance
 209 should resonate in slower FV. In addition, there should be
 210 an association between ITI and finger velocity, such that
 211 when the finger that taps too quickly, it arrives too soon at
 212 key bottom and the ITI that it completes is shortened; when
 213 the finger moves too slowly, it arrives too late at key
 214 bottom and the ITI that it completes is lengthened.¹

We were also interested in how the relationship between
 ITI and FV changes over the course of the tap trajectory,
 from the initiation of downward movement to contact with
 key bottom. This follows from findings in other domains
 where continuous trajectories have been recorded (Glover
 and Dixon 2001, 2002; Glover et al. 2004; Andres et al.
 2008). For example, Glover et al. (2004) investigated
 grasping movements and found that perceived object size
 initially modulated grip aperture size but was corrected by
 movement termination. The authors argued that this
 reflected a transition from the initial execution of a motor
 plan susceptible to perceptual modulation to online control.
 Thus, we predicted that motor resonance effects on FV (as
 well as association between ITI and FV) should be stron-
 gest early in the tap trajectory, reflecting the effect of
 melodic motion implied by the just-triggered tone on motor
 planning, but that these effects should attenuate as online
 control ensues. Such a finding would suggest that the
 perception of melodic motion is instantiated in motor plans
 that control timed movements but may ultimately be lar-
 gely inhibited (Truslit 1938; cf. Repp 1993).

Methods

Participants

Twelve Macquarie University undergraduates (11 women;
 all right-handed) aged 18–24 ($M = 20$; $SD = 2.61$) par-
 ticipated for course credit. Years of private music lessons
 ranged from 0 to 9 years ($M = 3.19$; $SD = 3.09$). No
 participants were currently engaged in music playing.

Apparatus

Stimulus presentation was controlled by the software
 application FTAP (Finney 2001). Tonal stimuli were
 assembled into a sound font and loaded into a software-
 based tone generator, which was interfaced with a CME
 UF8 MIDI keyboard. Participants tapped on the highest key
 (C8). Stimuli were presented through headphones at 74 dB
 SPL. Output intensity was set to a fixed value to eliminate
 variations in triggered tone intensity between taps.

For kinematic recording, a three-dimensional passive
 optical motion capture system (Vicon MX+ with 4 MX-
 F13 and 4 MX-F20 2-megapixel infrared cameras operat-
 ing at a sampling rate of 200 Hz) captured participants'
 finger movements. Cameras were placed in a semicircle
 around the MIDI keyboard at a distance of ~ 4 meters and
 controlled by Vicon Nexus software. Reflective markers
 were placed on the top of the participant's right hand, on
 the proximal and middle phalanges of the right index fin-
 ger, and on the right index fingernail.

¹ Previous studies using MIDI velocity (a measure of the speed with
 which the key is depressed) partially supported this prediction. For
 example, MIDI velocity was faster following CP tones than CC tones
 (Ammirante et al. 2011). However, since MIDI only provides a
 measure of a tap's average velocity rather than continuous change in
 FV over the course of the tap trajectory, it cannot address our
 prediction, discussed in the next paragraph, that the locus of the motor
 resonance effect on ITI is in motor planning. Indeed, near-zero
 correlations between ITI and average velocity in Ammirante et al.
 (2011; see also Keele et al. 1987) may have been due to the
 inadequacy of average velocity for capturing dynamic changes.

262 Stimuli and procedure

263 Four original isochronous melodies used in a previous
 264 experiment (Ammirante and Thompson 2010) served as
 265 triggered sequences and are shown in Fig. 1. Successive
 266 triggered tones were 0, 1 or 2 semitones in pitch distance
 267 from previous tones. Melodies 1 and 2 contained the first
 268 five tones from a C major scale (i.e., C D E F G), and
 269 melodies 3 and 4 contained the first five tones from a C
 270 minor scale (i.e., C D E-flat F G). Melodies 2, 3, and 4 were
 271 derived from melody 1 in C major by subjecting it to three
 272 different transformations—(1) retrograde, (2) transposition
 273 up a perfect fifth and inversion (which entails a change in
 274 tonality to C minor), and (3) retrograde of (2). Each melody
 275 contained at least one occurrence of a CP tone, a CC tone,
 276 and local increases and decreases in the pitch distance
 277 between tones. Transformations ensured that the sequence
 278 position of these occurrences varied between melodies. To
 279 remove the influence of higher-order perceptual grouping,
 280 repeating patterns such as [C–D–E]–[D–E–F]–[E–F–G]
 281 were avoided.

