Melodic Direction's Effect on Tapping

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ABSTRACT

Behavioral response to pitch (pure tone) change was probed, using the tapping methodology. Musicians and non-musicians were asked to tap steadily to isochronous (2 Hz) beep sequences featuring pitch events: rise, fall, peak, valley, step-size change, and pitch re-stabilization. Peaks and valleys were presented in either early, middle or late ordinal position within sequences. Two non-western melodic step-sizes were used (144 and 288 cents). Inter-Tap Intervals (ITIs) were checked for correlations to melodic direction and step-size.

Three contradicting predictions regarding response to melodic direction and step-size were proposed: a) based on musicians' tendency to 'rush' on ascending melodic lines, the "High-Urgent" hypothesis predicted shortened ITIs in response to *rising* pitches; b) based on approach/withdrawal theories of perception and ethological research showing lower pitches interpreted as more threatening, the "Flexor/Extensor" hypothesis predicted shorter ITIs in response to *falling* pitches, due to stronger activation of the flexing muscles while tapping; c) based on previous research on temporal judgment, the "Δ" hypothesis predicted one effect in both melodic directions, correlated to the magnitude of pitch change.

Elicited ITIs were related to the stimuli's melodic direction. Following first pitch-change, the shortest elicited ITIs were to pitch-*rise* in double-steps, showing a main effect to melodic direction. Taps to *rising* lines maintained increased negative asynchrony through six taps after first pitch-change. However, peaks and valleys in mid-sequence position *both* yielded delays. The Urgent-High hypothesis gained support the most, but does not account, for example, for the delays on both peaks and valleys in mid-sequence.

I. INTRODUCTION

Adding findings on the impact of pitch in animals' and humans' non-verbal communication on behavior (Morton, 1977; Ohala, 1984), to findings on links between sound and motion in the lives of fetuses and babies, Boasson (2010) presented the *SAME* hypothesis – Sound As Motion-Equivalent – suggesting the existence of a complex set of responses and inhibitions which uses *all* sound parameters, including pitch, to extract motion from the surroundings and deduce optimal self-motion. Searching for behavioral correlates of pitch processing, this study harnessed the tapping methodology – used normally to research human responses to tempo change, prediction processes and motor preparation – as a window to the ear-muscle, pitch-locomotion route. The action performed in tapping is far from locomotion, and is probably propelled via a mechanism of synchronization to external stimuli, attuned to the temporal dimension. Nevertheless, tapping was chosen due to the possibility to detect and inspect unintentional effects of pitch, expressed in the muscles, in a non-verbal, non-invasive and simple paradigm. An isochronous stimulus, to which subjects were asked to synchronize their tapping, featured pitch (frequency) changes. Inter-tap intervals were checked for the effect of melodic direction and pitch step-size.

Several preceding studies imply that pitch change affects temporal judgment. Hirsh et al. (1990) reported their subjects performed more poorly in detecting small temporal fluctuations in an otherwise isochronous sequence of six very fast tones (200ms IOI) when the time-shifted tone's pitch was deviant; detection was poorer the larger the melodic interval was. The effects were dependent on the perturbations' position in the sequence, in manners that could be related to musical phrase structure: large upward intervals in initial positions and large downward intervals in final positions disrupted detection more, as time-shifts there were perceived perhaps as 'fitting'. Tekman (2001), in light of findings quite similar to Hirsh et al.'s, suggested that musicians' timing deviations stem from properties of the human auditory processing, rather than listeners shaping their auditory strategies to fit a musical environment.

Boltz (1998) found that subjects judged melodies (set in a Western scale) containing more pitch-contour changes or wider pitch-intervals as having a slower tempo than comparison melodies, though actual tempi did not differ. She offered an interpretation according to which humans generalize from motor experience into the auditory modality: slowing down in order to maintain balance while locomoting in a zigzag course, or requiring more time to traverse a longer distance, are daily facts, intervening, according to Boltz, with a temporal judgment of non-temporal information as pitch.

Probing Boltz's hypothesis, Ammirante, Thompson & Russo (2011) used the 'continuation tapping' paradigm; their subjects, synchronizing initially their tapping to a given isochronous beat, had then to maintain independently the same InterTap Intervals (500ms), hearing from the 21st tap on a randomly changing feedback pitch, self-generated by the tapping, which they were instructed to ignore. Contour changes elicited longer ITIs than contour-preserving tones; larger step-sizes elicited shorter ITIs. The authors interpreted the results as supporting an Ideomotor approach: a contour change requires slowing down, while preserving direction allows building-up speed, and traversing a larger (pitch) space in a given time implies faster motion, expressed in tapping sooner the next tap.

We did not find studies which addressed the effect of melodic direction on tap timing, the issue our study sought to probe. We presented our subjects with various pitch contours, in opposing melodic directions, and in two Non-western pitch step-sizes.

Three mutually exclusive predictions were raised as for the results. The "High-Urgent" hypothesis predicted that ITIs following upward pitch events will be shortened. Friberg et al. (2006) compiled a set of 'rules' – the KTH model – for music performers, based on analysis of actual performances. The "Faster uphill" rule states: "Increase tempo in rising pitch" (p.148). This phenomenon can also be attested by the first author of this study, a professional performing musician.

The "Flexor/Extensor" hypothesis predicted, on the basis of ethological research, that since lower pitches are perceived as more threatening, in both animal (Morton, 1977) and human (Ohala, 1984) non-verbal communication, including musical contexts (Huron et al., 2006), more activation of flexing – 'defending' – muscles should occur on falling melodic lines, resulting in an earlier tap. Rising lines should be perceived as appeasing, incurring more extensor muscle activity.

The "Δ" hypothesis predicted larger step-sizes will result in a larger effect-size, without dependency on the melodic direction. Not only Ammirante et al.'s (2011) findings support this approach. Indeed, a larger step-size resulted in a deteriorated temporal judgment in Penel & Drake's (2004) study as well. Their subjects showed reduced success in reporting subtle prolongations of inter-tone intervals when these appeared before larger pitch intervals. The authors link the phenomenon to music-performers' habit to prolong such intervals, and suggest that bottom-up auditory processing is the origin of musicians' biases, and not higher cognitive 'decisions'. In the auditory Kappa effect (Crowder & Neath, 1995; Henry & MacAuley, 2009), subjects judge silent time intervals preceding larger pitch intervals as longer. Repp (1995), on the other hand, did not find support for the Kappa effect within a musical context: although his listeners' temporal judgment as to notes preceding melodic jumps was poor, he did not find an interval size effect; his stimulus, it should be added, was a musical phrase within a tonal, metrical context. It is inconclusive, then, whether perceptual systems encountering bigger 'changes in the world' elicit a larger response, and whether the pitch domain would influence temporal aspects of motor performance.

II. METHOD, DESIGN AND PROCEDURE

A. Subjects

21 subjects volunteered to take part: 11 musicians [6M, 5F; average age: 36, SD 7.53; 2 LH] and 10 non-musicians [6M, 4F; average age: 37, SD 8.36; 1 LH]. Musicians had more than 15 years of musical education and were performing regularly. Non-musicians had up to 6 years of musical education in childhood, and were not performing music on any regular basis.

B. Apparatus and Stimuli

Isochronous beeps (sinus tone) of varying frequencies were presented, to which subjects were asked to tap in synchrony. A non-western scale was used to minimize tonality effects which could be associated with a feeling of 'arrival' or 'relaxation'. Also, Prince et al. (2009) showed that atonal contexts foster pitch-time interactions. In the Bohlen Pierce Scale, an interval of an octave and a fifth of the Western scale (duo-decime, twelfth) is the new 'octave', called Tritave. It is divided to 13 equally-spaced steps, intervals calculated as 1/13 root of 3 (between a minor and a major second on the Western scale, equal to about 144 cents).

