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Ideomotor effects of pitch on continuation tapping

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The ideomotor principle predicts that perception will modulate action where overlap exists between perceptual and motor representations of action. This effect is demonstrated with auditory stimuli. Previous perceptual evidence suggests that pitch contour and pitch distance in tone sequences may elicit tonal motion effects consistent with listeners' implicit awareness of the lawful dynamics of locomotive bodies. To examine modulating effects of perception on action, participants in a continuation tapping task produced a steady tempo. Auditory tones were triggered by each tap. Pitch contour randomly and persistently varied within trials. Pitch distance between successive tones varied between trials. Although participants were instructed to ignore them, tones systematically affected finger dynamics and timing. Where pitch contour implied positive acceleration, the following tap and the intertap interval (ITI) that it completed were faster. Where pitch contour implied negative acceleration, the following tap and the ITI that it completed were slower. Tempo was faster with greater pitch distance. Musical training did not predict the magnitude of these effects. There were no generalized effects on timing variability. Pitch contour findings demonstrate how tonal motion may elicit the spontaneous production of accents found in expressive music performance.

Keywords: Ideomotor; Pitch contour; Pitch distance; Continuation tapping.

The ideomotor principle states that "perception and action will modulate each other reciprocally whenever they are similar" (James 1890; Prinz, Aschersleben, & Koch, 2009, p. 40). Central to this prediction is the proposal that perceptual and motor representations share a common code (Hommel, Müsseler, Aschersleben, & Prinz, 2001). Evidence for common coding has been demonstrated at the neural level in monkeys and humans (Rizzolati & Craighero, 2004), where perception of an action and performance of the same action activate common brain areas. Reciprocal modulation has been demonstrated in behavioural experiments that have investigated interference effects of actions on perception (e.g., Wohlschläger, 2000) and, conversely, perceptual features on action (e.g., Simon, 1990).

Some recent studies have investigated ideomotor effects in the auditory domain. Reciprocal stimulus–response compatibility effects have

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been found between the pitch height of a target tone (e.g., higher or lower) and the spatial position of the keys on the response apparatus. Rusconi, Kwan, Giordano, Umiltà, and Butterworth (2006) and Lidji, Kolinsky, Lochy, and Morais (2007) investigated modulation of action; Repp and Knoblich (2007) investigated modulation of perception and obtained complementary results. In the current study, effects of auditory perceptual features on action were further investigated. Of interest were modulating effects of pitch contour (the pattern of upward and downward changes in pitch height over time) and pitch distance (the magnitude of frequency separation between successive tones) in tonal sequences. Previous perceptual evidence suggests that in sequences of tones, pitch contour and pitch distance may each elicit tonal motion effects that are consistent with the listener's implicit awareness of the lawful dynamics of moving bodies.

Boltz (1998) obtained perceptual evidence of an interaction between pitch contour and the tempi of isochronous sequences of discrete tones. Participants listened to pairs of melodies and indicated whether the comparison melody was slower or faster in tempo than the target. In addition to the tempo of each melody, pitch contour was manipulated. Although participants were not instructed to attend to pitch contour, their global tempo judgements appeared to reflect the accumulation of illusory tempo perturbations. Where comparison melodies contained fewer contour-changing (CC) tones than the target, tempo was more likely to be judged as faster. Conversely, where comparison melodies contained more CC tones than the target, tempo was more likely to be judged as slower. Remarkably, these effects persisted even when there was no actual difference in tempo between the two melodies. These findings suggest that a temporal interval completed by a contour-preserving (CP) tone may be perceived to unfold more quickly than an interval completed by a CC tone. In addition, these data imply that in an isochronous sequence varying in pitch height, pitch contour may elicit the perception that tempo is variable.

Boltz (1998) suggested that the interaction between pitch contour and tempo may have been an effect of tonal motion reflecting listeners' implicit awareness of the lawful acceleration trajectory of a locomotive terrestrial body equipped with a vestibular system and constrained by gravity.[1] When running a zigzagging (i.e., contour-changing) course, it must slow down when changing directions in order to maintain balance, but when running a unidirectional (i.e., contour-preserving) course, it may either maintain a constant gait or accelerate. (See Viviani & Stucchi, 1992, for a comparable perceptual effect with continuous visual stimuli.) Further evidence that pitch contour elicits the perception of tonal motion may be found in studies of pitch memory. In the *auditory representational momentum* effect, memory for the final pitch of a unidirectional sequence of discrete pitches is biased in the direction of implied tonal momentum (Freyd, Kelly, & Dekay, 1990; Hubbard, 1993, 1995; Kelly & Freyd, 1987); for example, the final tone in a descending sequence is remembered as lower in pitch than it actually was. The interpretation that bias arises from momentum

