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RESEARCH REPORT

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The effects of metronomic pendular adjustment versus tap-tempo input on the stability and accuracy of tempo perception

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Abstract This study explores tempo stability and accuracy while comparing two subject-response modes: the traditional metronomic pendular adjustment task versus tap-tempo input. Experiment 1 questioned if a single correct tempo measurement consistently emerges from repeated listenings, and if subject-response mode affects tempo stability and accuracy. Experiment 2 assessed incremental improvement between two repeated sessions, and questioned the incidence of self-pacing or congruent effects of potential delays on tempo responses. While single-session studies have shown that listeners find some tempos more enjoyable, can notice discrete differences in pace, and can remember rhythmic speed over prolonged periods of time, the current study employs a multiple-session format focusing on two diametrically opposed subject-response modes. The findings show that tempo responses by listeners without formal music training were consistent across listening sessions, and that responses from tap-tempo input were significantly more stable and accurate than responses from metronomic pendular adjustment tasks.

Keywords Tempo stability · Tempo accuracy · Tracking · Metronomic pendular adjustment · Tap-tempo input

Introduction

When listening to music we often respond by tapping our feet, dancing, or snapping our fingers. In doing so, we are carried along by a fundamental characteristic of rhythm called *pulse*. Pulsations or ticks which occur at regular time intervals are referred to as *beats*, and the average number of beats occurring over a given period (usually beats per minute or "bpm") cause us to feel the prevailing pace of a musical piece referred to as beating speed or *tempo*.

Temporality lies at the heart of performance, and therefore to some extent, the effect of music on everyday listeners depends on the choice of speed with which it is to be performed. For instance, if a piece is performed too slowly, the beat can disappear, but if performed too quickly the successive beats may become indistinguishable (Boltz 1998; McAuley and Semple 1999). Personal interpretation of tempo is evident and well documented (Wapnick 1987). One example is Beethoven's *Funeral March* (Third Symphony), which, although written to be performed at 80 bpm (roughly 12.5 min of music), was regularly conducted by Koussevitzky at 74 bpm (a decrease in speed of 7.5% taking 13.5 min), by Beecham at 62 bpm (a decrease in speed of 22.5% taking 16 min), and by Toscanini at 52 bpm (a decrease in speed of 35% taking 19 min) [the *Musical Times* (1935) in Scholes 1972, p. 1017]. From a cognitive point of view, what seems to matter is not the actual tempo adopted in the performance, but the tempo listeners are led to imagine they are hearing (Dowling and Harwood 1986; Gabrielsson 1988). Highly rhythmic performances at a slow speed can give the impression of being quicker than really quicker ones with less rhythmic activity. As a result of such subjectivity, the perception and subsequent judgment of temporal pace have been a topic which has preoccupied researchers for over 80 years.

Since the early 1920s, studies investigating tempo ratings have attempted to determine if specific compositions are perceived to have a "correct" pace (Brown 1979; Hevner 1937; Lapidaki 2000), if some tempi are more enjoyable than others (LeBlanc 1981; LeBlanc and McCrary 1983; Sims 1987), if discrete tempo differences and shifts in pace are noticeable (Drake and Botte 1993), or if rhythmic speeds are remembered over prolonged periods of time (Levitin and Cook 1996). Several extensive reviews are available elsewhere (Boltz 1998; Brown 1979; Dowling and Harwood 1986; Ellis 1991; Lapidaki 2000). Reviews in the literature illustrate the

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empirical methods used to study tempo ratings, and these seem to have changed over time. Partially, such developments have had to do with the expansion of audio recording and playback methods. When looking at these trends in retrospect, the reliability of studies before 1980 becomes debatable. For example, studies before 1950 appear to have had a tempo bias reflecting yesteryear's preference for faster tempi as a result of quicker speeds that were adopted to fit performances on the short ''side length'' of shellac records (Bowen 1999; Johnson 2002). Moreover, studies between 1950 and 1980 may contain more than an acceptable level of ''perceptual noise'' as a by-product of analog recording and reproduction formats (for example, the gramophone, phonograph, reel-to-reel, eight-track cartridge, and compact cassette tape player), which were all subject to speed fluctuations of ±5% (Levitin and Cook 1996). Clearly, temporal speed was accurately preserved only from the mid-1980s, when digital platforms of music recording and reproduction became a new standard. Finally, reviews in the literature also illustrate that, for the most part, tempo studies have employed metronomic or pendular adjustment tasks, while only a few have employed motor production tasks such as tapping the beat. It is this later issue which is an overriding focus of the current study.