Short beeps of 50ms (including 5ms rise-time and 5ms decay, to prevent clicks) were played isochronously at 2Hz (500ms IOI, 120 on the metronome). This rate is often used in the tapping research, as it is well within the physically comfortable range, eliciting low ITI variability (e.g. Repp, 2010, cf. his review Repp 2005). Self-preferred, 'spontaneous' tempi average near this rate (Fraisse, 1982; Van Noorden & Moelants, 1999).

Each trial opened with between 7 and 12 beeps of identical frequency (386 Hz, labeled in Table 1 as 0), followed immediately by one of 20 different melodic contour/ step-size combinations over the next 6 beeps (see Table 1). The number of identical beeps at the beginning of each sequence was randomized to prevent prior 'knowledge' of the moment of first frequency change. The last frequency reached was repeated for 4 more beeps (5 beeps altogether) to test for after-effects.

Table 1: Melodic sequences used. Zero denotes the frequency, 386 Hz, which was repeated at each trial's outset between 7-12 times. Numbers denote steps in the Bohlen Pierce scale, equivalent to 144 cents, or 8.8%. Each trial's last frequency was repeated five times.

A. Continuous melodic lines								
Single step	Rising	0	1	2	3	4	5	6
	Falling	0	-1	-2	-3	-4	-5	-6
Double step	Rising	0	2	4	6	8	10	12
	Falling	0	-2	-4	-6	-8	-10	-12
B. Melodic direction reversals								
Single step	Late peak	0	1	2	3	4	5	4
	Middle peak	0	1	2	3	2	1	0
	Early peak	0	1	2	1	0	-1	-2
	Late valley	0	-1	-2	-3	-4	-5	-4
	Middle valley	0	-1	-2	-3	-2	-1	0
	Early valley	0	-1	-2	-1	0	1	2
Double step	Late peak	0	2	4	6	8	10	8
	Middle peak	0	2	4	6	4	2	0
	Early peak	0	2	4	2	0	-2	-4
	Late valley	0	-2	-4	-6	-8	-10	-8
	Middle valley	0	-2	-4	-6	-4	-2	0
	Early valley	0	-2	-4	-2	0	2	4
C. Step-size change								
Double to single	Rising	0	2	4	6	7	8	9
	Falling	0	-2	-4	-6	-7	-8	-9
Single to double	Rising	0	1	2	3	5	7	9
	Falling	0	-1	-2	-3	-5	-7	-9
D. Control stimulus								
No frequency change		0	0	0	0	0	0	0

The design interleaved two sub-designs (see Table 1): Eight sequences (2 x 2 x 2) of continuous melodic line with the variables melodic direction (MD, up/down), step size (SS, single/double), and step-size_change (yes/no); and twelve sequences (2 x 2 x 3) of melodic direction reversal, with the variables MD (peak/valley), SS (single/double), and ordinal position of reversal (early, middle, late). One more sequence was used as a control, in which the same frequency was heard throughout, for 17-22 beeps. Single and double steps were presented, to test for correlation between interval size and response. A step-size change was presented to check for the effect of a change in the 'rate' of melodic 'motion', within a context of an already given melodic direction.

Each trial block included all 20 contour sequences and the control, in a randomized order. Four seconds of silence separated between trials. There were 5 blocks, each lasting slightly over 5 minutes followed by a 30 seconds interval. Sequences were played and data recorded by software developed for the authors by Mr. Kfir Behar.

C. Procedure

The experimenter described the task ("tap as accurately in sync with the beat, whatever happens"). Subjects sat comfortably at a table, in a quiet room, with at least part of the forearm positioned on the table as a basis. They listened to the stimuli over head-phones (Sony MDR 605), tapping on a touch-microphone with the index finger of the dominant hand. The experimenter clicked the computer mouse once to start the experiment. The timing of the subjects' taps, from the sixth tap on, was recorded by the software.

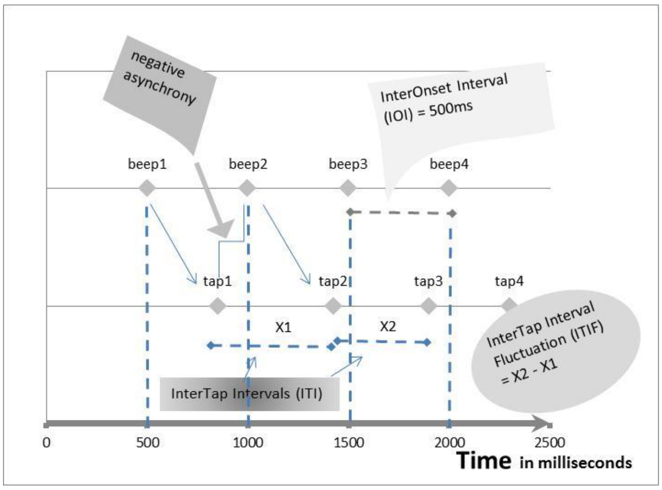

Figure 1: Beeps and Taps – Terms Clarification: taps' numbering lags one behind beeps, as their timing is believed to express a response to the previous beep.

III. RESULTS

A. Analysis Methods

Measures were the difference in deviations from the expected 500ms standard interval between consecutive taps. They are referred to as InterTap Interval (ITI) fluctuations. Thus, if following beep B1, tap T1's timing was 497ms, and following beep B2, tap T2' timing was 1013ms, the difference (ITI fluctuation) of +16ms is referred to; if T1's timing was 497ms and T2's 990ms, -7ms is noted. Thus, "-5ms" *does not* denote absolute asynchrony.

Taps 1, 2 & 3 were analyzed after each examined pitch event (first_change, step-size_change and MDR). After pitch re-stabilization only taps 1 & 2 were analyzed, due to missing data. All point-elevations on graphs (except Fig. 1) are in relation to the 500ms ITI standard (the zero axis). Each pitch event was heard approximately simultaneously with a tap. Therefore, response to the event's content was first expressed on the next tap, which was tagged T1, to be followed by T2 etc. (see Fig. 1).

B. Control

A control sequence of isochronous tones with no pitch change (see Table 1D) was introduced once every block with a random length of 17 to 23 tones. Subjects' ITI fluctuation averages per control trial were averaged per subject. The average thereof, across subjects, was 0.26ms (SD = 1.64ms). As another control, subjects' taps to the initial unchanging tones of each trial – from the sixth tone until first_change – were analyzed as well. Each trial's ITI fluctuation averages were averaged per subject. This averaged at 0.25ms (SD = 1.44ms). As one of the criteria used in the following analysis of ITI responses to melodic events is the accumulated ITI fluctuation over three taps, another control was calculated. The first three taps to those unchanging tones were summed, and averaged in the same way. The average thereof was 0.81ms (SD = 5.83ms). The ITI fluctuation variability of subjects was assessed on the taps to recurring pitch. Results were in line with tapping literature: Repp (2010) reports a standard deviation of 2% of InterOnset Interval for musicians trained in tapping, and about twice as much for non-musicians, and the present data yielded a standard deviation of 17.5ms for musicians *untrained* in tapping (3.5% of the 500ms IOI), and 26.8ms (5.35%) for non-musicians.

The results in the control sequence and of the other analysis that was done on recurring pitch conditions show very small average ITI fluctuations – well under one millisecond. Therefore the following results of the different conditions analyzed, though reporting effects on a scale of single milliseconds, are nevertheless significant.

