The Ambiguous Tactus: Tempo, Subdivision Benefit, and Three Listener Strategies

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The present study models listeners' tactus choices relative to the metric structure of fully musical excerpts using data from a tapping experiment. Viewed from the standpoint of metric structure, tactus was ambiguous between individuals and within excerpts, providing no evidence that this behavior has a global basis in tempo or in a subdivision benefit. Tactus was more consistent within individuals, however, when viewed as following from one of three basic strategies: (1) tapping with a subdivided pulse, (2) tapping with the fastest consistent pulse in the music (a pulse with no consistent subdivision), or (3) using a mixture of these two strategies based on inconsistent rhythmic activity at the musical surface. Music training correlated positively with the first of these strategies. Since individual listeners engage with musical meter in different ways, ambiguity of tactus should be an expected feature of any audience's response to metrical music.

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The list of empirical studies dealing with listeners' sense of tactus in fully musical stimuli is short but growing. In the broader context of synchronization studies, the terms *referent level* (Drake, Penel, & Bigand, 2000a; Jones & Boltz, 1989), *pulse* (Large, 2008; Snyder & Krumhansl, 2001; Toivianen & Snyder, 2003), *tempo* (Moelants, 2002; Moelants & McKinney, 2004), and *perceived tempo* (Drake, Gros, & Penel, 1999; McKinney & Moelants, 2006), all capture the idea that a functionally isochronous tapped response to music represents a listener's choice of main beat. Further, all are roughly equivalent to the present terminological choice of *tactus*. Unlike "tempo" or "pulse" however, tactus has the advantage of a unique definition in musical fields, yet a definition that is malleable in context. For instance, a performer will, consciously or not, choose a tactus prior to performance, but this particular periodicity may or may not match an audience's tactus, and neither of these beat levels might correspond to the tactus implied by a meter signature. While I reject the sometimes historical notion that a tactus exists "in the score,"[1] the performers' and the listeners' choice of main beat can both be properly considered a tactus, even if they disagree, provided that ownership remains clear.

In a context that is broader in terms of musical style or audience size, however, tactus can be even more ambiguous. McKinney and Moelants (2006) found that tactus varied widely and regularly between subjects and within individual musical excerpts. This observed ambiguity presents a problem for the widely held view that there exists an optimal zone for tempo perception and production, a "preferred tempo" that can be visually represented as the peak region of a resonance curve (Fraisse, 1982; London 2004; Madsen, Duke, & Geringer, 1986; Moelants, 2002; Parncutt, 1994). A resonance curve approach assumes a tempo range within which pulses are maximally salient, usually centered between 100 and 120 bpm (500–600 ms), with salience degrading to negligible levels on either side of that range by roughly 33 bpm (1800 ms) and 250 bpm (240 ms) (Drake & Bertrand, 2001; Fraisse, 1982; Parncutt, 1994; Van Noorden & Moelants, 1999). The often-tacit assumption is that the salience of pulses based on their tempo relates directly to the perception of *musical* pulses. Recent research, however, has found that a resonance curve is insufficient when predicting tactus in excerpts of fully musical stimuli (Martens, 2005; Moelants, 2002; Moelants & McKinney, 2004), and a typical result from McKinney and Moelants (2006) is reproduced as Figure 1. Note that a musical pulse exists near the center of the resonance curve at ca. 110 bpm, yet the pulse ca. 220 bpm, well above the "preferred-tempo" range, was chosen as tactus by a majority of listeners.

While some degree of ambiguity may be due to subjects' music training (Drake, Penel, & Bigand, 2000a & 2000b),

[1] Cf. summary in Houle (1987), pp. 3–12.

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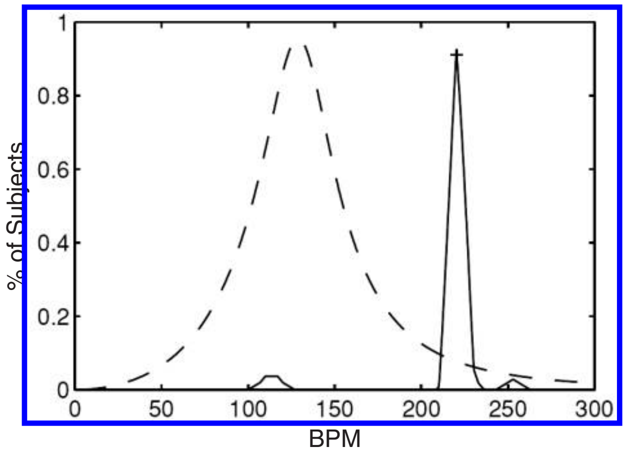

FIGURE 1. A tapped-tempo peak above the "preferred-tempo" range (Figure 2B from McKinney & Moelants, 2006, p. 159).

McKinney and Moelants (2006) joined Drake, Jones, and Baruch (2000) in casting doubt on the impact of subjects' prior experience, and looked instead to the music itself for the source of ambiguity. They developed a model that included dynamic accents present in the audio signal, together with a resonance curve—still operant but now in the perceptual background. The task of quantifying and ranking different types of musical accent is no small feat, and the authors seemed cognizant of the challenge.

The initial purpose of the present study was to approach a similar question, but working from the standpoint of metric structure. Several authors have surmised that the presence of a subdividing pulse layer will enhance the salience of a pulse, or provide a "subdivision benefit" (Hasty, 1997; London, 2004; Parncutt, 1994; Temperley, 2001). To date, this perceptual phenomenon has not been investigated in fully musical material, and the concept necessitates some preliminary definitions and clarifications. Repp (2003, 2008) investigated the effect of subdivision on sensorimotor tasks, coining the specific term "subdivision benefit" to label, for instance, a decrease in tapping asynchrony variability when a subdividing pulse is present. Following the other authors listed above, I use the term in reference to the explicitly perceptual phenomenon of choosing a tactus, of necessity measured via physical response. Nevertheless, Repp's subdivision benefit may be related to the present concept of pulse salience as a less direct measure of comfort and/or preference, and may thus also figure into the process of perceiving a tactus.

Consistent Pulses

To speak of a subdivision benefit in this way is to assume that at least two beat layers exist, where all beats in the slower layer are also beats in the faster layer. I accept David Epstein's (1995) and Jonathan Kramer's (1988) separation between *rhythms* and their *pulses* as acoustic reality on the one hand, and a *meter* and its *beats* as cognitive inference on the other (cf. also London, 2004). Consider the dot diagrams in Figure 2. These diagrams follow Yeston (1976) and Lerdahl and Jackendoff (1983), except that each dot represents the onset of an actual

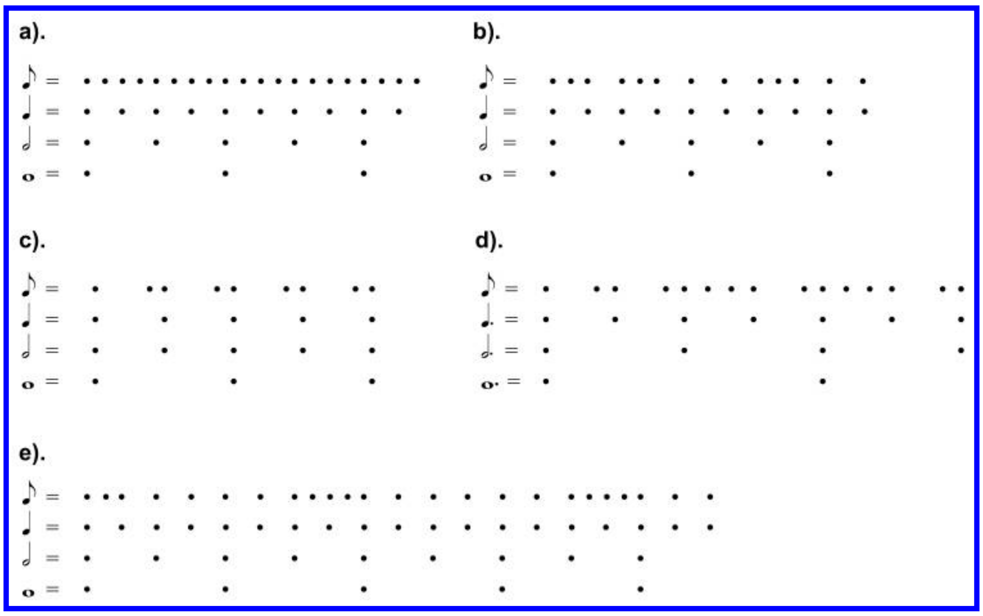

FIGURE 2. Rhythmic dot diagrams.

acoustic event. Figure 2a shows one possible configuration of music written in simple duple meter, with several consistent pulse layers, or consistent rhythmic activity. We would expect these sounding pulses to activate identical patterns of expectation in a listener's mind, and thus we would expect pulses and beats to be identical when listening to this rhythmic complex.