Early experiments (ca. 1900–1955) had listeners tap on a telegraphic key (Frischeisen-Kohler 1933; Harrison 1941; Rimoldi 1951; Wallin 1911a, b); their responses were captured (i.e., recorded to a shellac disk or reel-to-reel audio tape) and then compared to metronomic clicks as calibrated by the experimenter. Other studies had listeners judge which set of clicks (each originating from a different metronome proceeding at a distinctive speed) was most appropriate for a particular melody (either heard from a live performance or reproduced from a gramophone/phonograph recording). Later studies (ca. 1955–1980) had listeners report their preferred tempo between two tempo versions of the same piece (either heard from a live performance or as reproduced from a compact cassette tape recording), or judge whether the second piece was similar/different or faster/slower than the first; their responses were noted on an answer sheet (Geringer 1987; Geringer and Madsen 1984; Handel 1993; Hevner 1937; Kuhn 1987; Wapnick 1980; Yarbrough 1987). Other studies had listeners determine the tempo appropriateness of automated music (either heard from a player-piano or an electric organ), and then if necessary, modify the music via manual adjustment of a lever or panning knob to the left for deceleration or to the right for acceleration (Behne 1972; Farnsworth et al. 1934); their responses were either noted on an answer sheet or captured (on compact cassette tape) and then compared to metronomic clicks as calibrated by the experimenter. More recent studies (ca. 1980–2002) employ computer software interfaces featuring continuous variable control over music in ''real time.'' With this technology, listeners evaluate the tempo appropriateness of audio files (either heard via PC speakers or stereo headphones), and then if necessary, modify the heard music by adjusting a ''slider'' button viewed as a pictograph on a computer screen with a mouse-pointing device (Lapidaki 2000; Lapidaki and Webster 1991). In other studies, listeners tap in synchrony to a click track (or to music heard aloud), and then either continue the sequence in the original tempo or manipulate a tempo transformation including alterations such as acceleration, deceleration, doubling, or halving the beat (Drake et al. 1997; Franek and Mates 1997; Franek et al. 1998, 2000; Yoner and Yamda 1998). Finally, a few studies have looked at the mind's ability to retain tempo information by comparing the metronomic adjustments of imagined versus heard-aloud traditional folk songs (Halpern 1988), or digitally recorded pop songs sung from memory to the actual tempos on commercial CDs (Levitin and Cook 1996; Reed 2002).

The general picture that emerges from the literature is that ordinary listeners are fairly consistent in both their tempo judgments and preferred tempo rates, that variances of detection accuracy are fairly dependent on the initial tempo (IT) [slow IT (<80 bpm) versus fast IT (>120 bpm)], and that threshold differences for detecting tempo changes co-vary with the temporal movement of the target tempo (TT) [acceleration (IT<TT) vs. deceleration (IT>TT)] (Drake and Botte 1993; Ellis 1991; Franek et al. 2000; Geringer and Madsen 1989; Jones and Yee 1997; Kuhn 1974; Madsen 1979; Vos et al. 1997; Wang and Salzberg 1984; Yarbrough 1987; Wapnick 1980). Moreover, imagined tempo ratings are almost consistent (Halpern 1988), and tempo memory for familiar pop songs is fairly precise (Levitin and Cook 1996; Reed 2002).

Nevertheless, viewing this body of literature in retrospect, one cannot but question the integrity of some of the more accepted methodological features employed over time. For example, there are questions of music exposure and data collection (i.e., single session vs. repeated measurement over time), as well as questions about the ecological validity of empirical tasks and devices used for data collection (i.e., perceptual vs. production response modes). Regarding the former issue, it appears that the majority of tempo studies have typically collected data in a single session, and report a fairly accurate level of skill. Yet, the few studies which employ data collection from multiple sessions report that tempo for particular pieces varies dramatically from session to session, and while many listeners do demonstrate tempo stability over time, they are not necessarily very accurate (Lapidaki 2000; Lapidaki and Webster 1991; Reed 2002).

The second issue concerns subject-response tasks employed in tempo studies. For the most part, these include comparison of click tracks, alignment of levers, tweaking of panning knobs, adjustment of slider buttons, adjustment of pendular weights, fine-tuning of LCD settings, and verbal assignation. It is imperative to question if these tasks are ecologically valid representations of tempo perception. For example, Wohlschlager and Koch (2000) point out that from a psychophysics frame of mind that such tasks require the listener to generate regular periodic actions (i.e., pendular adjustments) at a tempo matching the tempo of an external stimulus (i.e., music heard aloud), while disregarding other external pacing signals (i.e., metronome clicks). Then, both the frequency and phase of the oscillation (i.e., detection and compensation of the phase shift) must be controlled in order to achieve a perfect synchronization. Therefore, the process involves the simultaneous monitoring of several tasks, some of which are attending to the musical stream, physical manipulation of an apparatus, monitoring disparity of the stream with a beat, and iteration of adjustment routines. Such mental processes might not necessarily be an essential part of tempo perception per se, and may in fact interfere with cognition that relates to perspicacity. This issue is raised in light of the accepted developmental lines related to musical skills (Andress et al. 1979; Dowling and Harwood 1986; Greenberg 1979; Hargreaves 1986; Malbran 2002; Zimmerman 1971). Accordingly, the portraiture of tempo is to be found in performance-based motor responses grounded in aural tracking and movement synchronization. Clearly, the ability to synchronize requires codification of duration, and this ability involves different subskills including "tactus tracking of the musical fragment, flexibility and fluency in the tapping motion, and the distribution of onsets in time" (Malbran 2002, p. 72). The correspondence and sustainability of tactus tracking, that is tapping in time to the pulse beat, demand attention and maintenance throughout the performance. Since 1752, music instrument teachers have viewed foot-tapping as an aid in the development of pulse (Karpinski 2000, p. 155). Further, for more than half a century, music theory instructors have employed simultaneous hand-tapping accompaniment to sight-singing as part of ear-training procedures (outlined by Hindemith 1949; Starer 1969). Taking the above into account, one could surmise that tap-tempo tasks represent tempo perception in a more valid fashion, and that even among listeners without formal music training (regardless of social class, ethnic background, or religion), motor responses involving clapping or tapping the beat are familiar actions stemming from experiences which cross the developmental gamut of the human life span.