C. First Change

In the following analysis of the three taps (T) following the event of first_change, data for T2 and T3 from stimuli involving an early peak/valley on the tone following first_change (see Table 1B) were excluded, as that additional pitch event might have affected ITI. Consequently, each subject's value analyzed was the average of 20 responses: four stimuli (rather than five), times five blocks.

A 2 X 2 repeated measures ANOVA (melodic direction [MD] – up, down; step-size [SS] – single, double) by group (musicians/non-musicians) of T1 showed a main effect of MD: *upward* changes elicited significant negative ITI fluctuations (i.e. shorter ITIs, mean -2.1ms, t-test vs. control: p = .032) while *downward* changes elicited positive, statistically insignificant ITI fluctuations (mean +0.6ms) (see Table 2 and Fig. 3). No main effect of SS was found on T1. Unpacking an interaction of MD X SS pointed to the FirstChange_*up*_double condition as eliciting the strongest ITI deviation on T1 (-3.8ms, effect size 0.66[1], t-test vs. FirstChange_*down*_double: p = .008), while other conditions elicited statistically insignificant responses.

Examination of the significant interaction that was found on T1 for MD X group showed, that non-musicians had shorter ITIs than musicians on upward changes (-3.8ms, -0.6ms respectively) and longer on downward changes (+1.6ms, -0.3ms respectively). Thus, on T1, musicians did not respond significantly differently according to MD while non-musicians did (t-test for non-musicians FirstChange_up vs. FirstChange_down: p = .026) (see Fig. 4). A t-test comparing the *difference* in ITIs between FirstChange_up and FirstChange_down in musicians vs. non-musicians on T1 proved significant (p = .041). Non-musicians' ITI fluctuation at FirstChange_up_double T1 amounted to -5.4ms (effect size 1.01, significance vs. 0: p = 0.02).

On a similar ANOVA of T2 only SS's effect approached significance, and the interaction with MD continued, still

[1] Effect size calculated as the difference in means from the control condition, divided by the pooled standard deviation.

largely because of FC_up_double which has 'sunk' by -6ms more, to an accumulated deviation (T1+2) of -9.0ms. Probing the main effect shown by the ANOVA for SS on T3 revealed a reverse situation: while single steps elicited a continued shortening of the ITI (in spite of the ongoing isochronous tones), responses to double steps began "repent" (T3: single -0.8ms, double +2.3ms respectively; see Figure 3). The two sub-conditions (up, down) elicited similar response within each SS (see Fig. 2).

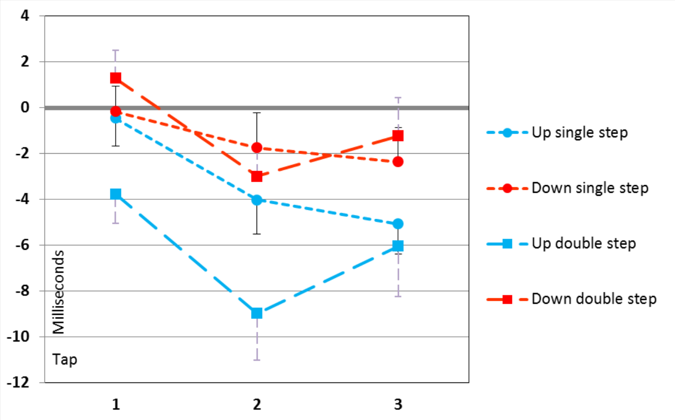

Figure 2: Responses to first_change. In the figures in this article, values are the accumulated deviation from the expected 500ms InterTap Interval, denoted by the zero axis; blue for rising lines and red for falling lines; wider dashes for double step stimuli; error bars show standard error.

Table 2: Statistically significant ANOVA results for first_change

First_change Sub-condition	MD	SS	MD x SS	MD x group
T1	*F(1,19)=* 6.260 p=0.022	-	*F(1,19)=* 5.313 p=0.029	*F(1,19)=* 5.575 p=0.033
T2	-	*F(1,19)=* 4.009 p=0.060	-	*F(1,19)=* 5.055 p=0.037
T3	-	*F(1,19)=* 5.478 p=0.030	-	-
T{1+2}	*F(1,19)=* 10.001 p=0.005	*F(1,19)=* 8.000 p=0.011	-	-
T{1+2+3}	*F(1,19)=* 8.263 p=0.010	-	-	-

Table 3: **Statistically significant ANOVA results for first_change with tap as variable.**

Sub-condition	MD	Tap	SS x Tap	MD x Tap x Group	MD x SS x Tap
T {1,2,3}	*F(1,19)=* 8.263 p=0.010	*F(2,18)=* 5.142 p=0.017	*F(2,18)=* 4.950 p=0.019	*F(2,18)=* 5.438 p=0.014	*F(2,18)=* 2.982 p=0.076
T {1,1+2, 1+2+3}	*F(1,19)=* 12.160 p=0.002	*F(2,18)=* 4.783 p=0.022	*F(2,18)=* 3.686 p=0.046	-	-

Examining the deviations from one tap to the next reveals only part of the picture. ANOVAs conducted on the accumulated values of T{1+2} and T{1+2+3} (the values actually shown on the figures), showed a strong main effect of MD, and on T{1+2} (before the 'repent' of the double steps) also for SS (MD means: T{1+2} rising -6.5ms, falling -2.4ms; T{1+2+3} rising -5.6ms, falling -1.8ms. SS means: T{1+2} single step -2.9ms, double step -6.0ms. For statistics details see Table 2). ANOVAs adding the Tap factor (T{1,2,3} and T{1, 1+2, 1+2+3}) increased MD's effect and revealed interactions summarized on Table 3. Effect size of ITI shortening on rising MD at T{1+2} was 0.95.

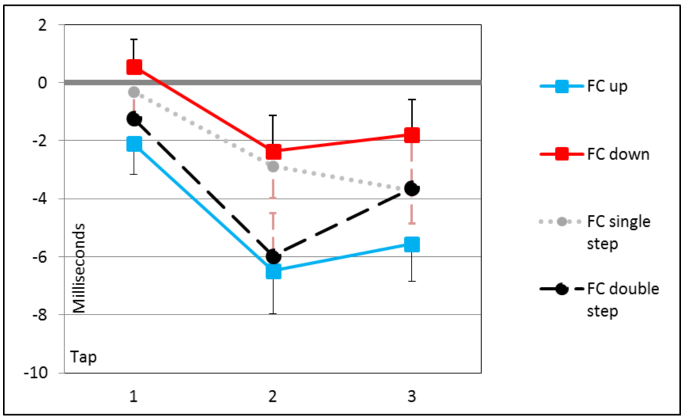

Figure 3: Responses to first_change (FC), by melodic direction and by step size

A prominent result is the *overall* ITI shortening in response to first_change, gathering significance (vs. 0) on the ITI fluctuation accumulations T{1+2} and T{1+2+3} (mean ITIs and significance vs. 0 – T{1}: -0.8ms, p = .337; T{1+2}: -4.4ms, p = .001; T{1+2+3}: -3.7ms, p = .002).