A logical question follows: what degree of consistency in rhythmic activity is necessary or sufficient to convey a corresponding sense of beat? As a practical matter, the question of pulse consistency is most pertinent to the fastest rhythmic layer. If that layer contains a consistent pulse, all slower layers will also be consistent by definition, as in Figure 2a. Structures like those shown in Figure 2b and 2c are more common in real music, however, with inconsistent rhythmic activity at what is often called the musical surface (Figure 2b), or even inconsistent activity at multiple layers (Figure 2c). Will the events that make up these inconsistent pulse layers be perceived as part of the metric structure to the same extent as the slower, consistent layers?

Answering these questions is important for defining which pulses are considered to be subdivided and which are not, and thus is important for identifying to which pulse layers a subdivision benefit might accrue. Intuitively, while there is *some* eighth note activity in Figure 2b (or, put another way, there are very brief periods of an eighth note pulse), there may not be enough to say that the passage *contains* an eighth note pulse. On the other hand, although a high degree of pulse consistency is one of the basic requirements for the sensation of beat, *absolute* consistency is not. Montague (2001) states succinctly, "the implication of regularity is more important than its actual occurrence" (p. 40).

One hallmark of beats is that they allow listeners to group their attacks (actual and implied) into slower periodicities, i.e., to be heard as implying meter (cf. London, 2004, pp. 42–46). Patel, Iversen, Chen, and Repp (2005) analyzed the results of Povel and Essens (1985), and labeled as "weakly metrical" those rhythmic patterns within which at least 32% of ostensible beats did not correspond to actual attacks (p. 230). These patterns were least likely to induce a beat in the Povel and Essens study, and the authors of the later study go on to frame their predictions for synchronization success using this threshold. These predictions were confirmed in their results in the form of significantly greater tapping variability in response to weakly metrical patterns versus strongly metrical patterns (p. 232). Although the Patel et al. (2005) stimuli were not fully musical, to my knowledge this is the only empirical study that demonstrates what we might call a "consistency threshold." I will adopt this threshold for present purposes and rephrase as such: periodicities in which less than 69% of beat-points coincide with attacks are unlikely to be felt as beats and, following London, are unlikely to contribute to a slower pulse's salience via a subdivision benefit. Put another way, these periodicities are neither strong candidates for, nor primary contributors to, tactus.

Note that, since a consistent quarter note pulse already articulates an (imagined) eighth note pulse 50% of the time, fewer than 40% of the "offbeat" eighth notes need to be additionally articulated for that pulse to be considered consistent. Returning to Figure 2b for an example, the quarter note pulse is clearly consistent, while the eighth note pulse falls short of the threshold (65% articulated). In Figure 2c neither the eighth nor the quarter note pulse is consistent, begging the question of whether a quarter note pulse is perceptible in this structure, even though there is some eighth note activity—the half note pulse is the fastest consistent pulse in Figure 2c. In a compound meter such as that shown in Figure 2d, rhythms that articulate two out of every three eighth notes do not quite meet the threshold for consistency, but in Figure 2d's rhythm, the eighth note level is considered consistent (71.4% articulated).

In order for a pulse to be considered subdivided, then, it must be subdivided by a pulse that meets this minimum standard for consistency. In the context of the experiment detailed below, these standards will be applied to the initial portion of each excerpt, during which time almost all successful synchronizations took place. The initial portion of each excerpt was defined as either twelve counting beats (as indicated by the piece's meter signature), or eight seconds, whichever covered a shorter span of time. Imagine the rhythmic structure shown in Figure 2e notated in 4/4 and performed at quarter note equals 100 bpm; the first twelve quarter note attacks would be performed in just under eight seconds. Despite the eighth note bursts that occur twice during this short span, the overall number of attacks at that level fails to meet the 69% threshold, and thus the eighth note pulse is not considered consistent. Yet inconsistent surface pulses such as those found in Figure 2e may figure into the choice of tactus in some situations, and will be discussed at more length below.

Subdivision Benefit and Tempo

Despite the intentional opposition of a subdivision benefit and a strictly tempo-based approach to tactus thus far, the former is intuitively constrained by the latter. A subdivision benefit will not accrue to infinitely slower metrical levels, and a subdivision benefit is trivial when the surface pulses in music are exceedingly fast. The "existence region" for pulse, 33–300 bpm (Parncutt,

1994) is a convenient starting point; this is the tempo window outside of which pulse sensations cease to exist (p. 437). Pulses greater than 300 bpm will be unlikely tactus candidates simply because of tempo, so a claim that a 580 bpm eighth note pulse imparts a subdivision benefit to its 290 bpm quarter note counterpart is confounded by this tempo boundary. Since the salience of pulses degrades markedly as tempo nears 300 bpm, I will adopt a more conservative upper limit for investigating the effect of subdivision, 240 bpm, as reported by London (2004) and as seen in the resonance curve of Van Noorden and Moelants (1999) and in Figure 1 above.

At the slow end of the existence region, we would not expect pulses slower than 66 bpm to impart a subdivision benefit since duple and especially triple groupings of such pulses lie outside the existence region. What remains, then, are metrical structures performed at tempi such that the fastest consistent pulse (hereafter "FCP") lies between 66 and 240 bpm. It will be instructive to see a subdivision benefit play out over the full range of musical FCPs, but a portion of the data analysis below will focus on excerpts with FCPs that fall within this window.

Purpose

The purpose of this experiment was to investigate tactus in real music, and in particular to determine whether subject responses could be better accounted for by a subdivision benefit or by a tempo-based resonance model. The following hypothesis served as a guide: In music that has at least two consistent pulses faster than 33 bpm, a listener's tactus will usually be a consistently articulated pulse that is divided by at least one other consistent pulse. Corollary: a listener's tactus will not be the fastest consistent pulse (FCP) in the music.

Method

Stimuli

Thirty excerpts were drawn from pieces in the Western classical tradition (1600-present). All excerpts were taken from readily available commercial recordings (see Appendix A). The excerpts were approximately 20 s in length, and were chosen for their particular combination of metric structure and performance tempi, according to the overall desire that the 30 excerpts cover a wide range of tempi—i.e., that the possible tactus choices across all excerpts lay above, below, and within the tempo range of a typical resonance curve. Despite the ostensible triviality of excerpts with FCPs above 240 bpm or below 66 bpm, given the above hypothesis, responses to such excerpts were thought to broaden the context of tactus relative to excerpts containing the target FCP rates. Eight of the 30 excerpts contained a FCP above 240 bpm, while three contained a FCP below 66 bpm. Further, excerpts represented the most common meters (simple duple, simple quadruple, simple triple, and compound duple) and maintained a high degree of temporal regularity throughout. Excerpts were manipulated prior to the experiment in WAV format to equalize amplitudes across all excerpts by ear and bring them within the range of comfortable hearing.

Each excerpt was followed by approximately 5 s of silence, which was itself followed by a 10-s chunk of a distractor stimulus. These stimuli were musical or nonmusical sounds free of metric content or regular pulse, but nonetheless aurally engaging. They were drawn from commercial recordings of free jazz, Eastern European folk music, 'sounds of nature,' or high quality home recordings of the author's then 9-month-old daughter striking various toy percussion instruments while vocalizing. Any components of these recordings that involved a steady pulse (i.e., two or more successive similar IOIs) were removed or rendered unsteady via computer editing.