On the surface, perceptual and production-tracking tasks do not seem to be comparable as they are not analogous modes. Purely from a psychophysics point of view, the former does not necessarily measure phase relationships, while the later is undoubtedly a measure of in-phase synchronization with the music. Nevertheless, it is prudent that researchers find the best conditions engendering more or less accurate performances, given the nature of the temporal tasks needed to study tempo. The current study, then, investigated the perception of music tempo within a repeated session paradigm in an attempt to evaluate the effects of metronomic pendular adjustment versus tap-tempo input tasks on the stability and accuracy of temporal responses.

Experiment 1

Experiment 1 attempted to answer two questions: does a single correct tempo emerge from repeated exposures of prerecorded commercially available CDs? Does the mode of subject response (metronomic adjustment versus tap-tempo input) influence tempo stability and/or accuracy?

Method

Participants

Twenty-nine ($n = 29$) undergraduate students enrolled in music appreciation courses volunteered in return for extra credit points; the majority (79%) reported that they had not had previous formal music education including instrument tuition. The students were between the ages of 21 years and 28 years (mean = 23.5, SD = 1.5), with a predominant proportion (83%) of females.

Stimuli

Sixteen experimenter-selected music items were used in the study: one practice trial and a block of 15 items. The pieces were specifically chosen because of their compliance to metric regularity, temporal predictability, and magnitude of melodic activity (i.e., changes in contour and pitch jumps). These factors are important because melodic structure is able to induce perceptual temporal differences even when none exist (Kuhn 1987). For example, a melodic pattern which seems to be temporally disjointed and unrelated is perceived to unfold at a slower pace than a melody with compatible rhythmic structures, while a melodic pattern containing relatively few changes in contour and pitch skips is judged as unfolding at a quicker pace than a melody containing more changes in pitch direction and a greater magnitude of pitch skips (Boltz 1998). The current set of stimuli included both vocal and instrumental genres in light of anecdotal evidence that language and syllabic structure of texts relate to the articulation of singers and might influence tempo association (Brown 1979). In total, there were three symphonic pieces, four Israeli popular songs (three vocals, one instrumental), and nine American popular songs (seven vocals, two instrumentals). A list of the items appears in Table 1. All pieces were in a duple meter (2/4 or 4/4) with tempos between 61 bpm and 133 bpm (mean = 100.5 bpm, SD = 24.17 bpm). It should be pointed out that the stimuli used were well within the tempo range between 48 bpm and 150 bpm [or 400–800 ms inter-onset interval (IOIs)], which has been found to be the most precise zone for tempo responses (Drake and Botte 1993; Franek and Mates

Table 1 Music stimuli used in the study

Music type	Composer/performer	Item title	Tempo (bpm)
Classical music	F. Mendelssohn	*Symphony no. 4* (second movement)	67
	J.S. Bach	*Orchestra suite no. 2* (Badinerie)	131
	A. Vivaldi	*Concerto In A Minor For 2 Violins*, (first movement)	97
Easy listening	The Mantovani Orchestra	"Look What They've Done To My Song Ma"	82
Light jazz-samba	Spyro Gyra	"Morning Dance"	101
Gershwin covers	Jon Bon Jovi	"How Long Has This Been Going On"	64
	Robert Palmer	"I Got Rhythm"	114
Rap/hip-hop	Quad City DJ	"Space Jam"	133
	Robin S	"Givin' You All That I've Got"	124
	Will Smith	"Wild Wild West"	109
Top-ten billboard	Dolly Parton	"9 To 5"	105
	James Ingram and Michael Mcdonald	"Yah Mo B There"	116
	Yehuda Poliker/Benzin	"Friday"	74
	Itzhak Klepter	"Come Here, Sunshine"	61
	Itzhak Klepter	"Freedom, Understanding, and Love"	111
	Itzhak Klepter	"A Walk in Tel-Aviv"	124

1997; Franek et al. 1998). All items were edited for length from their original CD tracks; each item was of a 90-s total exposure including a 10-s fade-out trailer. The stimuli were heard at a standard listening level (±65 dBA) in an effort to offset interaction effects between volume and perceived speed (Hirsch et al. 1956; Kellaris and Altsech 1992; Kellaris and Rice 1993; Kellaris et al. 1996; Wolfe 1983).

Apparatus

The study specifically focused on two metronomes: (1) *Cadenzia* Swiss-made (since 1944) analog pendular pocket-watch metronome (see Fig. 1). *Cadenzia* is a modified balanced-wheel watch capable of several revolutions with an adjustable "hairspring" permitting adjustments between MM = 40 and 208 bpm. *Cadenzia* features a double-weighted pendulum (i.e., weights on each side of the pivoting centered baton), with a small tempo hand marking oscillation rate, calibrated in continuous adjustments in real time by a thumbwheel. (2) *Korg MA-20* digital compact metronome (see Fig. 2). *Korg* has complete functionality for accurate (±0.2%) tempo production and display, with accompanying sound clicks (413–450 Hz) enabled or muted. *Korg* features a tap-tempo input function allowing for data entry by tapping four regular pulse beats, with intertap intervals calculated by algorithm and transformed to tempo rates between MM = 40 and 208 bpm, displayed on an LCD screen.