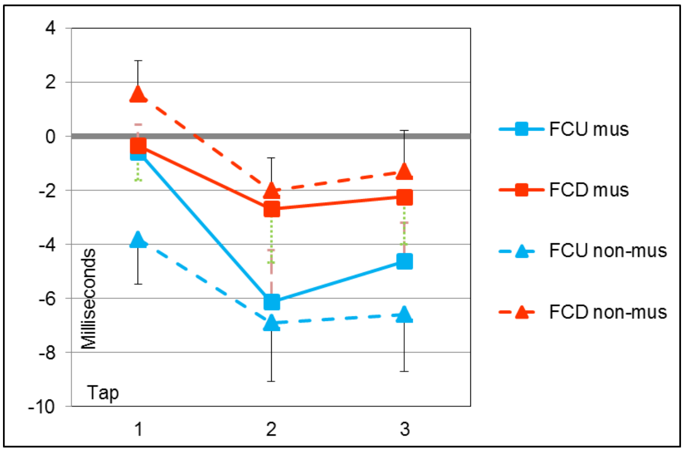

Figure 4: **First_change by MD, in musicians and non-musicians FCU – first change up; FCD – first change down.**

D. Melodic Direction Reversals

a) Overall: An ANOVA on the pooled data for melodic direction reversals (MDR: peaks and valleys in all three within-sequence ordinal positions; see Table 1B) did not show a main effect of MD on Tap 1, but two similar ANOVAs of the accumulated T{1+2} and of T{1+2+3} did show main effects of MD: peaks elicited longer ITIs than valleys (T{1+2}: *F(1,19)* = 5.804, p = .026, means – peaks: +2.4ms, valleys: -0.3ms; T{1+2+3}: *F(1,19)* = 7.357, p = .014, means – peaks: +2.7ms, valleys: -1.5ms) (see Fig. 5).

b) Ordinal position: a 2 X 2 X 3 repeated measures ANOVA (MD – peak, valley; SS – single, double; Ordinal position – early, middle, late) of Tap 1, by group, showed a main effect of ordinal position ($F(2,18)$ = 8.768, p = .002): a significant ITI shortening was elicited by early MDRs (-2.7ms, p value vs. 0: 0.029), while middle ones (and to a lesser degree late) produced delays (middle: +3.0ms, p value vs. 0: 0.0002). This effect, however, is probably confounded with that of first_change: as early MDRs were introduced on the tone following first_change, first_change's T2 – which, as reported, was tapped significantly early – was also early MDR's T1, the tap which differed most between the three ordinal positions. An ANOVA for early MDR's T{2+3} did not find any main effect or interaction.

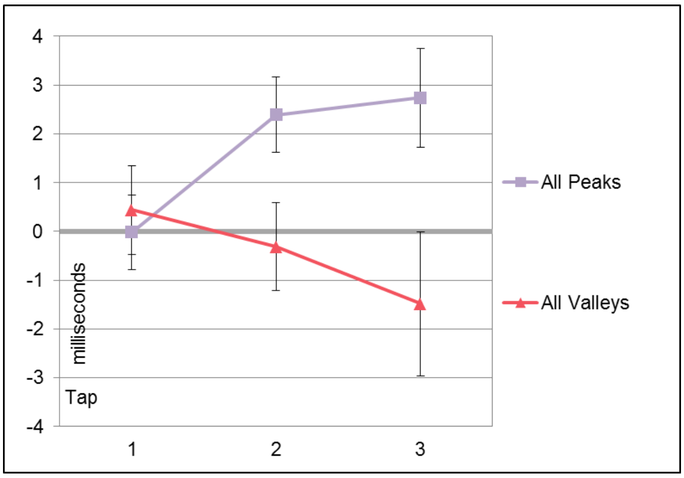

Figure 5: Responses to peaks and valleys – pooled data of all ordinal positions and step sizes.

For middle MDRs neither main effects of MD or SS, nor an interaction were found in the 2 x 2 repeated measures ANOVA. In general, in middle MDR, both peaks and valleys yielded significantly positive ITI fluctuations (effect size on T1: 0.66; on T{1+2}: 0.71; effect size on T{1+2} in non-musicians: 1.37. P values vs. 0 for middle MDRs' T{1+2} and T{1+2+3} <0.05; for T1 p = .06). On T1 peaks elicited somewhat milder delays, but from T{1+2}, peaks tended to elicit (even) longer ITIs than valleys (see Figure 6).
As a mirror image to the suspected confound of first_changes on early MDRs, an interference was suspected between late MDRs and pitch re-stabilization, being adjacent events in this

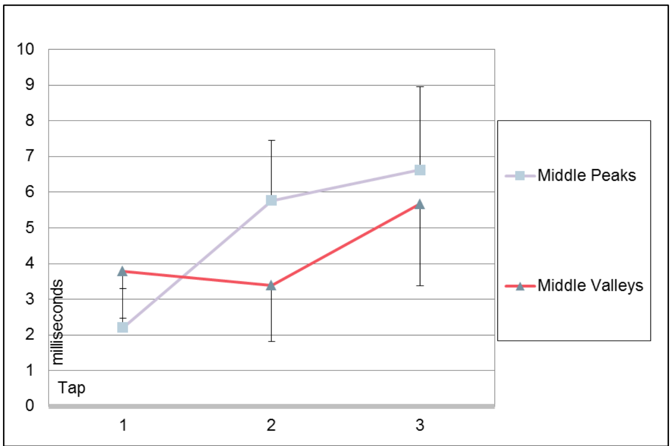

Figure 6: Responses to peaks and valleys in mid-sequence position

experiment's design. Therefore an ANOVA was run to monitor differences between T2 of late MDRs (i.e.: T1 of pitch re-stabilizations in those stimuli) and T1 of pitch re-stabilizations in other stimuli. No main effects or interaction were found. Thus, late MDRs' T1 and T2 could be analyzed similarly to middle MDRs.
In a 2 x 2 x 2 ANOVA (MD – peak, valley; SS – single, double; Tap – T1,T2) by group of late MDRs, a main effect was found for MD (F(1,19) = 8.441, p = .009). Peaks elicited longer ITIs than valleys (Peak means T1, T2: +0.6ms, +3.8ms; Valley means T1, T2: 0.0ms, -1.9ms). No main effect was found for SS and no interaction was found.
Running the ANOVA on the pooled middle- and late-MDR data (T1 and T2, not accumulated), by group, showed a main effect of MD (F(1,19) = 7.484, p = .013) and an interaction of MD and Tap (F(1,19) = 6.450, p = .020): on T2, peaks elicited significantly longer ITIs than valleys (means: +3.7ms, -0.7ms, paired t-test: p = .006; T{1+2} means: +5.0ms, +1.2ms, paired t-test: p = .014).

E. Continuous Melodic Lines

Although there were only four stimuli which did not contain any MDR or step-size_change over beeps 1 to 6 (see Table 1A), for the subjects, other stimuli were similar up to the point of change, which due to randomization was unknown. Thus, more data could be pooled to examine longer-term response development.
A repeated measures ANOVA 2 x 2 x 6 (MD – up, down; SS – single, double; Tap – 1 thru 6) was run, with data discarded gradually for each stimulus type only from the moment its melodic direction changed. On each tap, the accumulated ITI fluctuation up to that tap was calculated per subject.
A main effect of MD was found ($F(1,20)$ = 9.174, p = .007). As shown in Figure 7, upward continuous lines elicited earlier taps (means: Up -5.1ms; Down -0.8ms). No main effect was found for SS. The group variable was not significant.

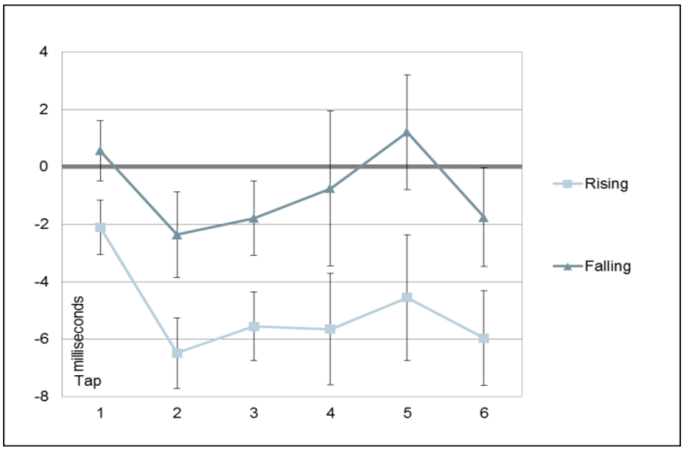

Figure 7: Responses over six taps to continuous melodic lines.