282 Participants completed the continuation-tapping task
 283 (Stevens 1886). In each trial, participants first synchronized
 284 their taps to a pacing signal presented at 500 ms IOI. The
 285 pacing signal consisted of 15 ms square-wave clicks. At
 286 their discretion, participants could begin synchronizing
 287 their taps with it. At this point, taps produced no auditory
 288 feedback. The sound of the pacing signal clicks ceased
 289 after seven taps, after which participants heard sine tones
 290 (200 ms in duration), the onsets of which were triggered by
 291 MIDI “note on” events approximately coinciding with key
 292 bottom contact (Goebl and Palmer 2008). Triggered contin-
 293 uation sequences consisted of 15 tones: 5 repetitions of
 294 the first tone of a melody followed by the melody itself,
 295 with successive taps triggering successive tones in the
 296 melody. The purpose of the 5 repeating tones preceding the
 297 melody was to allow for acceleration in ITI typically
 298 occurring at the transition between synchronization and
 299 continuation (Flach 2005). These taps were not analyzed. A
 300 trial ended with the fifteenth continuation phase tap, which
 301 repeated the final tone in the melody. Short trials were used

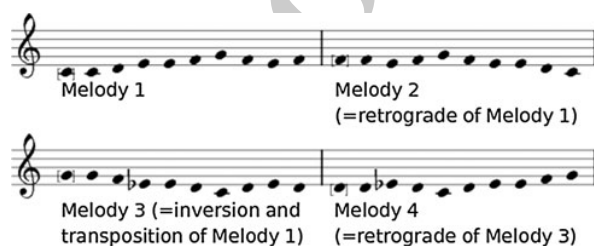


Fig. 1 The 4 original melodies used as triggered sequences. Tones in brackets were repeated 5 times preceding the melody. ITIs initiated by the final 8 triggered tones were analyzed

to minimize the influence of tempo drift, a common
 occurrence in continuation tapping.

Participants were instructed to maintain a steady beat at the tempo provided by the pacing signal and to ignore any changes in the pitch of the triggered tones. To ensure that local deviations in finger velocity were unintentional, participants were instructed to give an equal weight to each tap. To ensure that these deviations could not be offset by a longer movement, participants maintained contact between their fingertip and the key.

Participants completed five practice trials in which triggered sequences contained no changes in pitch height, followed by a single block of experimental trials. Within this block, 48 trials were completed, consisting of 12 repetitions of each of the 4 melodies. The order of presentation of the 4 melodies was randomized independently for each participant. The task took approximately 30 min to complete.

Data analysis

Of the total 576 trials (12 participants \times 4 melodies \times 12 repetitions), 539 were analyzed. The additional 37 trials (6%) were discarded due to data collection error. Inspection of the three-dimensional motion capture data revealed that most finger movement occurred in the vertical plane and was most pronounced for the fingernail marker. Thus, we focus on the motion of this marker for subsequent analyses. Missing samples in the motion capture data due to occlusion of the fingernail marker (<1%) were linearly interpolated.

Intertap interval (ITI)

Tap trajectories were easily identified as precipitous downward changes in the position/time trajectory. Key bottom contact was identified as the first occurrence of a sample containing an upward change in direction that followed each downward tap. ITIs were defined as the time difference in milliseconds between key bottom contacts. Since we were interested in local systematic deviations in ITI, a local difference score, which we call ITI Error, and which was defined as $ITI_n - ITI_{n-1}$, was entered into analysis (Pfordresher and Dalla Bella 2011). Thus, negative ITI Error indicated that the current ITI was shorter than the previous ITI, whereas positive ITI Error indicates that the current ITI was longer than the previous ITI.

The effects of the pitch structure of a given triggered tone on timing were measured in the ITI that it initiated (see Fig. 3, left panel). For each participant, ITI Error was averaged across trials for the 8 triggered melody tones in each of the 4 melodies. Having established that ITI Error did not vary between melodies, averages were concatenated into a 32-tone ITI Error profile for each participant

351 and then averaged across participants into a single ITI
352 Error profile representing the entire sample.