Design and test presentation

The study employed a single factor within-subjects repeated-measures design. The participants were four times exposed to a block of 15 items: one block per session, two sessions per metronome, totalling four sessions scheduled 1 week apart. The item sequence was reversed between sessions (i.e., ascending, descending,

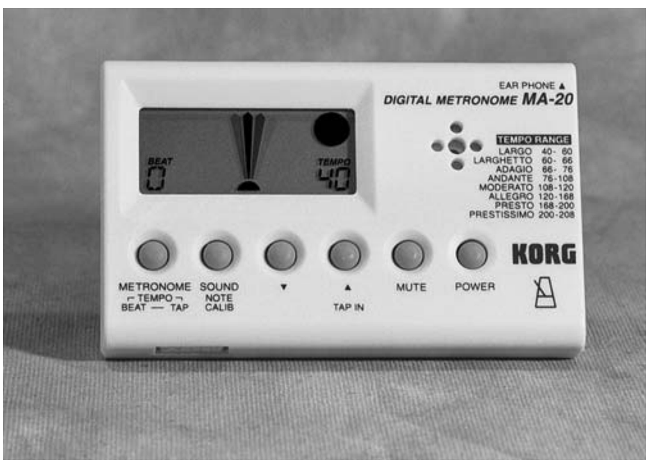

Fig. 1 *Korg* MA-20 compact digital metronome. (Photo: Dani Machlis)

Fig. 2 *Cadenzia* analog pocketwatch metronome. (Photo: Dani Machlis)

ascending, descending sequence) to offset effects of presentation order.

Procedure

Each session ran for approximately 30 min. All four sessions were identical with one exception: in the first session, a consent form was signed and a practice trial (“9 To 5” by Dolly Parton) was performed. During the sessions, the participants sat alongside the experimenter who instructed them to adjust the metronome pendulum (*Cadenzia*) or tap four regular pulse beats (*Korg*) as accurately as possible in the shortest amount of time. It was suggested that they tap a foot in time along with the music, as a guide. On a typical trial, each participant was exposed to the following sequences of events: the participant was handed a preset metronome. *Cadenzia* was preset to MM = 90 bpm resulting in a “12 o'clock” position of the tempo hand; *Korg* was preset to a mute tap-tempo input operation resulting in a blank LCD screen. Then, the first item of the 15-item block was heard. In the shortest possible time, the participants adjusted the pendular oscillation speed of the metronome (or tapped four regular beats) according to the tempo of the heard music, and then handed the metronome back to the experimenter, who logged the tempo setting on an answer sheet along with a note value equalling one beat. The metronome was subsequently reset to the initial default settings, and passed to the participant. The procedure was repeated another 14 times for the full 15-item block.

Critical perceptual thresholds

Measuring the consistency of tempo responses (i.e., stability of repeated measurement), or the accuracy of rhythmic tracking (i.e., exactness to the original beat) most certainly concerns critical perceptual thresholds related to pulse variance. Yet, the literature is fairly diverse and unequivocal on this subject. For example, the just notable difference (JND) for detecting two dissimilar tempos, or changes in tempo, has been reported as 2–3% (Povel 1981), 6–8% (Drake and Botte 1993), 5–10% (Woodrow 1951), and 6–13% (Ellis 1991). Reed (2002) claims that all deviations within 5% from the original tempo should be regarded as “hits,” and while deviations between 5% and 10% would also be regarded as rather good, deviations greater than or equal to 10% represent a noticeable tempo difference. However, Levitin and Cook (1996) teased out four thresholds based on distinctive response tasks: 3–4% for tapping tasks, 4.5% for adjustment tasks, 6% for tasks requiring perception of time-marker displacement, and 6–8% for alternative forced-choice comparison tasks. In view of the above, the current study set the critical threshold for the reliability of tempo ratings at 4–5% for metronomic pendular adjustment and 3–4% for tap-tempo input. Although it must be recognized that these thresholds of pulse variance exclusively serve in a descriptive capacity for the sake of comparing between subject-response modes, within the context of the study, the aforementioned limits represent a “standard unit,” hereafter referred to as pulse variance units (PVUs).

Results

Prior to the analyses, item beat values were standardized to a “quarter note” (i.e., the beat level). That is, in the event that listeners' spontaneous focus in the sequence (i.e., their referent level) was equal to a “half note,” the tempo data were multiplied by two, while if the focus in the sequence was equal to an “eighth note,” the data were divided by two. This standardizing procedure accounts for the fact that perception of beat from musical rhythms may target different levels of the hierarchical metrical structure obtained by subdivision and/or multiplication of the same sequence, each based on equal time intervals known as the pulse (Drake et al. 2000; Malbran 2002; Yoner and Yamda 1998).

Regarding the question of tempo consistency across repeated trials, the findings confirm that tempos were fairly consistent on each of the two session pairs for both metronomic pendular adjustment ($r = 0.73$, $P < 0.05$) and tap-tempo input ($r = 0.85$, $P < 0.05$); there was no difference in reliability between the two task modes ($z = 1.18$, NS). Moreover, no differences in average item tempo were found (metronomic pendular adjustment: mean = 100.25 bpm, SD = 3.42 bpm; tap-tempo input: mean = 101.65 bpm, SD = 2.54 bpm). In general, such findings seem to indicate that listeners without formal music training are capable of demonstrating a more or less stable tempo response from repeated exposures to prerecorded commercially available CDs. Yet, no correlation of average item tempos between metronomic pendular adjustment and tap-tempo input was found ($r = 0.01$, NS), and hence analyses turned to the question of differences between the two modes.