[1] Boltz (1998) offered an alternative interpretation of her findings for pitch contour that were based on musical structure. She suggested that participants may have "overgeneralized" certain pitch/timing structural associations learned from exposure to Western music, and that CC tones in music are often of prolonged duration compositionally and/or in expressive performance, functioning as melodic accents. Thus, she argues that participants may have imposed these expectancies onto the isochronous stimuli. This issue was addressed in the current study by testing the robustness of the pitch contour/tempo interaction in unstructured tonal sequences rather than musical melodies. Moreover, where the stimuli in Boltz's study were composed of the tones of a C major scale, the current study used pitch distances not found in Western scale structures (150 cents) and that are smaller (25 and 50 cents) or larger (350 cents) than the pitch distances occurring most frequently between tones in Western melodies (Huron 2001; Vos & Troost, 1989). In addition, whereas in Boltz's study (a) the proportion of CC to CP tones within a sequence did not exceed 1:3, and (b) each CC tone was always flanked by CP tones (thus potentially conflating their perceptual salience), in the current study both contour types were presented randomly, roughly equiprobably, and could occur in succession.

implied by a continuation of in pitch direction is supported by the fact that there is no pitch memory bias when the sequence contains a contour change (Freyd et al., 1990; see Freyd & Finke, 1984, Experiment 2 for a visual analogue).

On the basis of these perceptual data, the current study investigated whether (a) perception of pitch contour would modulate action; (b) modulated responses would be consistent with the predictions of tonal motion. Nonmusicians with a range of formal music training repeatedly tapped a single key of a MIDI keyboard with their index finger with the goal of maintaining a steady tempo. Auditory sequences were tones varying in pitch and triggered by each tap. Participants were instructed to ignore them.

To tap a steady beat, an individual must calibrate the appropriate distance and velocity of their finger trajectory for each tap. The general prediction investigated here was that representational overlap should occur between implied tonal motion of the just-heard tone and tap trajectory calibration. Immediate modulating effects of visually presented stimuli on finger calibration have been previously observed in grasping movements (Andres, Davare, Pesenti, Olivier, & Seron, 2004; Andres, Ostry, Nicol, & Paus, 2008; Castiello, 1996; Gentilucci & Gangitano, 1998; Glover, Rosenbaum, Graham, & Dixon, 2004). For example, Glover et al. (2004) presented participants with a word describing a graspable object that was either larger (e.g., "apple") or smaller (e.g., "grape") than a wooden block. The task was to read the word aloud and then grasp the block. The authors found that the size of the just-read object modulated grip aperture size during the grasping movement. This fast and automatic perceptual modulation of action may have reflected the activation of shared neural resources (Liepelt, Von Cramon, & Brass, 2008). In the current study, it was predicted that perception of acceleration implied by the pitch contour of the just-heard tone should modulate (a) the timing of an intertap interval (ITI) completed by a given tone and (b) the velocity of the tap that follows (TV = tap velocity). Thus, ITI and TV should be faster for CP tones, which imply positive acceleration, than for CC tones, which imply negative acceleration.

In addition to pitch contour, pitch distance between successive tones was manipulated. An association between pitch distance and spatial extent is reflected in common descriptors. Where there is increased frequency separation between two tones, they are often described as being "farther apart". Empirical evidence suggests that this association also affects timing in ways that are consistent with apparent tonal motion (Cohen, Hansel, & Sylvester, 1954; Crowder & Neath, 1994; Eitan & Granot, 2006; Henry & McAuley, 2009; Kadosh, Brodsky, Levin, & Henik, 2008; MacKenzie, 2007; Shigeno, 1986, 1993; Yoblick & Salvendy, 1970). In a synchronized tapping task to a continuous frequency modulating (FM) pacing signal, McAnally (2002) kept tempo constant and manipulated FM between trials and found that taps anticipated the zero phase of the stimulus to a greater extent with increased FM. These data imply that tempo was perceived as faster with greater pitch distance. Perception may have reflected implicit awareness of lawful motion: Just as greater spatial extent traversed by a moving body within a fixed time interval means faster motion, greater pitch distance traversed at a steady rate (i.e., cents/ms between phases) may have implied faster tonal motion. The current study aimed to replicate this previous finding with discrete tones and with a self-produced tempo. It was predicted that if greater pitch distance implies faster tonal motion, this should elicit faster ITI and TV.