353 A regression model previously used in Ammirante and
354 Thompson (2010) was applied to the grand-averaged ITI
355 Error profile and contained five factors: Pitch Contour,
356 Pitch Distance Change, Incongruence, Sequence Position,
357 and Pitch Height. For Pitch Contour, faster melodic motion
358 implied by CP tones were coded as -1, slower melodic
359 motion implied by CC tones were coded as +1 and all
360 other tones were coded as 0. Pitch Distance Change coded
361 the occurrence of changes in the pitch distance (in semi-
362 tones) between successive tones. Faster melodic motion
363 implied by increases of 1 and 2 semitones were coded as
364 -1 and -2, respectively, and slower melodic motion
365 implied by decreases of 1 and 2 semitones were coded as
366 +1 and +2, respectively. Null changes between successive
367 tones were coded as 0. Thus, for the melodic fragment
368 E-E-F, the F is coded as +1 because of the increase in
369 pitch distance from 0 semitones between E-E to 1 semitone
370 between E-F; in the fragment Eb-F-G, the G is coded as 0
371 because there is a pitch distance of two semitones between
372 both Eb-F and F-G, etc. An Incongruence code of +1
373 indicated that a tone simultaneously implied faster and
374 slower tonal motion. A single incongruence was included

375 in each melody where a CP tone (implying faster motion)
376 decreased in pitch distance (implying slower motion); all
377 other tones were coded as 0. Sequence Position was coded
378 from 1 to 8 for each successive tone in a melody and was
379 included to control for linear tempo drift over the course of
380 a trial. Pitch Height (in semitones) was numbered 0-7 and
381 controlled for the influence of the absolute pitch height of
382 individual tones. Codes for a sample melody are shown in
383 Fig. 2.

Finger velocity (FV) 384

385 To obtain FV data, the same position/time segments from
386 which ITI was calculated were smoothed and differentiated
387 by fitting fourth-order b-splines to the first derivative
388 (velocity) using a linear least squares method. Goodness-
389 of-fit values exceeded $r^2 = .97$ for each segment. Each
390 smoothed FV segment was resampled to contain 200
391 samples. Since the target tempo was 500 ms IOI, each
392 sample thus represented ~ 2.5 ms of normalized time.

393 Figure 3 (left panel) shows the smoothed finger velocity
394 for a single segment. For each tap trajectory, peak velocity
395 (P) was extracted along with the $P - 20$ samples preceding
396 and the $P + 10$ samples succeeding it (Fig. 3, right

Fig. 2 Regression codes for melody 4

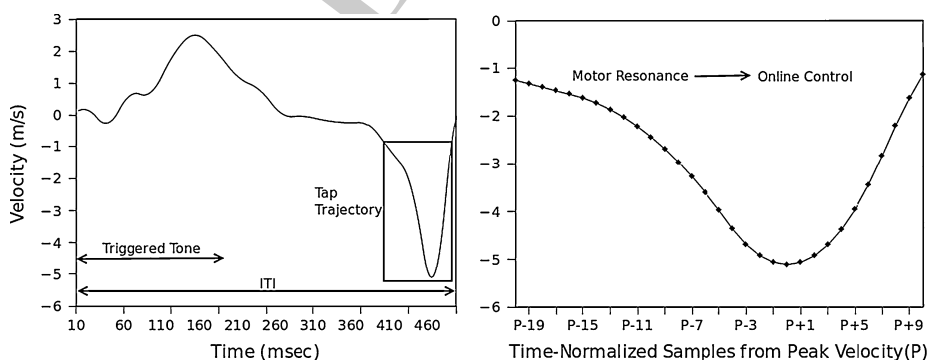
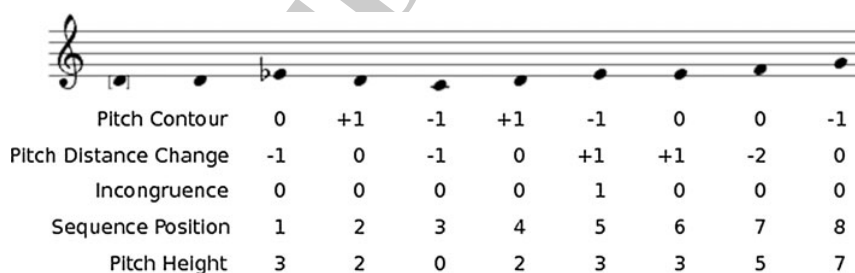