To compare the consistency and accuracy of tempo-tracking responses between the two task modes, differences in individual items between sessions were calculated. These actual differences (in number of beats per minute) were then transformed to a Weber Ratio representing a proportion value equal to the percentage of difference (see Table 2). The results show that tempo responses were highly more consistent and accurate when listeners employed tap-tempo input than when they employed metronomic pendular adjustment. Table 2(A) illustrates that listeners' responses were significantly more stable (i.e., less beats apart between session pairs) from tap-tempo input tasks. That is, the differences between the sessions employing tap-tempo input fell within 1 PVU, whereas the differences between the sessions employing metronomic pendular adjustment were above the critical threshold. A similar second analysis was carried out comparing the tempos noted to the targeted tempo-standard (i.e., the actual tempos

Table 2 Experiment 1: stability and accuracy of tempo responses

	Pendular adjustment		Tap-tempo input		*t*	*df*	*P*
	Mean	SD	Mean	SD			
A. tempo stability across sessions (consistency of tempo responses)							
Numeric[a]	6.09	2.16	3.93	3.33	3.52	28	0.01
Percentage[b]	6.30	2.23	3.84	3.03	4.04	28	0.001
B. Tempo accuracy to standard (distance between final adjustment and TT)							
Numeric[a]	6.67	4.26	3.08	2.80	4.33	28	0.001
Percentage[b]	7.04	4.30	3.07	2.84	4.96	28	0.0001

[a]Mean beats apart
[b]Difference (%)

heard on the original CDs as listed in Table 1). As can be seen in Table 2(B), listeners' responses were significantly more accurate (i.e., proportionally closer to the tempos as heard on the CDs) from tap-tempo input. That is, differences between the tempo responses and the targeted tempo standard from tap-tempo input fell within 1 PVU, while responses from metronomic pendular adjustment were above the critical threshold.

Given the wide array of tempos within the 15-item set (48–150 bpm), one might suspect that the aforementioned finding is an artifact related to particular items within a specific tempo zone. In fact, several researchers (Drake and Botte 1993; Ellis 1991; Franek et al. 1998; Jones and Yee 1997) have found that the sensitivity magnitude for differences between tempi depends on the tempo zone in which the tracking task is preformed. Accordingly, the music context itself has quite powerful consequences to either enhance or degrade listeners' sensitivity. Further, Brodsky (2002) found specific interaction effects of music tempo zones on perceptual motor control. For that reason, further analysis was conducted on the 15-item set variegated by three tempo zones: slow tempo (< 80 bpm, mean = 66.5 bpm, SD = 5.56 bpm, four items), medium tempo (80–120 bpm, mean = 104.3 bpm, SD = 11.96 bpm, seven items), and fast tempo (> 120 bpm, mean = 128 bpm, SD = 4.64, four items). To compare the consistency and accuracy of tempo-tracking responses between the two task modes as differentiated by tempo zone, the data were entered into a one-way within-subjects repeated-measures analysis of variance (ANOVA). The results demonstrate a significant interaction between the zone and stability for metronomic pendular adjustment ($F_{(2,56)} = 10.319$, MSE = 9.3695, $P < 0.001$), indicating significantly less stable rhythmic tracking in slower tempi. The results also demonstrate a significant interaction between the zone and accuracy for metronomic pendular adjustment ($F_{(2,56)} = 7.5092$, MSE = 23.641, $P < 0.01$), indicating significantly less accurate rhythmic tracking in slower tempi (see Table 3). As can be seen in Table 3, in faster tempi, responses from tap-tempo input are fairly more consistent and significantly more accu-

Table 3 Experiment 1: stability and accuracy of tempo responses variegated by tempo zones

	Pendular adjustment		Tap-tempo input		*t*	*df*	*P*
	Mean	SD	Mean	SD			
A. Tempo stability across sessions (consistency of tempo responses)							
Slow tempo (> 80 bpm)							
Numeric[a]	5.78	2.91	2.41	2.19	5.39	28	0.00001
Percentage[b]	8.46	4.63	3.53	3.26	4.88	28	0.0001
Mid tempo (80–120 bpm)							
Numeric[a]	6.14	2.76	4.14	3.56	2.90	28	0.01
Percentage[b]	5.83	2.59	4.12	3.68	2.30	28	0.05
Fast tempo (> 120 bpm)							
Numeric[a]	6.29	3.61	5.09	4.72	1.18	28	NS
Percentage[b]	4.94	2.73	3.65	2.76	2.01	28	NS
B. Tempo accuracy to standard (distance between final adjustment and TT)							
Slow tempo (> 80 bpm)							
Numeric[a]	6.70	4.99	2.18	2.18	5.83	28	0.00001
Percentage[b]	10.46	7.64	3.24	3.22	5.79	28	0.00001
Mid-tempo (80–120 bpm)							
Numeric[a]	6.04	4.56	2.87	2.40	3.68	28	0.001
Percentage[b]	5.80	4.28	2.79	2.50	3.65	28	0.001
Fast tempo (> 120 bpm)							
Numeric[a]	7.74	6.85	4.34	4.85	2.19	28	0.05
Percentage[b]	6.06	5.36	3.39	3.81	2.20	28	0.05

[a]Mean beats apart
[b]Difference (%)

rate than metronomic pendular adjustment; in medium tempi, responses from both task modes are just as consistent but responses from tap-tempo input are significantly more accurate than from metronomic pendular adjustment; and in slower tempi, responses from tap-tempo input are significantly more consistent as well as significantly more accurate than metronomic pendular adjustment.