F. Step Size Change

In four stimulus types, after setting an MD at a certain pace (SS), that pace was modulated – single-to-double, or double-to-single (see Table 1C). A repeated measures ANOVA (2 x 2 x 3: MD – up, down; SS – single-to-double, double-to-single; Tap {1}, {1+2}, {1+2+3}; by group) showed no main effects of MD or SS, but interactions with group. Separate similar ANOVAs were run for musicians and non-musicians.

A main effect of SS (*F(1,10)* = 5.712, p = .038) was found among *musicians* only (see Figure 8): while single-to-double remained near the standard ITI with a peak delay on T{1+2} of +1.5ms, the double-to-single condition elicited already on T1 a delay of +2.6ms, to become +6.7ms on T{1+2} and 5.9ms on T{1+2+3}, where significance vs. single-to-double peaked (paired t-test T{1+2+3} single-to-double vs double-to-single: p = .009). Of the two sub-conditions of double-to-single – rising and falling – it was the later that elicited a stronger ITI deviation: T1 +4.8ms, T{1+2} +7.5ms, T{1+2+3} +5.7ms.

In the non-musicians' ANOVA, no main effects were found of MD or SS, but a significant interaction MD x SS (*F(1,9)* = 6.475, p = .031). While the *Rising* step-size_change (SSC) single-to-double condition averaged -4.3ms and double-to-single +3.7ms, the situation was opposite in *Falling* SSC: +4.8ms and +1.6ms respectively. Thus, in single-to-double in non-musicians, MD played a crucial role (paired t-test: p = .002). Interestingly, SSC elicited a strong response from non-musicians already on T1 in two of the sub-conditions: an ITI prolongation was recorded in rising SSC double-to-single, and in falling SSC single-to-double (+4.3ms and +5.7, respectively). These two sub-conditions may imply an increasing tendency 'downwards'.

A bewildering result is the mirror image between the two groups results within the *falling* MD by T{1+2+3} (single-to-double: non-musicians +4.8ms, musicians -1.6ms; double-to-single: non-musicians +1.2ms, musicians +5.7ms). In rising lines, on the other hand, a 2 x 3 ANOVA (SS x Tap) of all subjects showed a main effect of SS (*F(1,20)* = 5.611, p = .028): on taps T{1+2} and T{1+2+3} double-to-single elicited longer ITIs than single-to-double (means: T{1+2}: +5.9ms, -0.6ms; T{1+2+3}: +3.6ms, -4.0ms; paired t-tests: p = .056, p = .017).

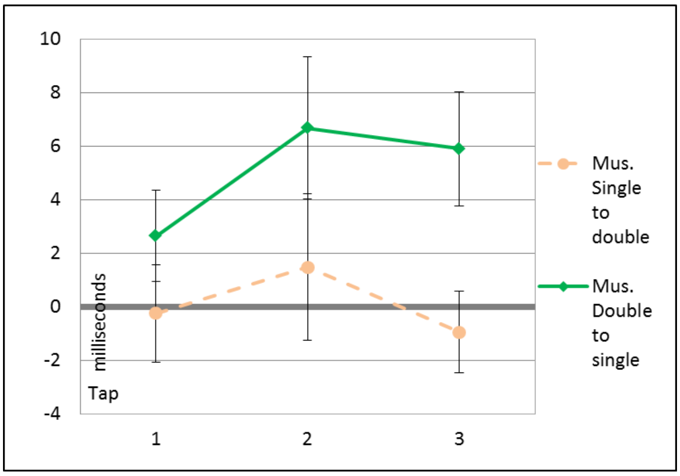

Figure 8: Mid-sequence step-size_change in musicians: single-to-double vs. double-to-single

G. Pitch Re-stabilization

The terms *up* and *down* in the pitch re-stabilization condition denote the deviation from the expected continuation of the melodic line: for example, at re-stabilization after a *descending* line, the first frequency re-iteration is perceived as surprisingly 'too high', before perception of the stopped melodic motion; therefore this condition is termed here *up*.

In the analysis of pitch re-stabilization results, data were pooled from all sequences, but those featuring a late MDR, which was presented only one tone before re-stabilization. Consequently, each value analyzed was the average of 20 responses: four stimuli (rather than 5 of same MD and SS) times five (blocks). ANOVAs (2 x 2: MD – up, down; SS – single, double) of T1, T2, and T{1+2} following pitch re-stabilizations, did not reveal any main effects or interaction. However, ITIs to all four sub-conditions [up single/double; down single/double], were significantly prolonged on T1 (mean: +1.6ms, p value of collapsed results vs. 0: .037). The delay continued on T2 (mean +2.4ms, p value vs. 0: .015). (see Figure 9).

Examining this significant prolongation revealed, that for musicians, MD's effect approached significance at T{1+2} (F(1,10) = 4.645, p = .057): a 'too high' surprise elicited yet larger ITI prolongation by the second tap (means: 'up' - +3.7ms, 'down' - +1.5ms). Though SS did not reach significance, it was up_double which elicited the strongest prolongation - +5.4ms.

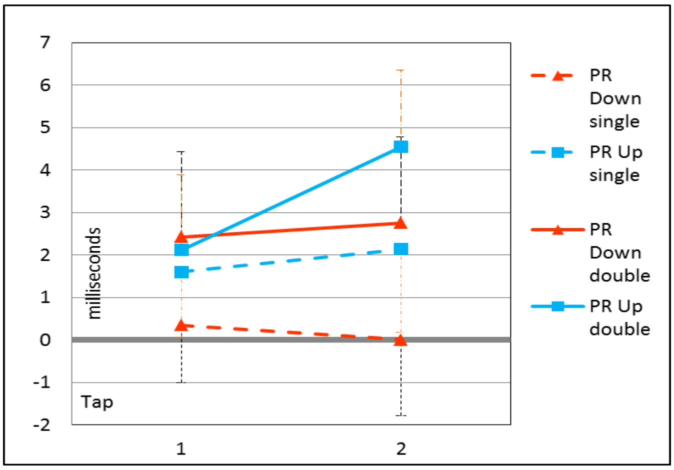

Figure 9: Pitch re-stabilization. Up & down, in single & double.

IV. A SUMMARY OF THE FINDINGS

Summarizing the results, the first pitch change in the sequence elicited a negative Inter-Tap Interval (ITI) fluctuation, becoming statistically significant two taps after the change (T2). At T1, Melodic direction (MD) was statistically significant while melodic step-size (SS) was not. MD and SS interacted: larger steps enhanced response contrast by MD, effecting rising lines more. Rising lines elicited a stronger deviation from the expected 500ms ITI, shortening it, while falling lines elicited a mild ITI prolongation. First_change upwards in double steps yielded the strongest negative ITI fluctuation response. Non-musicians showed far more differentiated responses to rising and falling melodic lines than musicians. Examining the accumulated ITI deviations on T{1+2} and T{1+2+3} showed a continued main effect of MD.