Fig. 3 (left panel) Finger velocity over the course of a single ITI. At the beginning, the finger has just made contact with key bottom (velocity is zero), which triggers a tone that sounds for the first 200 ms of the ITI. The finger releases from the key and travels upward (shown as positive velocity). At about 400 ms after the onset of the triggered tone, the next tap trajectory is initiated. The finger first accelerates and reaches a negative peak (indicating downward-directed velocity), and then slows back down to zero as the finger

makes contact with key bottom, completing the ITI and triggering the next tone. The boxed portion of the tap trajectory in which velocity exceeded -1 m/s was subjected to analysis. (right panel) a blow-up of the boxed portion of the tap trajectory in the left panel. Segments were resampled and 31 samples—20 before and 10 after peak velocity (P)—were analyzed. Motor resonance effects were predicted early in the tap trajectory followed by a transition to online control

397 panel), thus spanning a normalized time interval of
 398 ~ 77.5 ms (31 samples \times 2.5 ms). Besides being readily
 399 identifiable, we chose P as a reference point because its
 400 relative time of occurrence remains stable for tap trajec-
 401 tories varying in duration, distance, and peak velocity
 402 (Plamondon 1991). The boundaries $P - 20$ and $P + 10$
 403 were chosen because they represented the approximate
 404 distances in samples preceding P and succeeding P in
 405 which FV exceeded -1 m/s. This controlled for spurious
 406 near-zero FV values preceding P where the finger may
 407 have continued to dwell before initiating a tap trajectory,
 408 and succeeding P where the finger may linger at key
 409 bottom.

410 The effects of the pitch structure of a given triggered
 411 tone were measured in the finger velocity of the tap tra-
 412 jectory that followed ~ 400 ms after its onset (see Fig. 3,
 413 left panel). For each participant, FV was averaged across
 414 trials for the 8 melody tones in each of the 4 melodies and
 415 for each sample from $P - 20$ to $P + 10$. Local difference
 416 scores were defined as $FV_n - FV_{n-1}$. Thus, positive FV
 417 Error indicates faster finger movement and negative FV
 418 Error indicates slower finger movement. It is important to
 419 stress that, for each sample, FV Error indicates changes in
 420 FV relative to the *identical sample in the previous tap*;
 421 thus, for example, a negative value at $P - 5$ indicates
 422 slower movement relative to the $P - 5$ sample in the
 423 previous tap; whether or not the finger is positively or
 424 negatively accelerating at $P - 5$ *within the current tap* is
 425 not considered here. Finally, for each sample, participant
 426 averages were first concatenated into a 32-tone FV Error
 427 profile and then averaged across participants into a single
 428 FV Error profile. This procedure was repeated for each
 429 sample from $P - 20$ to $P + 10$ to yield a series of 31 FV
 430 Error profiles that span the tap trajectory.

431 Results

432 Motor resonance effects on ITI

433 The grand-averaged ITI Error profile was entered into a
 434 stepwise multiple regression with five predictors: Pitch
 435 Contour, Pitch Distance Change, Incongruence, Sequence
 436 Position, and Pitch Height. The result was significant,
 437 $F(5,26) = 3.85$, $P < .01$, explaining 43% of the variance
 438 and discarding only Pitch Height from the model.

439 Figure 4 shows that, as expected, ITI tended to be
 440 shorter when initiated by CP tones and longer when ini-
 441 tiated by CC tones, resulting in a correlation between ITI
 442 Error and Pitch Contour of $r = .37$, $P < .05$. The partial
 443 correlation with Sequence Position removed was $pr = .44$,
 444 $P < .05$. This improvement was due to the fact that the
 445 final triggered tone in each of the 4 melodies (marked with

an asterisk in the figure), regardless of its pitch contour,
 always initiated a lengthened ITI. Final lengthening may
 have reflected participants' awareness that the end of the
 melody had been reached. The correlation between ITI
 Error and Pitch Distance Change was only marginally
 significant, $r = .31$, $P < .09$, but the partial correlation was
 significant with Incongruence removed, $pr = .49$, $P < .01$.
 Thus, as expected, ITI was shortened when initiated by an
 increase in pitch distance and lengthened when initiated by
 a decrease in pitch distance, except when that decrease
 (implying slower melodic motion) occurred in a CP tone
 (implying faster melodic motion), in which case ITI was
 instead shortened (see Fig. 4). It is of interest that the
 partial correlation between ITI Error and Pitch Contour did
 not likewise improve by removing Incongruence, $pr = .29$,
 $P < .11$. As discussed below, this finding implies that,
 where there was incongruence, motor resonance effects of
 pitch contour occurred earlier and thus more strongly
 affected motor planning than pitch distance. In sum, con-
 sistent with previous findings (Ammirante and Thompson
 2010; Ammirante et al. 2011), changes in implied velocity
 of melodic motion were mirrored in ITI.