An interesting characteristic tempo response reported in the literature is a directional bias effect resulting from the temporal movement of the TT. That is, when the movement between the IT and TT is decelerated (i.e., IT > TT), listeners tend to underestimate the tempo (−bpm), but when the movement is accelerated (i.e., IT < TT), then listeners tend to overestimate the tempo (+bpm). While this phenomenon is not a primary issue of the current investigation, finding such effects in a subject-response mode might point out counter-indications in future tempo research protocols. Therefore, an analysis of metronomic pendular adjustment as a subject-response mode was carried out (see Table 4). It should be pointed out that such effects are exclusive to pendular metronomes as tap-tempo input does not involve external pacing signals such as metronomic clicks or pendular (baton) oscillations. Hence, in comparison to pendular metronomes, tapping has been reported (Franek et al. 2000) to be a relatively neutral response mode that is free of temporal biases. As can be seen in Table 4, the results of the current study confirm such directional biases: the direction of the TT not only caused explicit error types (underestimation vs overestimation), but also caused listeners to be nearly twice as inaccurate when temporal movements decelerated.

Discussion

The findings of experiment 1 substantiate that listeners without formal music training are able to determine the tempos of music heard aloud, and that they do so quite consistently and fairly accurately not only on one occasion, but rather repeatedly—time after time after time. The results indicate that stability and accuracy of responses are somewhat dependent on the mode of subject response. Most specifically, the study found that tap-tempo input is a more reliable representation of tempo perception than metronomic pendular adjustment. These findings were uniform in analyses which considered the complete item set despite their great tempo variability, as well as in analyses which considered smaller item subsets variegated by tempo zones. Therefore, it might be concluded that the employment of tap-tempo tasks is ecologically more valid as a methodological procedure to measure tempo than metronomic pendular adjustment tasks. This conclusion is especially true for slower tempi in which the study found metronomic pendular adjustment to be particularly vulnerable for tempo inconsistencies and inaccuracies, as well as regarding decelerated temporal movements to which the study found directional biases. Finally, the results point to a nonsignificant correlation between the two tasks, which might not only account for variances between the tasks, but be indicative of the extent to which the two modes do not embody the same level of perception, production, and/or measurement of tempo.

Nevertheless, two factors might have contributed to the above reported differences between the subject-response task modes. First, as improvements in tempo responses across sessions have already been reported (Drake and Botte 1993), there may have been an element of practice through repeated exposure. Second, responses may reflect a degree of self-pacing or congruent effects of potential delays. To rule out these possibilities, experiment 2 was conducted.

Experiment 2

Experiment 2 attempted to answer two questions: is tap-tempo input a more reliable measure of tempo perception (as reported in experiment 1), or do listeners simply get better at tapping the beat with practice? Does music tempo influence listeners' pacing of task performance and subsequent response-completion time?

Method

Participants

Twenty-three ($n = 23$) undergraduate students enrolled in music appreciation courses volunteered in return for extra credit points; the majority (74%) reported that they had not had previous formal music education including instrument tuition. The students were between the ages of 20 and 25 years (mean = 22.9, SD = 1.70), with a predominant proportion (73%) of females.

The stimuli, apparatus, design and test presentation, procedure, critical perceptual thresholds, and analyses employed in experiment 2 were identical to those of

Table 4 Experiment 1: effects of temporal movement (IT: MM = 90)

	Deceleration IT > TT		Acceleration IT < TT		*t*	*df*	*P*
	Mean	SD	Mean	SD			
Pendular adjustment							
Numeric[a]	−3.24	4.00	2.04	4.73	4.58	28	0.001
Percentage[b]	9.51	7.23	5.80	4.66	2.57	28	0.05

[a]Mean beats apart
[b]Difference (%)

experiment 1, but with three exceptions: (1) participants were exposed only twice to the 15-item block, with sessions scheduled 1 week apart; (2) the procedure required the participants to adjust a metronome pendulum or tap four regular beats, each for half of the items in the block in alternation, whereby in the second session, both the block and tasks were reversed (i.e., ascending/descending presentation orders swapped, and adjusted/tapped items mirrored); and (3) response-completion times (RTs) were logged for each item. It should be noted that within the context of Experiment 2, RTs refer to the time between the onset of the heard music and task completion, as visually indicated by the time elapsed on the chronometer display of a PC-controlled media player.

Results

Item pulse beat values were standardized to a quarter note. Then, average item tempos and RTs were calculated. To answer the question if tap-tempo input is actually a more reliable measure than metronomic pendular adjustment or rather do listeners simply get better at tapping, whereas they might not improve at adjustment tasks, the analysis focused on comparing between two repeated sessions 1 week apart. The results show no differences in the average item tempo for the total 15-item set between the sessions (session 1: mean = 99.95 bpm, SD = 2.63 bpm; session 2: mean = 101.52 bpm, SD = 3.06 bpm), nor for average item RTs between the sessions (session 1: mean = 16.40 s, SD = 4.40 s; session 2: mean = 15.33 s, SD = 3.59 s). Moreover, the consistency of responses between sessions was high for both the actual tempos ($r = 0.56$, $P < 0.05$) and RTs ($r = 0.79$, $P < 0.05$). Subsequent analysis comparing between the task modes revealed no apparent differences in average item tempo (metronomic pendular adjustment: mean = 99.35 bpm, SD = 4.53 bpm; tap-tempo input: mean = 101.12 bpm, SD = 1.74 bpm); but again no correlation was found ($r = 0.12$, NS). Nevertheless, statistically significant differences of average item RTs were found (metronomic pendular adjustment: mean = 23.42 s, SD = 7.17 s; tap-tempo input: mean = 8.30 s, SD = 2.12 s; $t = 11.40$, df = 22, $P < 0.00001$). It should be pointed out that the RTs of the two tasks significantly correlated ($r = 0.43$, $P < 0.05$).