Both ITI and TV were of interest because of their accentuating role in expressive music performance. For example, in communicating an intended quality of a melody, a skilled performer often locally deviates from strict timing (temporal accent) and/or evenness of intensity (dynamic accent). In an early theoretical work strikingly anticipatory of contemporary issues of perception and action, Truslit predicted that tonal motion of a musical melody "should elicit in the listener a *corresponding motion experience*" (Truslit, 1938, as cited in Repp, 1993, p. 50, italics added). He proposed that the experience of apparent tonal motion is largely unconscious and normally largely suppressed in the listener, "its only outward manifestation [being] subtle tensions of the muscles" (Truslit, 1938, as cited in Repp, 1993, p. 51), but deliberately exaggerated in expressive musical performance in the form of temporal and dynamic accents. Following Truslit, Leman (2009) has proposed that musical communication between performer and listener may be rooted in shared action associations elicited by musical sound. In the current study, it was of interest to determine whether tonal motion would spontaneously elicit temporal (ITI) and dynamic (TV) accents found in expressive music performance.

Method

Participants

Thirty-four undergraduates (28 females) from Macquarie University participated for course credit. Their average age was 22.0 years ($SD = 4.9$), and the number of years of formal individual music lessons ranged from 0 to 10 ($M = 1.74$; $SD = 2.66$). No participants reported any form of hearing impairment.

Apparatus

FTAP (a program for running tapping experiments) was used for stimulus presentation and data collection (Finney, 2001). Square and sine wave tonal stimuli were assembled into a sound font and were loaded into a software-based tone generator that was virtually interfaced with a CME UF8 MIDI keyboard. To minimize latency, the experiment was run in console mode on a non-networked PC as superuser. Under these conditions, FTAP should produce output with millisecond resolution (Finney, 2001). This was confirmed by the latency diagnostics that FTAP outputs for each trial; mean time between calls to the program's output scheduler was 0.49 ms.

Participants heard stimuli through Sennheiser HD 515 headphones at 74 dB SPL. They were seated at a table on which the MIDI keyboard was placed. To prevent fatigue, the wrist and forearm of participants' writing hand were supported by a platform level with the keys of the MIDI keyboard. Left-handed participants ($n = 2$) tapped on the lowest key of the keyboard (C1); right-handed participants ($n = 32$) tapped with their index finger on the highest key of the keyboard (C8). This allowed the other fingers of the hand to be further supported by the side panel of the keyboard. The MIDI velocity output parameter was set to a fixed value to eliminate variations in tone intensity between taps.

Stimuli and procedure

The continuation-tapping paradigm (Stevens, 1886) was used. For each trial, participants first synchronized their taps with a pacing signal for 20 taps. Participants could begin synchronizing with the pacing signal at their discretion. Synchronization pacing signal ticks were 15-ms square waves presented at a fixed interonset interval (IOI) of 500 ms. At this point, taps did not trigger any auditory feedback. After 20 taps, the pacing signal stopped and was replaced by tap feedback tones. Continuation tones were sine tones 250 ms in duration with onsets triggered by tapping. Participants attempted to maintain the tempo set by the pacing signal. The continuation phase ended after 31 additional taps. To maintain task vigilance, after each trial participants were presented with the standard deviation of the continuation-phase ITIs of the current trial and were instructed to try to achieve as low a score as possible.

It was stressed that the goal was to maintain a steady beat at the tempo provided by the pacing signal and that any variation in pitch between tones should be disregarded. Participants were instructed to give an equal weight to each tap. Thus, any observed changes in tap velocity were presumed to be unintentional. In addition, they were instructed to maintain contact between their fingertip and the key. The spring resistance of the key always returning the finger to the same tap onset position ensured that a change in tap velocity should not be offset by a longer movement trajectory.

Pitch distance of the tones was manipulated between trials, and pitch contour was manipulated within trials. The purpose of this design was to control for circumstances in which acceleration implied by pitch contour and pitch distance locally conflicted. For example, according to the predictions of tonal motion, a tone that both (a) changes contour and (b) is of a greater pitch distance than previously should imply both negative and positive acceleration, respectively. In the absence of previous literature to draw from, it was desired that these potential ambiguities were avoided.

There were five pitch distance conditions: monotone, 25, 50, 150, and 350 cents between successive continuation-phase feedback tones. The monotone condition feedback tone was C5 (523.25 Hz). For each pitched condition, there were five continuation-phase feedback tones—a central C5 tone, two above, and two below. Continuation-phase tone sequences began on any of the five tones and randomly ascended and descended stepwise (e.g., Tones 2, 1, 2, 3, 4, 3, etc., where numbers refer to the relative pitch height of the individual tones). As pitch distance was defined as the distance between successive tones, of which there were always five, it was always equal to one quarter of the pitch range of sequences.