In melodic direction reversals (MDR) too, MD was more significant than SS, valleys eliciting shorter ITIs than peaks. Still, a tendency was noted for double step-size to elicit stronger responses. The results for MDR, though, should be separately examined by ordinal position, in spite of the fact that responses to early and late MDRs proved not to be significantly affected by first_changes and pitch re-stabilizations. In Early MDRs, an effect of MD appeared only by T3, and late MDRs were significantly different only on T2, where pitch re-stabilization might have had an influence. Middle MDRs may be 'purer', and there both peaks and valleys elicited a similar behavior of longer ITIs. Thus, further research may clarify MD's effect in MDRs.

In longer continuous melodic lines, a strong main effect was found for MD, rising lines eliciting significantly more negative mean asynchronies than falling lines. Shorter ITIs in rising lines on T1 and T2 were not compensated for over the next four taps, remaining about 5-6 ms 'ahead'. The relatively long time-span of this behavior (3 sec.) is remarkable. Furthermore, the similar behavior of musicians and non-musicians lends even more weight to this finding. SS did not prove significant over longer continuous melodic lines.

In step-size_change, SS proved significant in musicians only, double-to-single condition eliciting delays. In non-musicians, changes implying a 'downwards' tendency elicited significant delays: rising lines double-to-single (as if nearing a truncation of the ascent?) and falling lines single-to-double (exaggerating the downward inclination?). While in rising lines the two groups behaved alike, falling lines yielded opposite results.

Pitch re-stabilizations elicited significant delays, but no main effect of MD or SS appeared, and no interaction.

The significant ITI shortening to first_change could have been a 'surprise' response. As described in section 2.2, in the experiment's design first_change events were preceded by a long sequence of identical frequencies. But the main effect of MD calls for attention, as a surprise should have been caused by any change, with a bigger response for the bigger changes (double steps). Also the interaction between MD and group, namely the fact that musicians did not respond differently by MD while non-musicians did, is noteworthy, and perhaps opposite to expected. Musicians were not more 'attuned', 'sensitive', or 'alert' to this first_change, but rather the opposite – they seem to have suppressed, in a 'disciplined', 'professional' way, a 'natural' response to pitch change. In other words they were more able to ignore the irrelevant pitch information, suggesting a better separation of the information streams of pitch and rhythm. The sub-condition yielding the strongest response, change upwards in double-steps, reminds of the most common opening of melodies – a leap upwards, characterizing also other non-verbal communication patterns, in humans and animals. It is not unthinkable that the auditory system has a special sensitivity, or 'priority', to a stimulus of that kind. It should be added, that this 'priority' should occur in processing levels 'low enough' to execute a response within less than 500ms – perhaps *much* less: from the moment the stimulus is heard until the next tap – which itself is most of the time in negative asynchrony (several tens of milliseconds in non-musicians), minus the time needed to commit the muscle action to target – ca. 150-200ms (Yifat Prut and Michal Yoles, the Hebrew University of Jerusalem Medical School, Ein Karem Medical Center, personal communication). That gives a span of ca. 300ms.

Mid-sequence MDRs, wherein both peaks and valleys elicited delays, seem to replicate Boltz's (1998) findings – of subjects judging melodies rich with contour changes as slower than others, and Ammirante et al.'s (2011) who found longer (self-paced) ITIs under similar conditions.

The finding of continued deviation from the standard 500ms in the longer continuous lines condition is quite noteworthy, because of the ongoing beep sequence which kept 'reminding' subjects 'where the beat is'. Such a prolonged tapping sequence which is several milliseconds above or under the standard reminds of what Repp's (2001) subjects, including his non-musicians, could do surprisingly well: instantaneous 'phase resetting' in response to subliminal timing perturbations even when tapping in anti-phase . But why should events in the pitch dimension, such as a continuous rising melodic line, evoke phase resetting in the time dimension?

There are noteworthy findings in the step-size_change condition. One is musicians' 'slowing' when melodic motion rate slows (double-to-single step condition). This may fit the Ideomotor approach, the auditory Kappa effect and the "Δ" hypothesis (discussion thereof follows). The second is non-musicians' tendency to delay taps following 'downward-implying' changes – rising double-to-single, and falling single-to-double. Third, while the two groups' behaviors converge in rising lines, they differ in falling. Rising lines seem to elicit a more unanimous response, independent of musical education.

The lack of main effects at pitch re-stabilization may result from the fact that T1 already expressed the subject's realization that a period of no pitch-change has begun, while the different sub-conditions refer to a context belonging one beep ago, or, until the tap – a second ago. Still, the positive ITIs are of interest, as a sort of mirror image to the negative ITIs at first_change.

It is interesting to note free comments that were given by the subjects following the experiment. Most found the task not difficult, some found it boring. Many found synchronization to rising lines easier; some said these lines were clearer and more alerting. Several subjects thought the stimulus was not iso-chronous, and that rising lines had a faster tempo. Only a very few referred to the falling lines. Several subjects remarked they found it much easier to synchronize once they realized the stimulus was in duple (or quadruple) meter; as a matter of fact, of course, the stimulus was not in any meter whatsoever, and the 'events' could arrive on an odd or even position, due to randomization of the number of first identical pitches. This relates in an interesting manner to perception's inclination to impose a binary structure upon equi-tonal auditory stimuli ('subjective accenting', the 'Tick-Tock' effect), a phenomenon often studied in IOIs of 600ms, close to the rate in the present study (Abecasis et al., 2005). Lastly, although the Bohlen Pierce scale was used to minimize Western music connotations and tonality effect, some musicians found the double step-size sequences akin to Western diminished chords; indeed, this step-size equaled 288 cents – quite close – too close perhaps – to the Western minor third (300 cents), from which diminished chords are constructed. Luckily, of all tonal connotations, the diminished chord lends the least tonal context.

V. DISCUSSION

A. Assessing the Predictions

Of the three hypotheses offered in advance, this study's results supported the High-Urgent hypothesis most. To support the "Δ" hypothesis a main effect should have been more often shown for step-size (SS), especially perhaps to T1 following first_change; a main effect, though, was shown for SS (aside *later* taps following first_change) only in the condition which focused on 'pitch motion rate' and was devoid of novelty in MD, namely step-size_change. To support the Flexor/Extensor hypothesis, *falling* lines should have produced shorter ITIs. The results showed the opposite: whenever a main effect of MD was recorded, as in first_change and longer continuous melodic lines, *rising* lines produced stronger ITI fluctuations, and ITIs were shorter.

Several of this study's findings align with the High-Urgent hypothesis: the shorter ITIs on the three first taps to *rising* lines in first_change, and the negative 'phase shift' on *rising* longer continuous melodic lines. However, this hypothesis may not predict response to melodic direction *change*, rather than to melodic motion *initiation* following a stationary context. In the pitch re-stabilization *upward* double-step condition – where an expectation for continuing a 'strongly descending' context is confronted with a note 'too high' (though of same pitch), ITI was considerably *longer* (+4.6ms). Mid-sequence MDRs do not fit the hypothesis either, because of the similar delay response, in both groups, to peaks and valleys. The longer ITIs in some of the sub-conditions within the step-size_change condition in non-musicians may fit the hypothesis, depending on the interpretation of those conditions as 'downward implying'.

The "Δ" hypothesis could have been supported more, perhaps, if larger intervals were used in the study. Those used were small – a single step constituted a change of around 8.8% in frequency. More extreme intervals could have created, perhaps, the threat impact predicted by the Flexor/ Extensor hypothesis, but not evidenced in the present study's results. Loudness may be a relevant factor as well in creating threat. Also, more information is desired on the relation between flexing and extending muscles in the tapping action: at what pre-tap latency does activity begin? Is this latency affected by the frequency of the just-heard stimulus? Non-invasive electromyography, applied during tapping, could supply information on the roots of observed behavior, and on covert behaviors otherwise inaccessible. Further, covert muscle activity during *passive* listening to pitch events could thus be explored without the confounding synchronization mechanisms involved in tapping to a beat.