Further analyses focused on individual session data (see Table 5). The results of within-sessions analyses found significant differences between the task modes in each session. As can be seen in Table 5, tempo responses from tap-tempo input were far more accurate than responses from metronomic pendular adjustment. That is, responses from tap-tempo input were within 1 PVU while those from metronomic pendular adjustment were well beyond the critical threshold (> 2 PVUs). Moreover, RTs when employing tap-tempo input were significantly shorter than RTs from metronomic pendular adjustment tasks in both sessions.

To answer the question if repeated exposure might have caused incremental improvements, the analysis focused on response accuracy and RTs across sessions (see Table 6). The results show no apparent improvements regardless of the task mode. That is, listeners do not seem to demonstrate greater accuracy or shorter RTs in the second session regardless of the subject-response mode. Such a result, had it surfaced, might have been indicative of practice effects (i.e., repeated exposure of tasks). Nevertheless, as can be seen in Table 6, a time-accuracy tradeoff for metronomic pendular adjustment responses as well as longer RTs for tap-tempo input seems to appear in the second session.

Finally, to explore the effects of self-pacing behaviors, analysis of the data set variegated by three tempo zones was conducted. The findings highlight a linear relationship between tempo and RTs (see Table 7). As can be seen in Table 7, RTs were found to be longest in slower tempi, a bit shorter in medium tempi, and shortest in faster tempi. However, Table 7 also shows that RTs for responses from tap-tempo input were significantly shorter than those from metronomic pendular adjustment regardless of the tempo zones; differences that represent an overall estimated 150% between the task modes. Most specifically, to examine possible interactions between tempo zones and RTs, a one-way within-subjects repeated-measures ANOVA was conducted for each task mode. The findings demonstrate a significant

Table 5 Experiment 2: consistency of tempo accuracy within sessions

	Pendular adjustment		Tap-tempo input		*t*	*df*	*P*
	Mean	SD	Mean	SD			
Session 1							
Accuracy (bpm)[a]	9.14	2.21	3.64	2.13	8.42	22	0.00001
Accuracy (%)[b]	9.57	2.43	3.65	2.24	8.12	22	0.00001
RTs (s)[c]	26.67	9.00	7.89	2.20	10.50	22	0.00001
Session 2							
Accuracy (bpm)[a]	10.18	3.60	3.66	2.28	8.80	22	0.00001
Accuracy (%)[b]	11.29	4.19	3.72	1.99	9.08	22	0.00001
RTs (s)[c]	21.10	6.02	9.20	2.50	11.37	22	0.00001

[a]Mean beats apart
[b]Difference (%)
[c]Response completion time (s)

Table 6 Experiment 2: consistency of tempo accuracy between sessions

	Session 1		Session 2		t	df	P
	Mean	SD	Mean	SD			
Pendular adjustment							
Accuracy (bpm)[a]	9.14	2.21	10.18	3.60		NS	
Accuracy (%)[b]	9.57	2.43	11.29	4.19	2.19	22	0.05
RTs (s)[c]	26.67	9.00	21.10	6.02	4.79	22	0.0001
Tap-tempo input							
Accuracy (bpm)[a]	3.64	2.13	3.66	2.28		NS	
Accuracy (%)[b]	3.65	2.24	3.72	1.99		NS	
RTs (s)[c]	7.89	2.20	9.20	2.50	3.77	22	0.002

[a]Mean beats apart
[b]Difference (%)
[c]Response completion time (s)

interaction between tempo zone and RTs from metronomic pendular adjustment ($F_{(2,44)} = 18.229$, MSE = 32.505, $P < 0.00001$), indicating significantly longer completion times in slower tempi, as well as an interaction between tempo zone and RTs from tap-tempo input ($F_{(2,44)} = 35.329$, MSE = 18,571, $P < 0.00001$), indicating significantly shorter completion times in faster tempi.

Discussion

The findings of experiment 2 demonstrate that listeners produced a similar stable tempo response in both sessions. That is, when looking at the complete 15-item set, no difference between the two task modes surfaced. Yet, when exploring the items within each session, differences between the task modes clearly appeared: tempo responses were significantly more stable and accurate when listeners employed tap-tempo input as opposed to metronomic pendular adjustment tasks.

The results of experiment 2 do not seem to indicate incremental improvements of task-performance across the sessions. Nevertheless, the findings point to the possibility that listeners were less careful in the second session as seen in a time-accuracy tradeoff.