Apparatus

All stimuli were played back using a program written in MAX/MSP through Sennheiser HD 570 stereo headphones. Subjects responded to the stimuli by tapping their dominant hand on an 8" by 11" piece of white plexiglass placed on a desktop. Underneath this plexiglass was another of the same size, with an Infusion Systems I-Cube Touchstrip piezoelectric sensor placed between the two layers. This sensor has a minimum activation force of approximately 25 g, and a mechanical response time of 1-2 ms. Subjects were not instructed to tap in any particular fashion; they could tap with one or more fingers, knuckles, entire hand, fist, etc. Output from this sensor was fed into a MAX program and each tap was recorded as real-time milliseconds, measured from the start of the excerpt. The MAX program only accepted input from the I-Cube sensor once every 4 ms, so this was the necessary quantization of the tapping data. Nevertheless, the apparatus allowed consistent data to be collected regardless of individual tapping style, and was able to obtain uniform within-subjects data for subjects who altered their tapping style during the study.

Subjects

The subjects were 29 adult volunteers, 24 of whom were graduate or undergraduate students, five of whom were members of the community at large. The group was balanced in terms of gender (16 female, 13 male), and the age of the subjects ranged from 18–57 years, with a median of 26 years. Most subjects had responded to a campus advertisement and were part of a psychology subject pool; some graduate students and community members were recruited as acquaintances of the author. They represented a wide range of music training, musical performance experience, and listening habits, but were relatively uniform in overall educational level, in that all were pursuing or had completed at minimum an undergraduate degree program.

Procedure

Subjects began by filling out a questionnaire on their music training, performance experience and habits (both formal and informal), classroom training in music, dance training, experience and habits (both formal and informal), and their habits and experience in the consumption of classical music, whether live or recorded. They were then seated at the testing station and briefly allowed to become comfortable tapping on the 8" by 11" surface. They were given verbal instructions to tap on the pad at a steady, comfortable rate (spontaneous tempo). This activity familiarized subjects with the tapping apparatus and provided an adequate warm-up to the synchronization task. Subjects were then given verbal instructions to "tap at a steady and comfortable rate along with the musical excerpts." They were presented with one test excerpt to become comfortable with the synchronization task. When subjects expressed that they were ready to begin, the excerpts were presented in random order. Each excerpt was followed by approximately 5 s of silence and a 10-s distractor stimulus. Four or more successive taps in synchrony with a musical pulse constituted a usable response. Shifts in tactus after the initial synchronization were rare and were not considered in the results.

Results

The tapping results of the experiment replicated the general findings of McKinney and Moelants (2006), in that listeners typically tapped at different tempi in response to individual excerpts, with those tempi corresponding to excerpts' metrical levels. Of the 30 excerpts, 24 had bimodal response distributions, four had trimodal distributions, and two had tetramodal distributions (only possible due to mutually exclusive hemiolic interpretations of some excerpts' meter, as discussed further below). The number of tactus choices available to listeners in each excerpt was indeed constrained by tempo, with 98.5% of synchronizations occurring within the 33–300 bpm existence region for pulse; the remaining 1.5% were split roughly evenly below 33 bpm and above 300 bpm. Thus, while resonance models fail to explain or predict tactus in specific pieces, the salience of musical pulses is unquestionably constrained by tempo in this way. Tactus was therefore limited by an excerpt's tempo as well as by its metrical structure; for each excerpt, subjects generally tapped no faster than the fastest consistent pulse (97.95% at or below the FCP) when the FCP was within the 33–300 bpm window, and they rarely tapped slower than 33 bpm regardless of the FCP rate (99.99% at or above 33 bpm).

Spontaneous Tempo and Tactus

Before investigating the data for a subdivision benefit, I will address tempo-based pulse salience in two ways. The first is subjects' spontaneous tempo rates. Pretest rates for all subjects are shown in Table 1 along with each

TABLE 1. Spontaneous Tempo and Mean Tapping Rates with Comparison.

Subject	Pre-test spontaneous tempo	Mean tapping rate	*p*
1	78	147.5	< .0001
2	105	162.5	< .0001
3	126	148.8	< .033
4	95	150.3	< .0002
5	112.5	152.9	< .011
6	102	140.2	< .0001
7	111	127.6	ns
8	63	137.0	< .0001
9	93	126.9	< .0015
10	118.5	126.9	ns
11	106.5	124.0	< .035
12	97	115.7	< .038
13	84	114.6	< .0001
14	114.5	118.5	ns
15	80.5	114.1	< .0001
16	83	98.1	ns
17	71	108.8	< .0001
18	101	95.1	ns
19	71	105.4	< .0002
20	76	91.8	< .012
21	79	111.3	< .001
22	67.5	94.7	< .008
23	102	90.5	ns
24	64	81.3	ns
25	58	74.2	< .008
26	66	71.3	ns
27	92	75.4	< .0001
28	87	77.1	ns
29	128.5	61.4	< .0001
Means	*90.78*	*111.86*	*< .0008*

subject's mean excerpt tapping rate. For 20 of the 29 subjects these two values were significantly different, with *p* values from a two independent samples *z*-test shown in the rightmost column. Note that most of the significant differences resulted from faster excerpt tapping rates relative to spontaneous tempo, but the responses of five subjects showed the reverse relationship, two significantly so (subjects 27 and 29). The spontaneous tempo rates of most subjects, then, did not seem to direct those subjects' choice of tactus in the musical excerpts.

Individual Resonance Curves

We can posit another possible role for tempo, however, by considering spontaneous tempo and tactus to be unrelated behaviors, and by instead imagining that individual subjects possess a peak of maximal tempo salience *in the context of the tapping task*. In this scenario, each subject has his or her own perceived-tactus resonance peak distinct from that suggested by spontaneous tempo. How would such behavior look in the context of the study excerpts? Figure 3a orders the 30 excerpts along the x-axis by ascending FCP (the FCPs of the last two excerpts, 444 and 504 bpm, lie beyond the graph's *y*-axis). Reponses for three hypothetical subjects are included; the tactus choices of these fictitious individuals were based on a normally distributed resonance curve centered at 80, 120, and 180 bpm, respectively, with the consistent musical pulse closest to the center of each curve acting as tactus. Their data sets include trendlines (degree five polynomial), which are visually emphasized in the figure over the individual plots for ease of comparison. As we would expect, all three hypothetical subjects' responses are limited by, and thus match, the FCP for generically slow excerpts (1-7), after which their responses fall away from the FCP one by one as the FCP rate increases beyond their individual peak resonance tempo.

Intuitively, actual subjects responding to these same excerpts, and guided by similar resonance tempi, should have mean tactus rates similar to those of their hypothetical counterparts. Further, given a set of tactus possibilities that are defined by the pulses of individual excerpts, we would expect that the tactus choices of these hypothetical/actual subject pairs should be similarly distributed relative to their shared personal tempo rate. Comparisons of this type were made between each study subject and a hypothetical subject as follows. First, the responses of eleven hypothetical subjects were tabulated (with resonance peaks at 60, 80, 91, 100, 120, 140, 160, 180, 200, 240, and 275 bpm). Next, each actual subject's mean tactus rate was compared with the mean from each