468 ITI/FV correlations

469 The goal of the current study was to investigate the kine-
 470 matic correlates of ITI Error. It was predicted that ITI Error
 471 should positively correlate with FV Error early in the tap
 472 trajectory, reflecting a motor resonance effect of melodic
 473 motion on the execution of motor planning. Correlations
 474 between the ITI Error profile and each of the FV Error

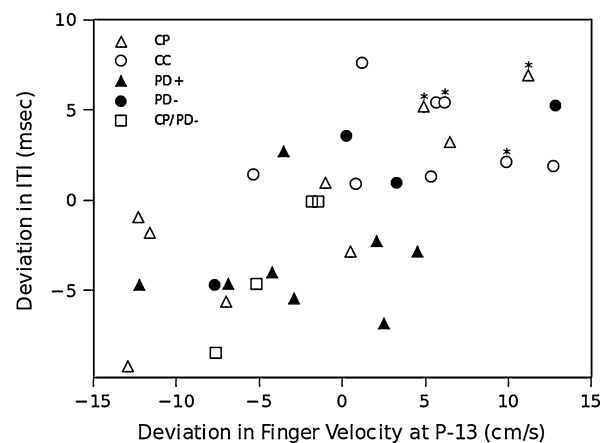


Fig. 4 Effects by pitch structure of the 32 melodic tones on ITI Error and FV Error at the $P - 13$ sample averaged across trials and participants. Melodic tones marked with an asterisk were sequence final and elicited lengthened ITI and slower FV regardless of pitch structure. The four incongruent tones, which were CP and contained a decrease in pitch distance, are shown as hollow diamonds. ITI and FV at $P - 13$ were positively correlated, $r = .69$, $P < .001$

475 profiles from $P - 20$ to $P + 10$ are shown in Fig. 5. The
 476 results supported our prediction: positive correlations early
 477 in the tap trajectory indicate that shorter ITI was associated
 478 with faster FV and longer ITI was associated with slower
 479 FV, and peak at $P - 13$, $r = .69$, $P < .0001$. Figure 4
 480 shows that effects of pitch structure on FV at $P - 13$ were
 481 highly consistent with ITI: shorter ITIs initiated by CP
 482 tones and larger pitch distances were completed with faster
 483 FV; longer ITIs initiated by CC tones and smaller pitch
 484 distances were completed with slower FV. The peak in the
 485 positive correlation between ITI and FV at $P - 13$ is fol-
 486 lowed by a negative trend that peaks at $P - 1$ but only
 487 reaches marginal significance, $r = -.32$, $P < .07$; that is,
 488 shorter ITI was associated with slower FV and longer ITI
 489 was associated with shorter FV. This may reflect a transi-
 490 tion from the execution of motor planning to online control
 491 (Dixon et al. 2004). There were no systematic associations
 492 between ITI and FV toward the end of the tap trajectory.

493 Local effects were investigated by analyzing within-trial
 494 correlations between ITI and $P - 13$ and ITI and $P - 1$.
 495 Correlations between ITI and $P - 13$ were statistically
 496 significant ($P < .05$) in 30% of trials and were significantly
 497 positive across trials in 11 of 12 participants (Mean
 498 $r = .45$, $SD = .20$). Correlations between ITI and $P - 1$
 499 were statistically significant in 27% of trials and signifi-
 500 cantly negative across trials in 10 of 12 participants (Mean
 501 $r = -.4$, $SD = .25$).