When examining the results of experiment 2 for self-pacing and congruent effects of potential delays, the findings demonstrate a positive relationship between tempo zones and RTs. In addition, the findings show significantly longer RTs in the slower tempo zone for metronomic pendular adjustment, while significantly shorter RTs in the faster tempo zone surfaced for responses from tap-tempo input. Given the nature of the empirical task—rhythmic tracking to temporal stimuli which unfold over time—one might expect that more time should elapse when stimuli unfold slowly and that less time should elapse when stimuli unfold quickly. That is, judgments about tempo and oscillation rates may simply be more difficult and hence take longer especially when adjusting a metronome pendulum in slower tempi, while tempo judgments may simply be easier and hence quicker when taping regular pulse beats in faster tempi. Therefore, and in light of the current findings, the question of task-mode suitability for tempo responses in particular speed zones must be raised.

Finally, the results of Experiment 2 again illustrate no correlation between the tempo responses from metronomic pendular adjustments and tempo responses from tap-tempo input—even when listening to the same music items. Hence, these results also seem to indicate that the two tasks may not be compatible, and that while each may have advantages depending on the temporal requirements, the two are not necessarily analogous.

General discussion

The current study focused on two overriding issues. The first issue questioned tempo responses across repeated sessions. That is: do listeners perceive a more or less single "correct" tempo for a song each time it is experienced? In the current study, tempo measurements were collected over and over again in a repeated session paradigm. The results of the study indicate that listeners were consistent and accurate across listening sessions, regardless of tempo range (i.e., slow, medium, and fast speed zones). This conclusion reinforces recent mappings related to music processing (Honing 2001;

Table 7 Experiment 2: response completion times (in seconds) variegated by tempo zones

	Pendular adjustment		Tap-tempo input		t	df	P
	Mean	SD	Mean	SD			
Slow tempo (< 80 bpm)	29.53	10.22	9.84	3.11	9.46	22	0.00001
Mid tempo (80–120 bpm)	22.72	7.94	8.85	2.21	9.48	22	0.00001
Fast tempo (> 120 bpm)	19.60	5.74	6.55	4.25	11.66	22	0.00001

Temperly 2001), which point to the perception and representation of pulse beat as a fundamental ability not based on formal or advanced musical training.

The second issue targeted by the study questioned if the mode of the subject response would influence stability and accuracy of tempo responses? That is, the study explored the ecological validity of empirical tasks and devices used for data collection in tempo studies. Unfortunately, it is quite common to find that "tempo" is treated as if it were solely applied to the pendular metronome or to verbal assignation. Taken to an extreme, one might presume that there is little value in studying human responses to composed music to begin with. After all, listeners have been seen to be much more accurate in discriminating tempo from metronomic clicks (Wapnick 1980) than art music. However, unlike ticks from a metronome, metrically regular patterns that emerge from *music* are cues for perception and memory (Povel 1981). As frequently reported in the literature, tempo studies seem to have encouraged a tradition of exploring tempo behavior through the employment of discernment tasks. Truly, there may be much to be gained by having listeners choose the pace appropriateness of a ticking metronome or prerecorded click track, modify the speed lever of a player piano or tweak a control knob of an electronic organ, and adjust the oscillation of a pendulum baton or fine-tune heard music by aligning a slider pictograph with a mouse. Then again, judgments based on perceived congruencies of metronomic rates (bpm) might not represent tempo perception to the fullest. As there seems to be a clear relationship between the cognition of tempo and motor theory, one behavior that seems to be more directly related to both the explicit and implicit rhythmic kinesthesis of tempo is tapping. Tap-tempo input characterizes motor processes based on an internal sense of rhythmicity within a temporal context. To perform the tactus of a musical fragment in a synchronic way has been considered to be an indicator and predictor of rhythmic development (Shaffer 1982). The current study, then, explored the possibility that a tap-tempo input task might be a more valid and reliable representation of tempo perception than the more standard, traditional, and most frequently employed metronomic pendular adjustment task. The findings of the study show that responses from tap-tempo input were not only *as* stable and accurate as those from metronomic pendular adjustment, but were in fact significantly *more* stable and accurate. Further, these differences were apparent in all tempo ranges and speed zones.

It is interesting to note several other differences that surfaced between the two subject-response task modes. First, tap-tempo input is not biased by slower tempi as was seen in responses from metronomic pendular adjustment; the later was significantly less stable and more inaccurate with pieces <80 bpm. Second, tapping is not predisposed to temporal movements between IT and TT as was metronomic pendular adjustment; the later caused listeners to underestimate the TT when the temporal movement was decelerated (IT > IT) and to overestimate the TT when the temporal movement was accelerated (IT < TT). Third, responses from tap-tempo input are completed in a more timely fashion than responses from metronomic pendular adjustment; the later took roughly 150% more time to complete tasks in all three speed zones, and were especially longer in slower tempi. Most certainly, these above factors indicate clear advantages in favor of tap-tempo input as the preferred mode of subject response in studies investigating tracking behavior related to tempo perception. Moreover, such an advantage is not based on the ease with which listeners can improve at tapping over metronomic pendular adjustment as incremental improvements with repeated exposure did not surface either for metronomic pendular adjustment or for tap-tempo input.

When all this is taken into account, it seems remarkable that listeners without formal music training can adjust the pendulum of a metronome with near stability and accuracy to begin with. It is even more astonishing that 80 years of tempo measurements have relied on a practice that is well below what seems to be acceptable as an empirical condition for gathering data—which is to be considered both ecologically valid and reliable enough to quantify the consistency and accuracy of temporal performances. The current study, then, suggests that tap-tempo input is a far more suitable method to investigate tempo, and by employing such a method, listeners without formal music training can clearly demonstrate tempo perception and tracking abilities that are far more stable and accurate than has been previously considered.

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