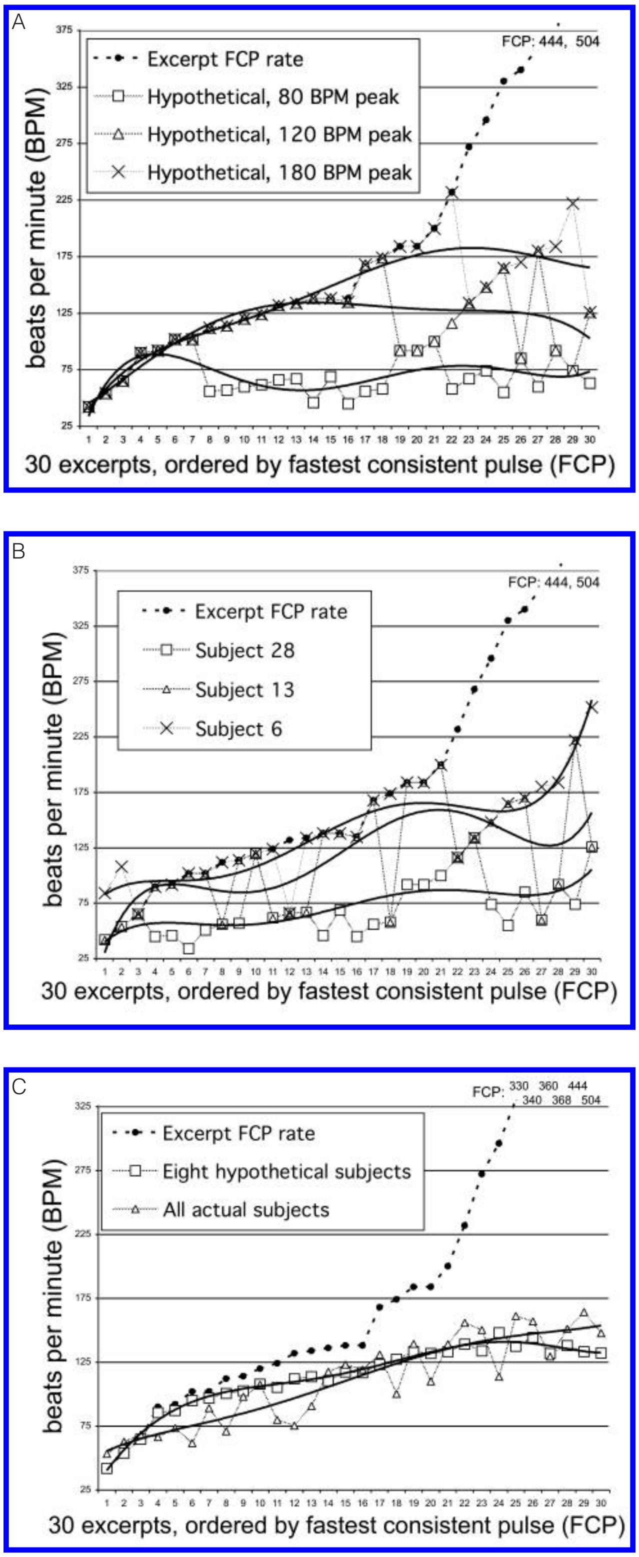

FIGURE 3. Hypothetical and actual subject responses to study excerpts. (A) Three hypothetical subject responses based on individual resonance curves. (B) Three actual subject responses. (C) Mean actual responses (*n* = 29) and mean hypothetical responses (*n* = 8).

TABLE 2. Comparison of Variance in Matched-Mean Responses of Actual and Hypothetical Subjects.

Subject	Mean perceived tactus rate	Hypothetical peak at *x* bpm (mean)	Means *z* score	Variance *F*-test *p* value
1	162.5	275 (164)	−0.108	**.016**
2	152.9	240 (152.4)	0.031	.29
3	150.3		−0.146	.35
4	148.8		−0.345	.36
5	147.5		−0.593	.06
6	140.2	180 (139)	0.110	.45
7	137.0	160 (135)	0.139	**.015**
8	127.6	140 (126.7)	0.088	.08
9	126.9		0.016	**.004**
10	126.9		0.020	.06
11	124.0		−0.330	.12
12	118.5	120 (114.7)	0.310	**.007**
13	115.7		0.113	**.028**
14	114.6		−0.005	.26
15	114.1		−0.061	**.032**
16	111.3		−0.344	**.008**
17	108.8		−0.717	.07
18	105.4		−0.985	**.018**
19	98.1	100 (94.7)	0.442	**.019**
20	95.1		0.069	.47
21	94.7		0.002	**.0003**
22	91.8		−0.468	.17
23	90.5		−0.577	**.038**
24	81.3	91 (80.7)	0.057	**<.0001**
25	77.1		−0.481	**.003**
26	75.4		−1.323	.30
27	74.2	80 (70.0)	0.681	**.0005**
28	71.3		0.264	**.017**
29	61.4	60 (57.2)	0.658	**.002**
Overall	*110.4*[a]	*113.4*	*−0.814*	

[a]This overall mean differs intentionally from that shown in Table 1. In Table 1, this value was a mean of individual subjects' mean tapping rates, ignoring differences in weighting due to failed synchronizations. In Table 2, this value is the mean of all tapped responses across all subjects.

hypothetical response using a one-sample *z*-test. Each actual subject was paired with a hypothetical subject according to the highest *p* value in these comparisons. Finally, the variation of responses within each of these matched-mean pairs was computed.

Table 2 shows these comparisons; each actual subject's mean tactus rate is given in the table's second column; subjects are ordered in the table in descending order of mean tactus rate. In the third column, the resonance peak and resulting mean tactus are listed for the hypothetical subjects with which each actual subject was paired. The fourth column gives the *z* scores from the comparison of means, all of which are insignificant by design. The rightmost column gives the *p* value of the comparison of variation in tactus choice; significant values appear in boldface. The tactus rates of 16 out of the 29 subjects varied significantly from those of their respective hypothetical counterparts, despite their similar mean rates. Thus, the *distribution* of tactus choices for the 16 actual subjects was significantly different than would be expected if the subjects had, in fact, been guided by a peak resonance tempo alone. McKinney and Moelants (2006) demonstrated that their results were inconsistent with the hypothesis that a global resonance tempo guides the tactus choices of a group of subjects; the present results are inconsistent with the idea that a resonance tempo guides all or most individual subjects as well.

A comparison of Figures 3a and 3b demonstrates visually how subjects with similar means can vary significantly in terms of tactus choice. Figure 3b shows the responses of three actual subjects who were paired with the three hypothetical subjects used in Figure 3a. (See Table 2 for details). The response trends in each figure differ noticeably; the fastest-tapping actual subject in Figure 3b (Subject 6) surprisingly chooses a division of the FCP as tactus in the two slowest excerpts, then falls away from the FCP as it passes 200 bpm. Subject 6 is not averse to tactus rates up to 252 bpm, however, and, unlike the fastest-tapping hypothetical subject (180 bpm), Subject 6's tactus choices parallel the rising FCP in response to the fastest excerpts.

Subject 28, the slowest-tapping subject in Figure 3b, taps along with the FCP only for the slowest three excerpts. While this subject's hypothetical doppelganger (80 bpm) shows a relatively flat response line centering around this peak tempo of 80 bpm throughout the excerpt set, Subject 28's responses also trend upward with the increasing FCP. Subject 13's tactus seems to shuttle back and forth irregularly between the FCP and slower metrical pulses after excerpt 7, unlike the hypothetical 120 bpm subject who is more consistent in following the FCP up to ca. 130 bpm before opting for a grouping of the FCP as tactus.

The response trend of three subjects shown in Figure 3b is also evident across all actual subjects. Figure 3c presents the mean tactus rate of all 29 subjects for each excerpt, along with the analogous mean rates of eight hypothetical subjects with peak tempo resonance at 60, 80, 100, 120, 140, 160, 180, and 200 bpm. The mean tapping rate across all actual subjects was 110.7 bpm, not significantly greater than that of the eight hypothetical subjects, mean 110.0 bpm ($p = .928$). The two response plots, though matched in terms of overall mean, trend differently as the FCP increases. Mean hypothetical responses are fairly flat once the FCP passes 120 bpm at excerpt 11, increasing from 108 bpm to a high of 138 bpm over the remaining excerpts. Over that same span, the actual subjects' mean tactus rate increases from 77 bpm to a high of 156 bpm, reflecting the continuously increasing FCP. In view of this discussion, it seems that a peak resonance tempo is less predictive of tactus than a definable relationship with the FCP, to be discussed below.

Subdivision Benefit

Returning now to the original hypothesis of a subdivision benefit, the results suggest that if such a benefit does exist, it does not exist for all subjects, or not for all subjects equally. Of the 781 successful tactus choices, only 439 (56%) were a subdivided pulse (hereafter "SP"). Since most excerpts had multiple SPs and only one FCP, and since eight excerpts had minimally salient FCPs that were faster than 240 bpm, this percentage is surprising.