Participants completed the five pitch distance trials seven times in blocks, with each block consisting of one trial for each condition. Order of trials within a block was randomized. With short breaks offered between blocks, the task took approximately 30 min.

Data analysis

Continuation-phase taps were subjected to analysis, with the synchronization phase serving the purpose of ensuring that tempo was consistent between participants. Some acceleration typically occurs at the transition between synchronization and continuation phases (Flach, 2005). Thus, the first 5 continuation taps were discarded, and the final 26 continuation taps (25 ITIs) were subjected to analysis.

"Note on" events were registered during the downward movement of the key by a sensor at a fixed position near the key bed. TV for each "note on" event was a value on a linear scale from 1 to 127. ITIs were defined as the time difference between MIDI "note on" events. Rare ITIs that exceeded 800 ms (0.09%) were probably due to unregistered taps and were discarded.

For the analysis of pitch contour effects, each tap was classified according to pitch direction of the two tones preceding it (current tone direction and previous tone direction). Each ITI was likewise classified according to the pitch direction of the tone initiating it (current tone direction) and the tone initiating the previous ITI (previous tone direction). An example is displayed in Figure 1A. Sequential pitches are referred to by pitch direction (U for "up" and D for "down"). Thus, the four pitch contour types were UU, UD, DU, and DD, where, for example, type DU changes contour while DD does not. These are displayed in Figure 1b.

For each of the four pitched conditions, data from the seven trials were pooled—7 (trials) × 26 (continuation-phase taps, or 25 ITIs, per trial) × 4 (pitched feedback conditions = 728 taps, or 700 ITIs, per participant)—and were classified by pitch contour and absolute pitch height. For the latter, averages were calculated for outer tones, in which either the just-heard tone or the previous tone was 1 or 5 (i.e., CC tones = 121, 212, 454, and 545 sequences; CP tones = 321 and 345), and for inner tones, in which neither the just-heard tone nor the previous tone was 1 or 5 (i.e., CC sequences = 232, 323, 343, 434; CP sequences = 123, 234, 432, 543). Since effects of relative pitch height of sequence tones were of primary interest, the purpose of this additional classification was to rule out two potentially confounding effects of absolute pitch height. First, where a just-heard tone was either 1 or 5, spurious effects could occur because of associations between absolute pitch height and tempo (e.g., Eitan & Timmers, 2009) or the perceptual salience of the outer sequence tones (Lester, 1986). Second, where a previous tone was either 1 or 5, it could be argued that modulated ITI and/or TV may have arisen from certain expectancies. In this case, over the course of the experiment a participant might become sensitized to the sequence constraint that only Tone 2 could follow Tone 1, and only

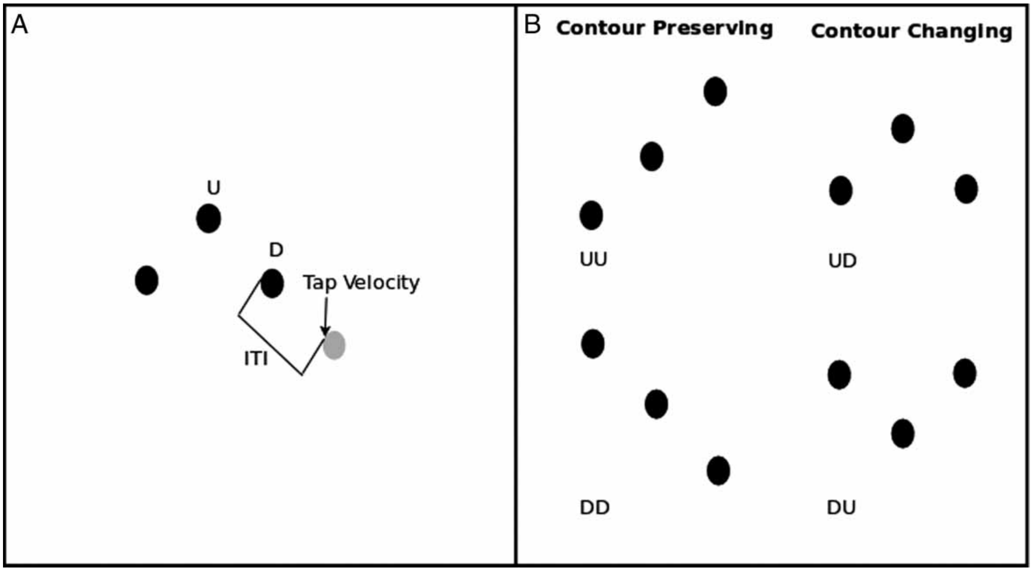

Figure 1. *(A: left panel): Triggered tones are displayed as dots, where the relative height of the dot indicates pitch height. U = up. D = down. A UD type contour is displayed. ITI (intertap interval) was measured, in this example, from the onset of the D tone to the onset of the following tone (grey dot). Tap velocity was measured at the tone following D (grey dot). The last dot is greyed out to indicate that the tone could trivially be either a D tone or a U tone. (B: right panel): The four contour types.*

Tone 4 could follow Tone 5. On the other hand, where a previous tone was 2, 3, or 4, it was equiprobable that a CP or CC just-heard tone could follow. Thus, no expectancy should have been generated.