502 Motor resonance effects on FV

503 Finally, correlations between pitch structure and FV across
 504 the tap trajectory were examined using the codings from
 505 the regression analysis. As shown in Fig. 5, the partial

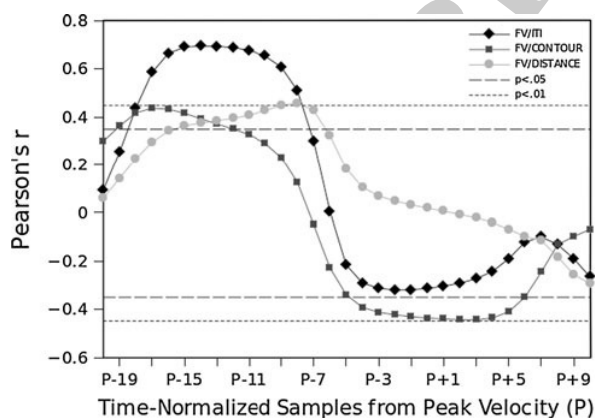


Fig. 5 Correlations between FV samples across the tap trajectory and (1) ITI, (2) Pitch Contour (partial correlation with Sequence Position removed), and (3) Pitch Distance (partial correlation with Incongruence removed). Dashed lines indicate $P < .05$, and dotted lines indicate $P < .01$

506 correlation between FV and Pitch Contour with Sequence
 507 Position removed peaks at $P - 17$, $pr = .44$, $P < .05$,
 508 indicating faster FV following CP tones and slower FV
 509 following CC tones. Also shown is the partial correlation
 510 between FV and Pitch Distance Change with Incongruence
 511 removed peaks at $P - 8$, $pr = .46$, $P < .01$, indicating
 512 faster FV with an increase in pitch distance and slower FV
 513 with a decrease in pitch distance. These correlations pro-
 514 vided further evidence that motor resonance effects are
 515 elicited earlier by Pitch Contour ($P - 17$) than by Pitch
 516 Distance ($P - 8$). Each of these positive associations early
 517 in the tap trajectory were followed by trends in the opposite
 518 direction (significant only for Pitch Contour, $P < .05$) as
 519 the finger approached peak velocity. These findings again
 520 supported the prediction that motor resonance effects on
 521 motor planning should occur toward the beginning of the
 522 tap trajectory and should attenuate with the gradual transi-
 523 tion to online control (Glover et al. 2004).

524 Discussion

525 Participants completed the continuation-tapping task with
 526 successive taps triggering tones in melodies. Consistent
 527 with previous findings (Ammirante et al. 2011; Ammirante
 528 and Thompson 2010), triggered tones elicited systematic
 529 error in the ITI that they initiated. These findings supported
 530 the general hypothesis that certain pitch structural changes
 531 between successive discrete tones may be perceived as
 532 exhibiting melodic motion, and the specific hypothesis that
 533 pitch contour and pitch distance may be psychoacoustic
 534 correlates of turn and displacement, respectively, in phys-
 535 ical space (Boltz 1998; Cohen et al. 1954; Yoblick and
 536 Salvendy 1970; Shigeno 1986, 1993; Crowder and Neath
 537 1994; MacKenzie 2007; Henry and McAuley 2009). Where
 538 CP tones (i.e., unidirectional motion) and increases in pitch
 539 distance (i.e., larger displacement) implied faster melodic
 540 motion, ITI was shorter. Where CC tones (i.e., turns) and
 541 decreases in pitch distance (i.e., smaller displacement)
 542 implied slower melodic motion, ITI was longer.

543 The goal of the current study was to investigate the
 544 kinematic correlates of ITI Error. Based on the Common
 545 Coding model of overlapping perceptual and motor repre-
 546 sentations (Hommel et al. 2001), a motor resonance effect
 547 on motor planning was predicted in which participants
 548 should be unable to disambiguate the perception of tonal
 549 motion from the velocity of a to-be-generated finger tra-
 550 jectory. This was supported by continuous recordings
 551 showing that CP tones and increases in pitch distance
 552 elicited faster FV in the tap that followed; CC tones and
 553 decreases in pitch distance elicited slower FV. Interest-
 554 ingly, motor resonance effects were elicited earlier by pitch
 555 contour than by pitch distance. The magnitude and

556 direction of this difference (~ 22.5 ms earlier for
557 pitch contour) is consistent with the reported latency of
558 the mismatch-negativity component of evoked-response
559 potentials to pitch contour and pitch distance in electro-
560 physiological studies (Trainor et al. 2002; Fujioka et al.
561 2004). Continuous recordings also revealed significant
562 positive correlations early in the tap trajectory between ITI
563 and FV. These data suggest that when FV was initially
564 faster, the finger arrived at the key bottom sooner, short-
565 ening the ITI that it completed; conversely, when FV was
566 initially slower, the finger arrived at the key bottom later,
567 lengthening the ITI that it completed.²