Subdivision was positively correlated with tactus for some individual subjects, however. These subjects do seem to avoid the FCP, ostensibly benefiting from its subdivision of their tactus choices (e.g., Subject 28). At the same time, and contrary to the hypothesis, subdivision was negatively correlated with tactus for other subjects. These individuals seem perfectly comfortable choosing the FCP as tactus up to very fast tempi—no subdivision required (e.g., Subject 6). But the tactus choices of still other subjects (e.g., Subject 13) do not seem to be definable relative to the FCP.

These individual behavior patterns are more easily viewable over a subset of the study excerpts. Recall that at tempi above 240 bpm pulse salience degrades rapidly, so in excerpts with a very fast FCP subjects would likely choose a SP due to tempo alone. Similarly, subjects' responses relative to subdivision and the FCP are confounded in slow excerpts with no viable SPs, i.e., excerpts with only one consistent pulse above 33 bpm. These limitations eliminate the fastest eight and slowest three excerpts, resulting in a 19-excerpt subset of the 30 study excerpts (excerpts 4 through 22 in Figure 3). Table 3 lists subjects, reordered according to the frequency with which they chose an excerpt's FCP as tactus in these 19 excerpts. Note the continuum of responses in the third column, from subjects who chose exclusively FCPs as tactus to those who chose none; there was clearly no universal strategy relative to the FCP guiding tactus, $F(28, 484) = 6.67$, $p < .001$, and thus no global subdivision benefit.

TABLE 3. FCP Chosen as Perceived Tactus in 19-Excerpt Subset.

Subject	Mean perceived tactus rate (bpm) (19)	% FCP as perceived tactus (19)
1	146.1	100.0%
5	140.8	100.0%
4	137.3	94.7%
3	128.1	92.9%
2	132.2	92.3%
6	126.4	84.2%
8	124.9	76.5%
7	124.4	75.0%
10	121.8	75.0%
9	122.9	72.2%
13	115.4	68.4%
11	114.4	68.4%
14	109.4	63.2%
12	119.6	58.8%
15	111.6	57.9%
17	98.6	47.4%
19	98.4	47.4%
20	92.8	47.4%
16	92.4	36.8%
18	90.4	36.8%
22	90.1	36.8%
21	84.4	26.3%
23	83.5	26.3%
24	75.3	21.1%
27	68.5	10.5%
28	67.3	5.3%
26	70.4	0.0%
25	58.5	0.0%
29	53.6	0.0%

Discussion

The FCP and Three Listener Strategies

Are there any shared behaviors relative to the FCP within the subject population? Can we discover strategies that might break down the continuum in Table 3? Given the tempo limitations that created the 19-excerpt subset, there could be no less than two and no more than three choices for tactus in each excerpt. Focusing on each pulse's position with the metric structure, we can consider the possible tactus choices to be the FCP, SP1 (the layer that groups the FCP by 2 or 3), and SP2 (the layer that groups SP1 by 2 or 3). This method of labeling removes tempo from immediate consideration, and also facilitates the incorporation of the surprisingly frequent hemiolic responses, an example of which is given as Figure 4. The most obvious pulses in the piece's notation are the tripleted 8th-note pulse (the FCP) and the quarter note pulse (SP1a), which were indeed chosen most often. In addition, however, an alternative grouping of the FCP was chosen by 17.9% of subjects, the tripleted quarter note pulse (SP1b; there was no viable SP2 in this excerpt). Hemiolic tactus choices such as the tripleted quarter note in this excerpt may strike us as bizarre, but they simply reflect a differently constructed mental representation of the piece's meter.

Subjects' tactus choices across these 19 excerpts were coded as categorical responses, which served as variables

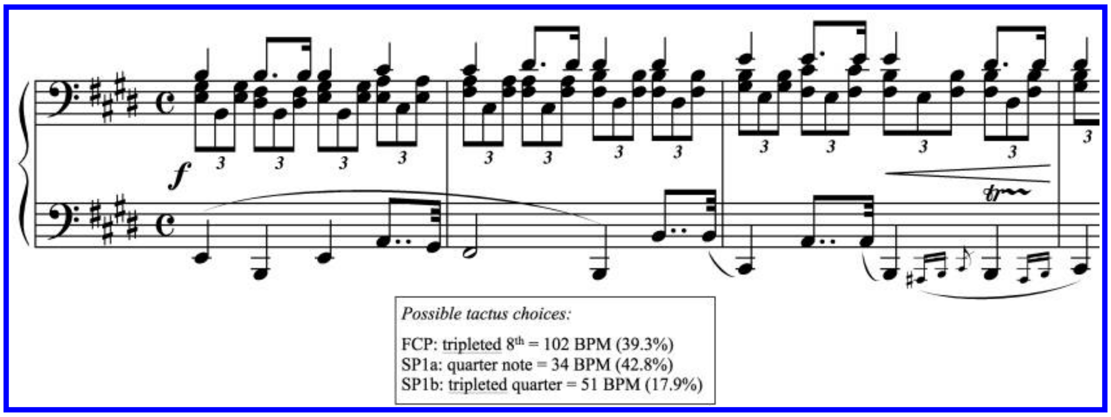

FIGURE 4. Chopin, *Prelude in E Major,* Op. 28/9, mm. 1–4.

in the first step of a two-step hierarchical cluster analysis. The second step in this analysis consisted of a single continuous variable; namely, each subject's mean tactus rate. The addition of this second stage was important for differentiating between subjects who only chose the slowest FCPs versus those who chose about the same number of FCPs, but from throughout the spectrum of available tempi. This two-step cluster analysis was performed twice on two different random orderings of the variables. In both analyses, the optimal number of clusters was three, as measured by the minimum Schwarz's Bayesian Criterion value. The same variables (19 excerpt responses and mean tempo) were then analyzed using a hierarchical cluster technique assuming three clusters.

The right side of Table 3 summarizes the results of this hierarchical analysis; although three clusters are statistically optimal, the Table includes two- and four-cluster partitionings as well. In the biggest picture (leftmost brackets), subjects grouped into two equal clusters ($n =$ 14 and 15, respectively), with the division falling between the subjects who chose 47.4% and 57.9% of FCPs as tactus. Viewing the subjects in three clusters (middle brackets) splits the under-50% FCP group into groups of six and eight subjects at roughly the 25% FCP mark. Adding a fourth cluster (rightmost brackets) breaks apart the original top cluster, separating off the five subjects who were almost completely devoted to (consciously or not) the fastest pulse in the music. These subjects chose at most one SP as tactus across all 19 excerpts.

Recall that in each of these 19 excerpts the random chance of choosing a FCP as tactus was either 33% or 50%, depending on the number of pulses within the 33–300 bpm window. The overall random chance of choosing a FCP across all excerpts, taking a simple average of the individual excerpts' probabilities, was 42.1%. While this method of combining probabilities is not mathematically rigorous, it does provide an interesting comparison with a three-cluster view of the subjects. The 57.9% boundary in Table 3 gives a p value of .08 when compared with the hypothetical 42.1% ($n = 30$; the .05 level is reached at 59.8%), suggesting that most of these subjects chose a FCP significantly more often than chance. On the other end, p reaches the .05 level at 24.4%, exactly corresponding to the break between the bottom two clusters. I will call subjects in the bottom cluster, with their focus on SPs, the "Deep" tappers. Those in the large top cluster are "Surface" tappers, and I will call those who chose a FCP as tactus near overall chance levels the "Variable" tappers. Finally, although p has already reached the $< .0001$ threshold by 77.5%, we might consider the top five subjects in Table 3 as "Super-Surface" tappers.