B. Melodic Direction Asymmetry in Brain Research

The present results may relate to recent findings in MisMatch Negativity (MMN) studies, exploring electric brain response to auditory stimuli deviating from a standard. Pratt et al. (2009) and Peter et al. (2010) found in humans larger MMN amplitudes to ascending frequencies than to descending ones, and Astikainen et al. (2011) showed similar MMN results in rats. These authors concluded the brain processes frequency rise and fall differently; Pratt et al. suggested relating findings to speech processing requirements, differing for consonants and vowels.

The typical MMN latency to frequency deviation, as reported in these studies, ranges from 200ms post-stimulus in change magnitudes comparable to the present study, becoming shorter in greater change magnitudes, down to 110ms. The behavioral response shown in the present study, specifically for rising double-step stimuli in non-musicians, occurred less than 500ms post-stimulus. In order to examine the dependence of this melodic direction response on the cortical MMN pattern, the next study, underway, explores earlier latencies of detection in hand/arm muscle action, by electromyographic data taken while tapping. Muscle action onset attesting a discrimination of melodic direction in latencies earlier than ca. 140ms, may suggest a lower level, 'direct', sensory-to-motor pathway.

C. Other Models

Ammirante et al. (2011), following Boltz (1998), suggested that perception 'infers' from terrestrial motion. Contour Change, therefore, inferring from 'zigzag' locomotion, elicits delays (i.e. longer ITIs), and Contour Preserving elicits 'faster' motion (i.e. shorter ITIs). Results of Mid-sequence MDRs in the present study seem to corroborate this idea, delays being elicited by both peaks and valleys. Late and early MDRs results do not 'follow the rule', but, as mentioned, the results might not be clean. First_change – setting into 'pitch motion', and pitch re-stabilization – setting into 'zero pitch motion', which elicited ITI shortening and lengthening respectively, support the Ideomotor approach as well. The MD main effect on first_change does not align with the Ideomotor 'rule', though, suggesting a more complex behavior. The sustained enhanced negative mean asynchrony in longer rising continuous melodic lines, though 'phase-shifted', does not constitute a *continuous reduction* in ITI, as predicted for Contour Preserving sequences by the Ideomotor approach. 'Faster' motion was not shown on longer falling continuous melodic lines either.

The *Imputed Velocity* model (the auditory Kappa effect: Crowder & Neath 1995, Henry & McAuley, 2009) suggests that wider melodic intervals within an isochronous context are 'interpreted' perceptually as covering a wider physical distance, therefore implying faster motion and encouraging faster behavior. This idea produces predictions similar to the "Δ" hypothesis. Only some of the present findings corroborate this idea. 'Slowing' from double to single step size while maintaining MD did produce longer ITIs but only in musicians; perhaps more pronounced step-size differences would have elicited similar behavior in non-musicians as well. The contrast between first_change and pitch re-stabilization could lend support to the Imputed Velocity idea as well: exiting 'stability' yielded faster responses and re-entering it yielded delays. But according to this model, double step-size should have elicited shorter ITIs on both MDs, while according to the results a main effect of SS in longer lines is absent. In other conditions as well, SS plays a minor role, or is tied in interactions with MD, as in FirstChange_up_double_step and in pitch re-stabilization up_double_step. Henry & McAuley (2009) do mention a trend which did not reach significance in their results for descending sequences to be more prone to the Kappa effect, but only in wider IOIs – ca. 800ms, and not in their 500ms IOI condition. They suggest this finding supports an *Auditory Gravity* model, which 'infers' acceleration onto falling melodic lines. In the findings of the present study, falling lines yielded longer ITIs than rising lines.

One more model which may explain the asymmetry between rising and falling pitch events should be mentioned, a model involving yet 'lower' mechanisms. De Cheveigné (2000) reported that subjects listening to frequency-modulated tones identified and discriminated better (five times better!) melodic peaks than troughs. In that he extended previous research by Demany and others (ibid.) about this perceptual asymmetry, in which a 'hyperacute' perception for peaks was found: in 'durationless' tones (6ms), peaks were identified within a modulated, 'moving-target' tone. De Cheveigné offers a model of peripheral mechanisms of the auditory system that could lie behind such a phenomenon. He concludes that the asymmetry stems from a temporal aspect of the pitch processing. A better discrimination could indeed 'allow' a faster tapping reaction, though of course in the present study subjects' task was not to respond fast, but rather aim at a specific point in time.

D. Musicians vs. Non-musicians

In line with the main body of tapping literature (Repp, 2010), musicians in the present study showed less ITI variability than non-musicians, and responded earlier to changes, though not always. In Repp's study, musicians corrected their synchronization to *tempo changes* faster than non-musicians, while corrections to subliminal *temporal phase shifts* were unusually quick in both groups. In the present study, significant ITI fluctuation was in some conditions delayed until T2 in non-musicians, but in some not, most notably following first_change, where a significant MD-related ITI difference was elicited in non-musicians already on T1, and in musicians only in T2. The independent variable in the present study, however, unlike in the classic tapping research, was not in the temporal dimension, while the responses were. In that sense, this study is novel.

It may be plausible that musicians' smaller variability stems not only from handling pitch 'professionally': sensitivity to tempo, acquired (and perhaps innate) synchronization skills, and an acquired ear-hand coordination may help; indeed, in the control conditions too, musicians' standard deviation was smaller. Therefore, the effect of pitch (frequency) on tapping in this study's results could have been larger if musicians' processing of pitch was not masked by their other, 'technical' skills.

E. 'Surprise' and Implicit Learning

Remington (1969) showed faster *reaction times* to repeated stimuli the longer the sequence; Squires et al. (1976), in an ERP study, found amplitudes of 'attentional' P300 components to deviant tones depended on the preceding sequence of standard tones: the longer the 'undisturbed' preceding sequence, the larger the amplitude on the deviant. Roeber et al. (2009) found also, that the longer the sequence of task-irrelevant standard-pitch stimuli, the smaller the ERP P300 component becomes, and, for their subjects' reaction-time main task, the faster the response. In a research paradigm somewhat akin to the present study, Bendixen et al.'s (2007) subjects had to perform (manually) a discrimination task (albeit a reaction-time, and not a synchronization task) in the *duration* dimension while hearing task-irrelevant pitch changes which followed rules unknown to the subjects. 'Rule violating' pitches yielded longer reaction times – 380ms vs. 330ms (as well as MisMatch Negativity and the attention-correlate P3a component), even when that rule had just emerged two pitches ago (see Lange, 2009 as well).

In order to test whether our results can be explained on the basis of a response to deviation from the expected, we examined the correlation between the identical-pitch-sequence (IPS) length preceding first_change (which varied randomly between 7 and 12 beeps) and between the ITI fluctuation on the deviant event. A mechanism related to deviation from the expected would cause a larger effect the longer the series of unchanging beeps preceding the first_change. A Pearson correlation was calculated between (the absolute) average ITI fluctuation on deviants following each IPS length and the integer series {7 to 12}. No significant correlation was found (R = .013).