Results

Coefficient of variation

General interference effects of tones were first assessed. Each participant's coefficient of variation (CV) values were averaged across seven trials for each of the four pitch distance conditions and the monotone control condition. In this case, CV was defined as the standard deviation of ITIs within a trial divided by its mean ITI and provides a standardized measure of tapping variability. A one-way mixed model repeated measures analysis of variance (ANOVA) on CV scores with pitch distance as within-subjects factor and years of training as a continuous between-subjects covariate revealed no main effect of pitch distance, $F(4, 128) = 1.58$, $MSE = 5.33 \times 10^{-5}$, $p < .19$, and no Pitch Distance × Training interaction, $F < 1$. Thus, consistent with a previous finding (Finney, 1997), no general interference effects of pitched tones were found, nor did we observe any effects that were dependent on musical training.

ITI

There were two predictions: (a) ITI should be faster following CP tones than CC tones; (b) ITI should be faster with increased pitch distance.

Mean ITI values according to pitch distance, absolute pitch height, previous tone direction, and current tone direction were entered into a 4 × 2 × 2 × 2 mixed model ANOVA with years of training as covariate. There were significant main effects of pitch distance, $F(3, 96) = 5.99$, $MSE = 589.61$, $p < .001$, and current tone direction (D < U), $F(1, 32) = 7.21$, $MSE = 32.94$, $p < .02$. The latter was qualified by a significant Current Tone Direction × Previous Tone Direction interaction, $F(1, 32) = 9.48$, $MSE = 66.73$, $p < .01$. There were no other significant interactions.

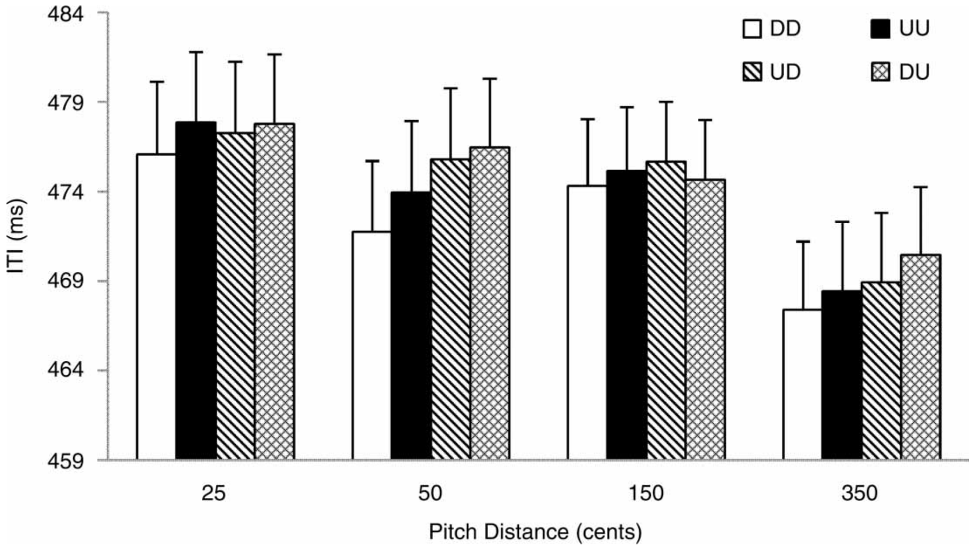

Figure 2. *Mean intertap interval (ITI; +*SE*) for pitch contour and pitch distance (*n *= 34). U = up. D = down.*

Post hoc analysis confirmed both predictions. Mean ITI values by pitch contour and condition are displayed in Figure 2. As expected, ITIs for CP tones were faster relative to ITIs for CC tones. These data suggest that positive acceleration implied by CP tones primed a faster finger trajectory whereas negative acceleration implied by CC tones primed a slower trajectory. Since the three-way Absolute Pitch Height × Current Tone Direction × Previous Tone Direction was not significant ($F < 1$), the interaction cannot be attributed to either the perceptual salience of the outer tones or expectancies for the tones that inevitably followed them.