From this point forward I will further explore and characterize the shared beat-finding strategies of subjects in these three subject groups. Figure 5 shows in detail the interaction of the three groups and the metric structure of all study excerpts. A picture of the metric structure is given along the y-axis in each chart; individual metric layers are labeled with a ratio that designates the number of subject taps per attack in an excerpt's FCP. Thus, bars in the 1:1 response category indicate tapping that was (nominally) isochronous with the FCP (i.e., tactus = FCP). Groupings of the FCP (i.e., SPs) are shown below the 1:1 responses, listed as 1:*n*, indicating one tap for each *n* attacks of the FCP. As above, ratios that are theoretically and perceptually exclusive are combined.[2] Thus the 1:2 or 1:3 response category contains all of the SP1 tactus choices, i.e., one tap for every two or three attacks in the FCP. Similarly, 1:4 and 1:6

[2] That is, mutually exclusive in "strict" metric theory, such as Lerdahl and Jackendoff (1983). I will add, however, that once a tactus is chosen, there can be no ambiguity in the strong sense for an individual subject (i.e., *both* 1:2 and 1:3 cannot exist), only ambiguity in the weak sense (i.e., *either* 1:2 or 1:3 can exist) (cf. Agawu, 1994).

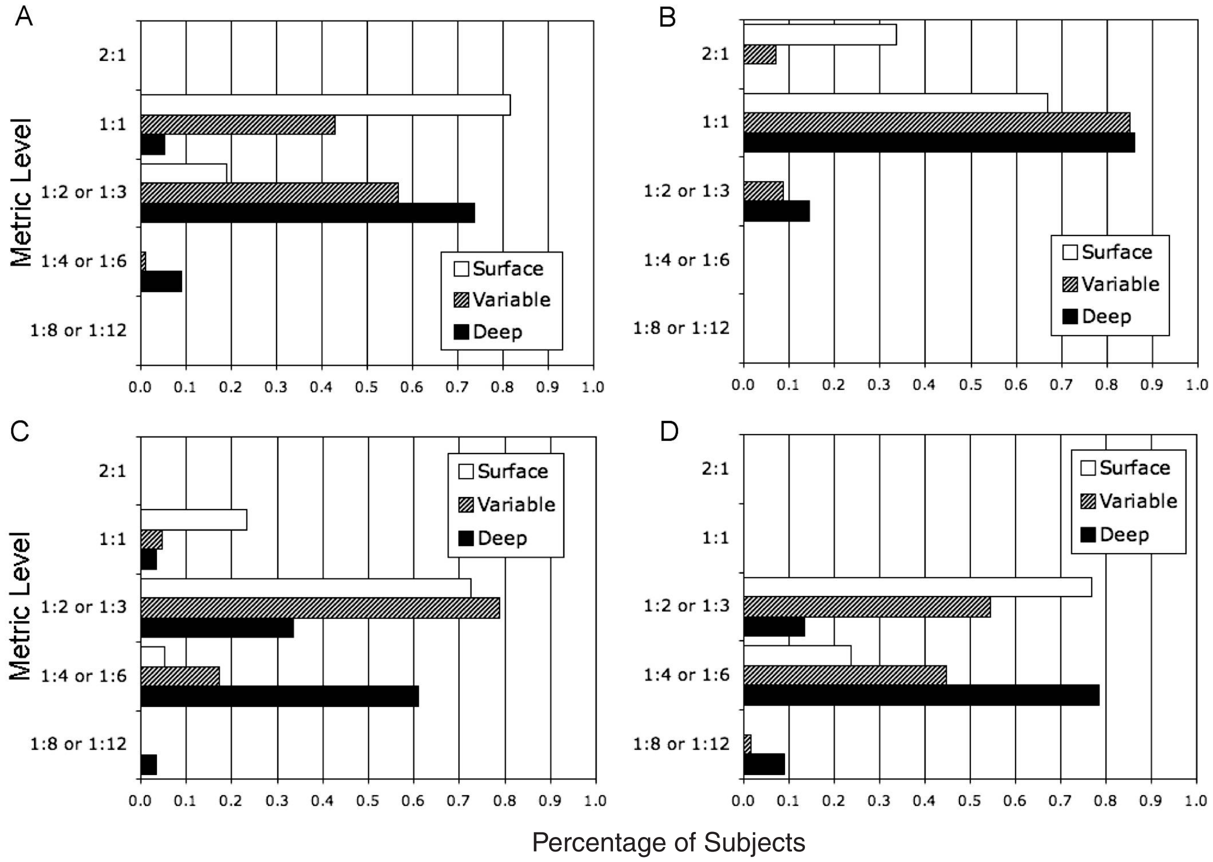

FIGURE 5. Perceived tactus by metric level and subject group in four FCP ranges. (A) FCP range 66–240 bpm (nineteen excerpts). (B) FCP range 33–65 bpm (three excerpts). (C) FCP range 241–340 bpm (four excerpts). (D) FCP range 341–540 bpm (four excerpts).

responses are combined (SP2), as are the rare 1:8 and 1:12 responses (SP3). Equally rare, the 2:1 response row at the top of each chart indicates two taps for every attack of the FCP. These responses are particularly interesting examples of tactus because these beats are inferred in whole or in part from the FCP, and perhaps also from inconsistent pulses at the musical surface.

Focus first on Figure 5a, which contains the responses to the 19-excerpt subset discussed above. The fifteen Surface tappers exhibited perhaps the most surprising behavior relative to an imagined subdivision benefit, avoiding SPs and choosing FCPs as tactus nearly 80% of the time overall; these subjects could not, or preferred not to, focus their attention below the surface pulse. On the other end of the spectrum, the six Deep tappers did seem drawn to pulses that were subdivided. The behavior of this group corresponds closely to the notion of a subdivision benefit. Finally, like the Surface tappers, the Variable tappers' behavior did not show evidence for a subdivision benefit, but neither did their behavior show a measurable preference for FCPs as tactus. Although their inconsistent strategy in choosing a tactus might suggest that they were not relying on metric structure at all in making these choices, their behavior can also be seen as responding sensitively to inconsistent rhythmic activity at the musical surface, an intriguing trait explored below.

Tempo Effect

Figures 5b–d show responses to the remaining excerpts, those that were excluded from the 19-excerpt subset. Subject responses to these 11 excerpts were likely based more on negotiating tempo boundaries than on any personal beat-finding strategy. These excerpts are collapsed into three sets based on the rate of their FCP:

Figure 5b: Slow excerpts, with only one FCP above 33 bpm (FCP range 33–65 bpm)
Figure 5c: Fast excerpts, with fast but theoretically tappable FCPs (FCP range 241–340 bpm)
Figure 5d: Extremely fast excerpts, with untappable FCPs (FCP range 341–540 bpm)

In response to the slowest excerpts (Figure 5b), tempo was certainly a factor for subjects in all groups, with most Deep tappers going against their tendency and choosing the 1:1 pulse, and with uncharacteristic uniformity from the Variable tappers. A full third of the Surface group's tactus choices occurred at the 2:1 inferred pulse rate; these pulses are absent or inconsistent and thus minimally salient, yet many Surface tappers evidently did not find the slow FCPs in these excerpts comfortable. For them, the effect of tempo was superordinate, causing them to perceive a tactus where there was no consistent pulse. This effect was also the likely cause of their high rate of failed synchronizations in response to these excerpts, as shown in Table 4. This failure rate was significantly higher than those of the Variable and Deep tappers within this set of excerpts ($p < .0001$ and $p = .048$, respectively).

Figure 5c begins to show an effect of the upper tempo boundary. The 1:1 tactus was decreasingly salient for Surface tappers, and not at all attractive to Variable and Deep tappers. As a result, the Variable group was again uncharacteristically uniform in choosing the 1:2 or 1:3 pulse, while a solid majority of Deep Tappers were attracted to pulses even more deeply embedded in the metric structure, 1:4, 1:6, and 1:8.[3]

Figure 5d indicates how cyclic these group behaviors may be. Given the very fast rates of the FCPs in these excerpts, the 1:2 pulse effectively becomes the FCP in terms of perception and performance, ranging as it does in these excerpts from 117 to 270 bpm. The group behaviors here are almost identical to those shown in Figure 5a, simply shifted one level down in the metric structure. The fact that the FCPs in these excerpts were too fast to tap did not deter many Surface tappers from attempting to do so, however. As shown in Table 4, Surface tappers failed to synchronize to 31.7% of trials with these excerpts, in almost all cases while trying to synchronize with an impossibly fast FCP. Despite their difficulty synchronizing to excerpts with extremes of FCP (Figures 5b and 5d), the Surface tappers were able to synchronize significantly more often when choosing a tactus in the 19 excerpts that contained moderate FCPs (see the second column in Table 4; 33–65 vs. 66–240, $p = .002$; 341–540 vs. 66–240, $p < .0001$).