Another factor which could influence results is implicit learning which may be developed along the experiment. Thus, one would predict that if 'deviation from the expected' influences ITIs, and if learning does indeed occur, then ITI fluctuation should decrease across an experimental session. A Pearson correlation between ITI fluctuation ranking, for each first_change type, over the 25 trials encountered in all blocks, and the integer series {1 to 25} was nonsignificant (absolute R values < 0.11). Implicit learning, if occurring, could also manifest itself in reduced standard deviations of ITI fluctuations over a subject's complete experiment. Standard deviations for each stimulus type were averaged in each block and ranked across blocks, per subject, and correlated with the integer series {1 to 5}. Average of the 441 Pearson correlations was insignificant (R < 0.1).

To summarize, ITI fluctuations on pitch events in the present study do not seem to have been systematically affected by 'surprise' or implicit learning.

F. The Contribution of the Present Study

The present study probed behavioral correlates of pitch. Some of its findings corroborate results obtained indirectly through other research questions and other paradigms. Ammirante et al.'s (2011) study is the closest in approach and paradigm so far, but there are important differences between the two. First of all, in the present design, the beep sequence to which the subjects had to synchronize was heard throughout the trial. This differs from Ammirante et al.'s 'continuation tapping' paradigm. The effects shown in the present study, some quite robust, were obtained therefore under a condition of a dictated isochronous stimulus. Second, while there were only five pitches in Ammirante et al.'s design which changed randomly, creating often only two-tone melodic patterns, most of the planned 'events' in the present study were set within longer contours, providing 'purer' conditions, and enabling examination of longer-term ITI developments (up to six taps), which did indeed prove significant. The first_change condition was not analyzed in Ammirante et al.'s study, while here it proved to yield insightful information; and as for pitch re-stabilization, not studied by Ammirante et al., though it did not elicit statistically significant results, it complimented the information extracted from the first pitch change event. Some intervals used by Ammirante et al. were Western – 100 and 300 cents, while in our study Western intervals were avoided. Last, musicians and non-musicians in the present study formed more distinct groups (see IIA) enabling examination of the influence of musical expertise.

VI. CONCLUSION

In spite of explicit instructions to synchronize tapping with isochronous tones sounding in their headphones, subjects deviated from the expected standard of 500ms in non-arbitrary manners, which were shown to be linked to pitch (frequency) events. Melodic direction proved to be an important factor, influencing behavior. The scale of deviations – single milliseconds – modest but robust, being averaged over thousands of taps, is subliminal; the randomization of the stimuli, within and between trials, and the short IOIs, assure an inability to 'plan'. Therefore, involuntary, subconscious mechanisms may be involved, effecting muscle action.

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REFERENCES

Abecasis, D., Brochard, R., Granot, R., Drake, C. (2005). Differential brain response to metrical accents in isochronous auditory sequences. *Music Perception, 22, 3,* 549–562.

Ammirante, P., Thompson, W.F., & Russo, F. (2011). Ideomotor effects of pitch on continuation tapping. *The Journal of Experimental Psychology, 64, 2,* 381-393.

Astikainen P., Stefanics, G., Nokia, M., Lipponen, A., Cong, F., Penttonen, M., Ruusuvirta, T. (2011). Memory-based mismatch response to frequency changes in rats. PLoS ONE, *6,9.*

Bendixen, A., Roeber, U. & Schröger, E. (2007). Regularity extraction and application in dynamic auditory stimulus sequences. *Journal of Cognitive Neuroscience, 19, 10,* 1664–1677.

Boasson, A.D. (2010). *Sound and movement interactions in infants' first Year and the sensation of motion in music listening*. M.Mus. Thesis, Tel Aviv University. (Hebrew, abstract in English, translation to English in preparation).

Boltz, M.G. (1998). Tempo discrimination of musical patterns: Effects due to pitch and rhythmic structure. *Perception & Psychophysics, 60, 8,* 1357-1373.

Crowder, R.G. & Neath, I. (1995). The influence of pitch on time perception in short melodies. *Music Perception, 12, 4,* 379-386.

de Cheveigné, A. (2000). A model of the perceptual asymmetry between peaks and troughs of frequency modulation. *Journal of the Acoustical Society of America, 107, 5 Pt. 1,* 2645-2656.

Fraisse, P. (1982). Rhythm and Tempo. In D. Deutsch (Ed.), *The psychology of music* (pp. 149-180). Orlando, FL: Academic Press.

Friberg, A., Bresin, R. & Sundberg, J. (2006). Overview of the KTH rule system for musical performance. *Advances in Cognitive Psychology, 2, 2-3,* 145-161. http://www.ac-psych.org

Henry, M.J. & McAuley, D.J. (2009). Evaluation of an imputed pitch velocity model of the auditory Kappa effect. *Journal of Experimental Psychology: Human Perception & Performance, 35, 2,* 551-564.

Hirsh, I.J., Monahan, C.B., Grant K.W., & Singh, P.G. (1990). Studies in auditory timing: 1. Simple patterns. *Perception and Psychophysics, 47, 3,* 215-226.

Huron, D., Kinney, D. & Precoda, K. (2006). Influence of pitch height on the perception of submissiveness and threat in musical passages. *Empirical Musicology Review, 1, 3,* 170-177.

Lange, K. (2009). Brain correlates of early auditory processing are attenuated by expectations for time and pitch. *Brain and Cognition, 69,* 127–137.

Morton, E.S. (1977). On the occurrence and significance of motivation-structural rules in some birds and animal sounds. *The American Naturalist, 111 (981),* 855-869.

Ohala, J.J. (1984). An ethological perspective on common cross-language utilization of F0 of voice. *Phonetica, 41,* (1984), 1-16. Germany: Karger.

Penel, A. & Drake, C. (2004). Timing variations in music performance: Musical communication, perceptual compensation, and/ or motor control? *Perception & Psychophysics, 66, 4,* 545-562.

Peter, V., McArthur, G., & Thompson W.F. (2010). Effect of deviance direction and calculation method on duration and frequency mismatch negativity (MMN). *Neuroscience Letters, 482,* 71–75.

Pratt, H., Starr, A., Michalewski, H.J., Dimitrijevic, A., Bleich, N., & Mittelman, N. (2009). Auditory-evoked potentials to frequency increase and decrease of high- and low-frequency tones, *Clinical Neurophysiology, 120,* 360–373.

Prince, J.B., Schmuckler, M.A. & Thompson, W.F. (2009). The effect of task and pitch structure on pitch–time interactions in music. *Memory & Cognition, 37, 3,* 368-381.

Remington, R.J. (1969). Analysis of sequential effects in choice reaction times. *Journal of Experimental Psychology, 82, 2,* 250-257.

Repp, B. (1995). Detectability of Duration and Intensity increments in melody tones: A partial connection between music perception and performance. *Perception & Psychophysics, 57, 8,* 1217-1232.

Repp, B. (2001). Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance, 27, 3,* 600-621.

Repp B. (2005). Sensorymotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review, 12, 6,* 969-992.

Repp, B. (2010). Sensorimotor synchronization and perception of timing: Effects of music training and task experience. *Human Movement Science, 29,* 200–213.

Roeber, U., Berti, S., Müller, D., Widmann, A., & Schröger, E. (2009). Disentangling effects of auditory distraction and of stimulus-response sequence. *Psychophysiology, 46,* 425–438.

Squires, K., Wickens, C., Squires, N. & Donchin, E. (1976). The Effect of Stimulus Sequence on the Waveform of the Cortical Event-Related Potential. *Science, 193,* 1142-1146.

Tekman, H.G. (2001). Accenting and detection of timing variations in tone sequences: Different kinds of accents have different effects. *Perception and Psychophysics 63, 3,* 514-523.

van Noorden L. & Moelants, D. (1999). Resonance in the Perception of Musical Pulse. Journal of New Music Research, 28, 1, 43-66.