568 This positive correlation between ITI and FV early in
569 the tap trajectory (Figs. 4, 5) was rapidly followed by
570 negative trend as the finger approached peak velocity. This
571 partially offset earlier FV Error and may account for the
572 modest size of ITI Error ($< 2\%$ deviation) observed here
573 and previously (Ammirante et al. 2011; Ammirante and
574 Thompson 2010). These findings are consistent with pre-
575 vious studies involving grasping movements, which have
576 shown that perceptual modulation of grip aperture size
577 occurs early in the grasping movement but attenuates as the
578 movement unfolds (Glover and Dixon 2001, 2002; Glover
579 et al. 2004; Andres et al. 2008). Glover et al. (2004)
580 suggested that this may be due to a transition from the
581 execution of a motor plan susceptible to modulation by
582 task-irrelevant perceptual variables (in this case, melodic
583 motion) to online control, which may be continuously
584 updated by perceptual feedback—in this case, likely pro-
585 prioception of the finger's approach to key bottom, the
586 availability of which has been shown to affect timing
587 behavior (Goebel and Palmer 2008; Stenneken et al. 2006).

588 Although the automatic perceptual modulation of motor
589 planning is proposed to directly account for these findings,
590 other centrally mediated interpretations of these data are
591 possible.³ For example, the information processing model
592 of motor timing posits a central timekeeping mechanism
593 (Wing and Kristofferson 1973) that, in continuation tap-
594 ping, flexibly adapts to perturbations in tempo by adjusting
595 its period. According to this model, it might be argued that
596 pitch structure elicited illusory local changes in perceived
597 tempo, prompting an adjustment in the period of the central
598 timekeeper, which, in turn, resulted in an issuing of a motor
599 command for a slower or faster tap. On the other hand,

since period correction is thought to be attentionally
mediated (Repp and Keller 2004), the cognitive costs
associated with persistent illusory tempo changes should be
observable as a concomitant increase in timing variability,
which has previously been shown not to be the case
(Finney 1997; Ammirante et al. 2011; Ammirante and
Thompson 2010). Moreover, period correction cannot
account for the online correction that immediately followed
early FV Error within the same ITI, since a completed
referent period would not have passed to which the time-
keeper could adapt.

The current study supports early theoretical work of
Alexander Truslit (1938, cf. Repp 1993), which has gener-
ated some renewed interest due to its remarkable antic-
ipation of current issues in the relationship between
perception and action in a musical context. Truslit pro-
posed that the motional quality commonly attributed to
musical melodies arises from the unfolding relations
between successive pitches being automatically and cov-
ertly simulated as action. He called this the listener's
"corresponding motion experience." Evidence from neu-
roimaging supports an action-oriented perceptual repre-
sentation of melody (Baumann et al. 2007; Chapin et al.
2010; Lee et al. 2011; Zatorre et al. 2009; Griffiths et al.
2009). Here we present behavioral evidence from a sample
of non-musicians that the perception of melodic motion
may be instantiated in motor plans that control timed
movements. The finding of online correction in FV near
mid-trajectory supports Truslit's additional claim that this
experience is ultimately largely inhibited in the listener
(Truslit 1938 cf. Repp 1993).

Truslit argued that an action-oriented engagement with
melodic sequences may underlie musical communication
between performer and listener in an expressive music
performance (see also, Leman 2009). A skilled musician
may emphasize melodic action associations shared with an
engaged listener through the same deviations from strict
timing (temporal accent) and evenness of intensity
(dynamic accent) that spontaneously emerged here.⁴
Indeed, some evidence suggests that, as with the current
sample of non-musicians, accentuation by musicians may
also be at least partly beyond deliberate control (Drake and
Palmer 1993; Penel and Drake 1998; Repp 1999).

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⁴ Although intensity was experimentally controlled, under normal
conditions faster FV would have also produced louder tones.

² In the context of music performance of melody with accompani-
ment, this same association between finger velocity and elapsed time
between tone onsets is termed *velocity artifact* and results in the
melody being played louder and ahead of the accompaniment
by ~ 30 ms (Repp 1996; Goebel 2001).

³ Elsewhere, we discuss in detail (Ammirante et al. 2011; Ammirante
and Thompson 2010) why an alternative interpretation based on the
perceptual salience of pitch structures does not adequately account for
these findings.

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