An additional comment on Table 4: one might be surprised at the synchronization acumen of the Variable tappers, especially compared with the surprisingly high failed rate of the Deep tappers in each excerpt set. It appears as though both the Deep and Surface groups failed to synchronize significantly more often than the Variable group (both total comparisons $p < .0001$). The Deep group's failed synchronization rate, however, was inflated by one of its members failing to synchronize to 47% of excerpts. Excluding this subject gives the Deep tappers an overall failed synchronization rate of 2%, compared to the Surface tappers' overall failure rate of 15.3% ($p < .0001$). In general, then, a significantly higher failed synchronization rate seems directly related to a consistent focus on the FCP that was shared among Surface tappers.

[3] There were no 1:12 pulses chosen as tactus in these excerpts.

TABLE 4. Failed Synchronization Rates, by Subject Group and FCP Range.

	FCP 33–65 bpm	FCP 66–240 bpm	FCP 241–340 bpm	FCP 341–540 bpm	TOTAL
Surface	31.1%	9.1%	16.7%	31.7%	**15.3%**
Variable	0.0%	0.0%	3.1%	0.0%	**0.4%**
Deep	11.1%	9.6%	12.5%	4.2%	**9.4%**

Finally, Figure 6 mimics the layout of Figure 3, with excerpts ordered along the x-axis by increasing FCP. Mean bpm responses of the Deep, Variable, and Surface groups for all 30 excerpts are plotted, again with trendlines to emphasize how each group's mean tapped response increased along with the increasing FCP, but at different distances from the FCP. The upper tempo boundary for tactus is evident in the Surface group's mean responses, which fall away from the FCP as it passes 200 bpm.

The anomalous responses in Figure 6 warrant a brief aside. In response to excerpts 11 and 12, for two examples, listeners in all groups chose a slower tactus overall than might be expected; in particular, very few Surface tappers chose the FCP despite its comfortable tempo. While four of the 30 musical excerpts are briefly analyzed below, a thorough treatment of each excerpt's details relative to the group responses lies beyond the scope of this article. It is hoped that the interested reader might use the information provided in the discography to pursue these questions.

Music Training

The results showed no effect of subjects' gender or age; more surprisingly, there also were no significant differences between the mean spontaneous tempo rates of any two groups. Unlike McKinney and Moelants (2006) and Drake et al. (2000), however, some significant correlations were found between self-reported music training and tactus, as viewed through the lens of the three basic tapping strategies. There were highly trained musicians in each group (>10 years), but 40% of Surface tappers (5.1 mean years training) reported no training; all Variable and Deep tappers reported at least six years of training (13.8 and 12.8 mean years training, respectively). Not surprisingly, the Surface group's mean years of training was significantly

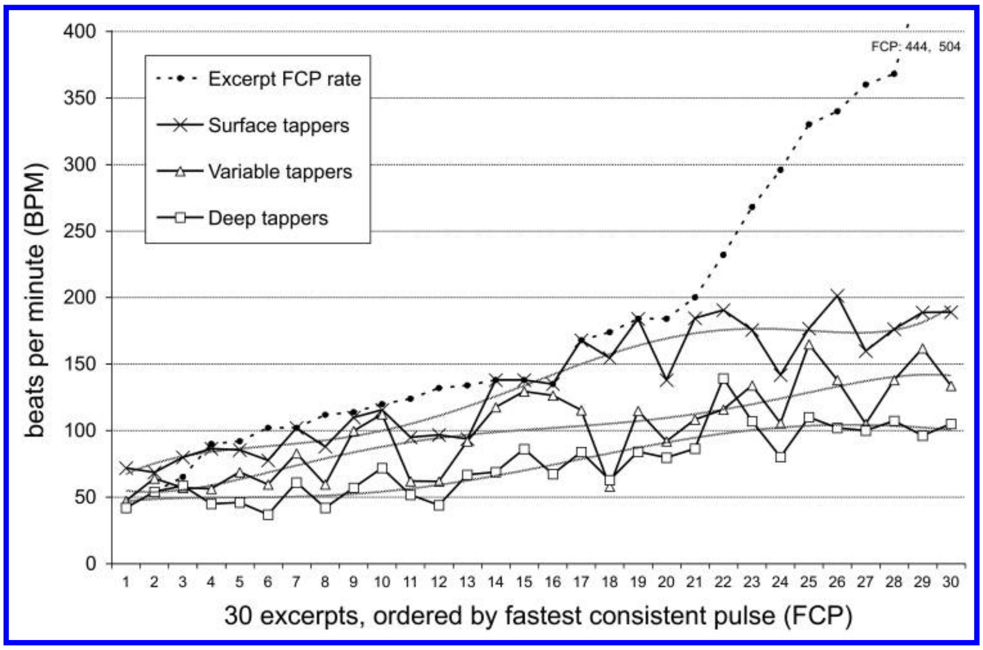

FIGURE 6. Mean perceived tactus choices, by three subject groups.

less than the Variable and Deep groups ($p < .0001$ and $p = .008$, respectively). This same comparison between the Deep and Variable groups was not significant.

The specifics of subjects' music training and experience suggest further avenues for study in this area. For example, each Deep tapper reported significant training in one or more of the following areas: conducting, low range wind and string instruments, composition, and dance. By contrast, the Variable tappers' shared experiences were in higher-range string and wind instruments, piano, voice, percussion, and guitar. These same areas of training were reported by the trained Surface tappers. It may be that increased experience with typically faster-moving musical lines or textures, especially on instruments that require faster and more overt physical movements to produce such lines, may have as great an effect on an individual's basic tactus strategy as does the presence or absence of music training. If self-reported years of training are taken as an adequate measure, these effects could be studied relatively easily within musician populations.

Variable Tappers

In many ways the behavior of Variable tappers is the most interesting. In fact, we might consider these listeners to be representative of the general musically informed concert-goer, and their tactus choices might very often be those that experts would judge to be most musical. One way to quantify this statement across a broad range of excerpts and genres would be to identify each excerpt's putative tactus and analyze responses from that basis. I took this approach, identifying a tactus for each excerpt using the initial meter signature along with other notational and stylistic information in the score (or from the recording, in the absence of a score). I found that Variable tappers chose the notated tactus as tactus in 67.4% of synchronizations. The Deep and Surface groups were similar to each other in this respect, choosing the notated tactus less often, 47.2% and 56% of the time, respectively—proportions that do not differ significantly from each other. Both of these proportions are indeed significantly smaller than that of the Variable group ($p < .0001$ and $p = .004$, respectively). We might say, then, that Variable tappers were more sensitive to, or at least more drawn to, the tactus level as expressed in or implied by composers' notation, and as communicated via the performances used in the experiments.

But just how is a tactus encoded in a score or a performance? Recall that Variable tappers responded neither consistently nor uniformly to consistent subdivision, or to a lack thereof, but rather seemed to respond very specifically to rhythmic activity at the musical surface in choosing a tactus. For example, when the musical surface of an excerpt contained a consistent pulse with little or no rhythmic activity faster than that pulse, Variable tappers tended to join the Deep tappers and chose a SP as tactus, as in the excerpts shown in Figure 7. The FCP in both examples is the quarter note, with few divisions. We might be tempted to attribute to tempo the Variable tappers' avoidance of the FCP in the Mahler example shown in Figure 7a, but tempo is certainly not a factor in their avoidance of Brahms' quarter note FCP, shown in Figure 7b (cf. Figure 6, excerpts 18 and 4).

FIGURE 7. Variable tappers join Deep tappers when FCP infrequently divided. (A) G. Mahler, *Symphony* No. 1, II, mm. 1–7, with subject responses. (B) J. Brahms, *Intermezzo,* Op. 76/7, mm. 1–8, with subject responses.