The pitch contour interaction was more robust for DD tones (DD < UD, $p < .001$; DD < UD, $p < .001$). In addition, UD tones generally elicited faster ITI than did DU tones. Thus, one possibility, consistent with previous ideomotor effects for single and paired tones (Lidji et al., 2007; Repp & Knoblich, 2007; Rusconi et al., 2006), is that an additional priming effect of D tones reflects a congruency in direction between pitch height of the just-heard tone and response termination.

As shown in Figure 2, the pitch contour interaction did not hold in the 25-cents condition. Since this pitch distance approaches threshold for pitch direction discrimination (Bates, 2005), one simple explanation may be that listeners are less sensitive to pitch contour where ambiguity arises in perceived pitch direction between successive tones. An alternative possibility is that, at ~25 cents/500 ms, tonal motion was too slow for pitch contour effects to emerge (Henry & McAuley, 2009). As both pitch distance and onset rate may contribute to the perception of tonal motion, effects of pitch contour might have emerged for a 25-cents pitch distance at a faster tempo. Similarly, effects observed at larger pitch distances might have been attenuated at a slower tempo.

For pitch distance, post hoc analysis revealed a significant linear contrast, $F(1, 32) = 15.46$, $MSE = 545$, $p < .001$, indicating that tempo was faster with increased pitch distance. These data imply that greater pitch distance traversed between more or less regular intervals implied faster tonal motion, which may have primed a globally faster tap trajectory and, by extension, a faster tempo. This is supported by the fact that tempo was significantly faster in each of the four pitched conditions than in the monotone control condition in which null pitch motion was implied

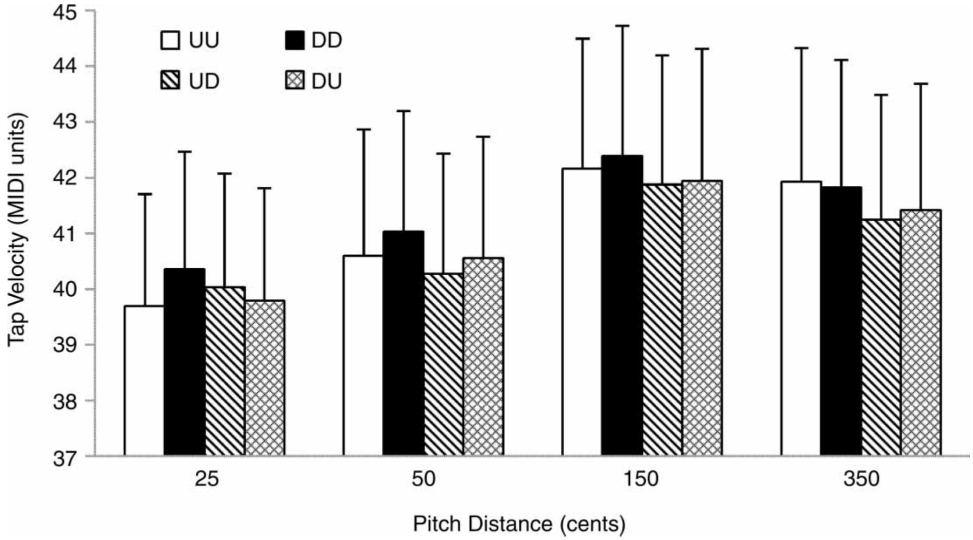

Figure 3. *Mean tap velocity (TV) values (+*SE*) for pitch contour and pitch distance (*n = *34). U = up. D = down.*

(MacKenzie, 2007): monotone ($M = 487.54$)/25 cents ($M = 477.25$), $p < .01$; monotone/50 cents ($M = 474.5$), $p < .01$; monotone/150 cents ($M = 474.95$), $p < .01$; monotone/350 cents ($M = 468.81$), $p < .001$.

TV

There were two predictions: (a) faster taps following CP tones than following CC tones; (b) faster taps with increased pitch distance.

Mean TV values according to pitch distance, absolute pitch height, current tone direction, and previous tone direction were entered into a 4 × 2 × 2 × 2 mixed measures ANOVA with years of training as between-subjects covariate. Only a main effect of absolute pitch height was significant, $F(1, 32) = 13.91$, $MSE = 47.30$, $p < .001$. However, the Current Tone Direction × Previous Tone Direction interaction was also significant, $F(1, 32) = 13.68$, $MSE = 2.47$, $p < .001$. There were no other significant interactions.