Conversely, when there is frequent division of a FCP (but still below the consistency threshold), many Variable tappers often join the Surface tappers, as shown in Figure 8 (cf. Figure 6, excerpt 7). Monteverdi's eighth note pulse is not consistent (59% articulated), but it is often present (in the recording used in the experiment, the continuo did not add any additional eighth note activity to the string parts shown in the figure). The quarter note is the FCP, and thus not attractive to Deep tappers, all but one of whom chose the half note pulse at 51 bpm as tactus. Nor were the eighth notes sufficiently consistent to create a surface pulse that would attract the Surface tappers; all Surface tappers chose the consistent quarter note level as tactus. The eighth note activity was sufficient, however, to attract a majority of Variable tappers to the quarter note level. In this situation, then, most Variable tappers behaved like Surface tappers, but perhaps for different reasons. The Surface tappers were forced to a slower level in the metric structure because the eighth note activity was inconsistent, while most Variable tappers were drawn up to the quarter note level *because of* that inconsistent eighth note activity.

FIGURE 8. C. Monteverdi, Ritornello from 'Prologue' *to L'Orfeo,* mm. 1–4, with subject responses.

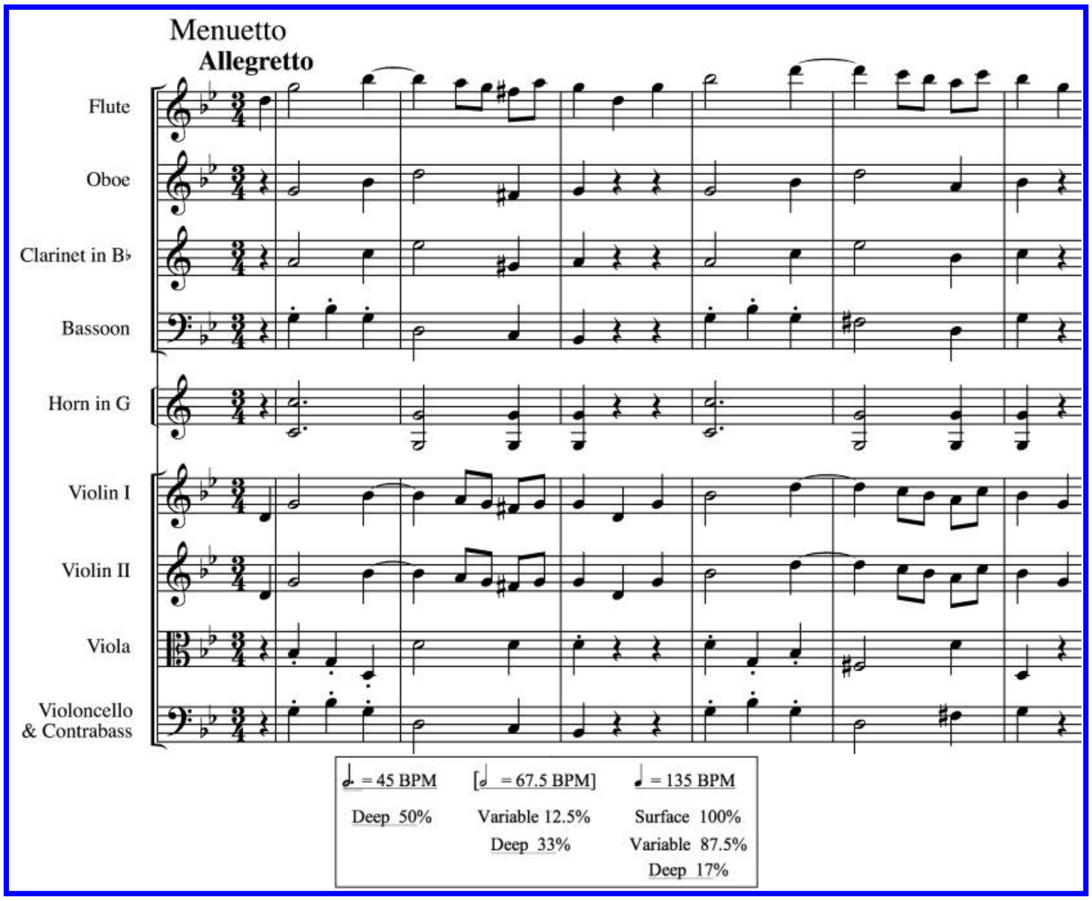

FIGURE 9. W.A. Mozart, *Symphony* No. 40, III, mm. 1–6, with subject responses.

One final example illustrates the flexibility of this group relative to unique musical features. Figure 9 reproduces the opening of a symphonic movement well known for its metric trickery (cf. Figure 6, excerpt 16). In response to this excerpt, 83% of Deep tappers chose a SP as tactus, although these responses were split between the metrical dotted half note pulse and the hemiolic half note pulse that is prominent in the treble voices. For the Variable tappers, the quarter note FCP is not regularly divided, so we might expect that they too would choose a SP as tactus. Not so, and it is perhaps due to the ambiguous SP choices that all but one Variable tapper chose the FCP as tactus along with all of the Surface tappers.

Conclusion

One criticism of any beat-finding study, especially one based on tapping along with a single musical pulse, is that *meter* is not being studied. Indeed, musicians may find such a focus patently unmusical, since they might claim to follow at least two pulses simultaneously while listening, and especially when performing. I have no doubt that this behavior occurred during the study; following Jones and Boltz (1989), tactus is simply a reference point from which a sense of meter is created. Once established, we are free to explore all of the meter's nooks and crannies. Thus the task around which this study revolved was one of establishing that basis for exploration, creating a figure (beat) against a ground (total rhythmic information); subjects certainly used at least some aspects of the ground in identifying their individual figures. Yet the Surface tappers' fealty to the FCP, seemingly irrespective of physical and/or cognitive constraints, might indicate a difficulty in extracting slower periodicities from the acoustic signal, difficulty in teasing any pulse aside from the FCP out of a dense rhythmic complex.[4] Beyond this general observation, however, it is difficult to surmise what aspects of the "ground"

[4] I am certain that with minimal instruction, most, if not all, Surface Tappers could be led to hear past the surface pulses; a "forced-tapping" paradigm such as that used in Drake, Penel, and Bigand (2000b) is an experimental example of minimal instruction.

individual subjects are aware of from excerpt to excerpt without a more controlled (but less ecological) methodology than that of the present study. What is needed to refine the view of beat-finding strategies outlined here is an extended series of studies with a stable pool of subjects, controlling stimuli for a host of musical parameters such as timbre and register while sacrificing as little of the fully musical as possible.

It is only logical that composers, endowed with psychological constraints similar to those of their audiences, often design into their works freedom of imagination relative to those psychological constraints. That is, they develop a means of musical communication that is not completely (pre)determined by the psychological makeup of their audiences. But how determined is this communication from the standpoint of individual listeners? Huron (2006) casts the issue as follows: "Psychological conformity is a prerequisite if a composer wishes individual listeners to hear a musical work in broadly similar ways. As we learn more about individual psychological differences, in the future it might be possible for composers to tailor works for particular subgroups or even individual listeners" (p. 390). Based on this comment, Huron seems to consider an ambiguous tactus undesirable, at least from the composer's standpoint. It seems likely, however, that communicating differently with individual listeners has always been occurring, regardless of composers' knowledge or intentions. Although an overall definitive main beat is routinely ambiguous, tactus has never been so for the individual.

It is possible that the present project could provide a basis for more purposeful "tailoring" of the type Huron suggests. But even within individual listeners, long practiced modes of listening are not completely fixed, casting doubt on both the stability of the partial psychological conformity posited here in the three strategies view, as well as on the possibility of composing toward this or that individual's musical predilections. A Variable tapper becomes engrossed with Bruckner and beings to focus on harmonic rhythm in future listening experiences. A Surface tapper takes up ballroom dancing and begins to feel slower-moving periodicities in music. Today's Deep tapper learns doumbek drumming and becomes tomorrow's Surface tapper. In all of these instances, the abstract availability of tactus options in the sounding music does not change, nor do the basic cognitive faculties of the listeners. What do change, and what will continue to change, are listeners' cumulative experiences with, and preferences relative to, the structured relationships between tactus options.

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