Mean TV values by pitch contour and pitch distance are displayed in Figure 3. As expected, taps were faster following CP tones than following CC tones (UU > UD, $p < .05$; DD > DU, $p < .001$; DD > UD, $p < .001$). As shown in Figure 3, consistent with the ITI findings, the effect was more robust for DD tones. In addition, as with the ITI findings, the interaction did not hold in the 25-cents condition.

While the data largely supported the first prediction for pitch contour, there was only a trend towards the second prediction for pitch distance. As shown in Figure 3, TV was faster with increased pitch distance for the 50- and 150-cents conditions but not the 350-cents condition. However, given the modest effect size, the failure to observe a linear increase in tap velocity with pitch distance may have been due to the limited sensitivity of the apparatus to detect global differences between trials.

Post hoc analysis of the main effect of absolute pitch height was further investigated in a separate ANOVA of the four pitched feedback conditions with pitch distance (4) and absolute pitch height (5) as factors. These data revealed a significant quadratic contrast, $F(1, 32) = 12.03$, $MSE = 37.22$, $p < .001$, indicating that TV following outer tones ($M = 41.5$) was faster than that following inner tones ($M = 41.08$). This was probably due to the greater proportion of CP to CC outer tones, since Tones 1 and 5 could only initially be approached unidirectionally. This finding is not discussed further.

The consistency between tap velocity and ITI findings for pitch contour suggested a causal relationship between TV and ITI such that where participants tapped faster, they reached the key bed sooner, and, as a result, the ITI completed by the tap was faster. In this case, the correlation between ITI and TV should be negative. However, mean correlations between ITI and TV for each trial did not support this association. ITI/TV correlations averaged by participant and by the four pitched conditions plus the monotone control condition did not differ, $F(4, 128) = 1.37$, $MSE = 0.01$, $p < .25$, *ns*. Moreover, these correlations were weakly positive ($M = .06$), indicating that TV was faster for slower ITIs and slower for faster ITIs. These modest ITI/TV correlations are consistent with a previous continuation tapping finding where no auditory feedback was present (Keele, Ivry, & Pokorny, 1987).

It should be noted that in the current study the TV values were measurements of flexion velocity at a single point near the end of a tap's trajectory. Thus, one possibility is that ITI reflected priming effects occurring over the course of the flexion trajectory that were largely inhibited at response termination. This explanation is supported by ideomotor effects of continuous grasping motions in other domains (Andres et al., 2008; Glover et al., 2004) and is consistent with Truslit's prediction (Truslit, 1938, as cited in Repp, 1993) that the listener's "corresponding motion experience" is largely suppressed. Moreover, suppression at response termination would also explain the robust pitch contour interaction for TV despite a modest effect size. We are currently investigating this possibility by recording the continuous tap trajectory using motion capture.

Discussion

The current data supported the prediction that pitch contour and pitch distance between successive triggered tones should each systematically influence timing and affect finger dynamics in a continuation tapping task. Pitch contour was randomly and continuously varied within trials. It had robust effects on intertap interval (ITI) and tap velocity (TV): (a) ITI was faster when initiated by CP tones than when initiated by CC tones; (b) taps were faster following CP tones than following CC tones. Pitch distance between successive tones was varied between trials. It did not have a significant effect on TV but, as expected, tempo was faster with increased pitch distance. The absence of a main effect of pitch distance on TV may have reflected the limited sensitivity of the apparatus to detect global differences between trials. Amount of musical training did not predict the magnitude of these effects. On the other hand, as there were no musicians in the sample, individual differences due to musical training cannot be ruled out entirely.

We propose that systematic changes in timing and finger dynamics resulted from "representational overlap" between perceptual and motor representations of action (Prinz et al., 2009). Where overlap occurs, perceptual modulation of action may be immediate and automatic. This perceptual modulation of action is thought to depend on shared neural resources associated with perceptual and motor representations of action (Liepelt et al., 2008). Truslit (1938, as cited in Repp, 1993) predicted that the perception of tonal motion in musical melodies unconsciously awakens a "corresponding motion experience" in the listener that is largely suppressed but observable in the form of reflexive muscle activity. Evidence from perception studies suggests that in isochronous tone sequences, pitch contour and pitch distance of tones may elicit apparent tonal motion effects consistent with the listener's implicit knowledge of the lawful dynamics of moving bodies. The current findings support the general prediction that the perception of acceleration implied by these pitch structural features should modulate action. Responses were immediate (occurring within ~500 ms) and unintentional: Where pitch structure implied positive acceleration, taps were faster; where it implied negative acceleration, taps were slower.

For pitch contour, previous perceptual studies have demonstrated that in an isochronous sequence, a temporal interval initiated by a CP tone may be perceived to unfold more quickly than when initiated by a CC tone (Boltz, 1998). Boltz suggested that this may be rooted in a listener's implicit knowledge of the lawful biological locomotion of moving terrestrial bodies, which, in order to maintain balance, must navigate directional changes in their trajectory by slowing down (Viviani & Stucchi, 1992). Also consistent with the proposal that acceleration is implied by pitch contour is the auditory representational momentum effect, in which memory for the final pitch of a unidirectional (but not contour-changing) sequence of discrete pitches is biased in the direction of implied tonal momentum (Freyd et al., 1990; Hubbard 1993, 1995; Kelly & Freyd, 1987). Thus, in the current study, where a CC tone implied negative acceleration, the following tap and the ITI that it completed were slower. Conversely, where a CP implied positive acceleration, the following tap and the ITI that it completed were faster.

For pitch distance, previous studies support a positive association between pitch distance and spatial extent (Cohen et al., 1954; Crowder & Neath, 1994; Henry & McAuley, 2009; MacKenzie, 2007; Shigeno, 1986, 1993; Yoblick & Salvendy, 1970). In the current study, taps and tempo were faster with greater pitch distance. These data suggest that, just as greater spatial extent traversed by a moving body within a fixed time interval means faster motion, in the context of the more or less isochronous sequences generated by the participants, greater pitch distance implied faster tonal motion (i.e., cents/ms "traversed" between tones). Thus, greater pitch distance may have primed a faster tap, which resulted in a faster tempo. This finding in a continuation task with discrete feedback tones complements McAnally's (2002) observation in a synchronization task with a continuous frequency-modulating pacing signal. He found that synchronization error (i.e., the tendency for taps to precede the zero phase of the pacing signal) increased with pitch distance.

Some previous studies have also found systematic deviations from isochrony in trained musicians instructed to perform notated melodies in strict tempo (Drake & Palmer, 1993; Penel & Drake, 1998; Repp, 1999). However, deviations in these studies were only somewhat consistent with the effects of pitch contour and pitch distance reported here (e.g., Drake & Palmer, 1993, Experiment 1). On the other hand, these deviations may have been due to other factors such as familiarity with the melody to be performed, visual cues in the notated score, physical constraints, and expectancies generated by meter and tonality. These factors were controlled in the current study in an effort to isolate apparent tonal motion effects of pitch contour and pitch distance. In addition, a sample of nonmusicians with a range of musical experience was tested on the grounds that in order to be operational in musical communication, perception of tonal motion should occur regardless of musical background (Leman, 2009).

Indeed, the current findings demonstrate how temporal and dynamic accents found in expressive musical performance may partly emerge without intention in nonmusicians. Accents are most often marked compositionally and/or expressed in music performance by (a) an increase in the duration of a tone and/or a lengthening of the temporal interval that follows (*temporal* accent); and (b) an increase in intensity (*dynamic* accent). On a piano, performance of a dynamic accent is accomplished by a faster tap (Drake & Palmer, 1993). Thus, although intensity was experimentally controlled in the current study, under normal conditions a faster tap would have produced a louder tone. As participants were generally successful at the current task, accents were smaller in magnitude than in an expressive musical performance, implying the role of a musician may be to exaggerate latent perception–action associations in order to effectively convey these associations to the listener (Leman, 2009). On the other hand, the spontaneous temporal and dynamic accents elicited by pitch contour are consistent with those found in corpus studies of composed melodies (Huron & Royal, 1996, Experiment 2), as well as with subjective perceptual ratings of relative accent strength of three-tone melodic contours (Thomassen, 1982).

Finally, although an unmediated ideomotor effect is proposed to account for these data, other accounts may appear reasonable. For example, the perceptual salience hypothesis proposes that CC tones stand out more than others. Thus, CC tones may function as *melodic accents* in a musical context, coinciding with points of stress and prolongation and serving to delineate larger structural units such as phrases within a musical flow (Lerdahl & Jackendoff, 1983). This association may, in turn, bias production (Drake, Dowling, & Palmer, 1991). An argument might also be made for an association between pitch contour and tempo based on Gestalt principles (Narmour, 1990). In this case, CP tones, which conform to the principle of good continuation, should be more easily processed than CC tones. Common to both of these hypotheses is the assumption that the perception of pitch contour is mediated by attention. As it has been previously demonstrated that variability in continuation tapping increases when selective attention is taxed (Sergent, Hellige, & Cherry, 1993), according to the perceptual salience and Gestalt hypotheses, the cognitive costs associated with the perception of CC tones should have resulted in greater variability in ITI with changes in pitch contour than in a monotone control condition. However, in the current study, this was not the case.

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