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A Response-Time Approach for Estimating Sensitivity to Auditory Tempo Changes

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One of the features of the auditory system is its ability to efficiently process events that occur in rapid succession. The aim of the present study is to propose a new way of investigating sensitivity to auditory tempo changes. More specifically, it proposes to compare the relative sensitivity (bias) to acceleration and deceleration in both musical and monotonal conditions. Bias was measured with (1) a conventional psychophysical method known as the method of constant stimuli (MCS) and (2) a so-called method of dynamic stimuli (MDS). The latter method consists in responding with a finger press as soon as a near-continual tempo change is detected. With the MCS, there was no preference, as estimated by the point of subjective equality, between acceleration and deceleration in the monotonal condition, but there was a preference in the musical condition that indicated more facility for estimating decelerations than accelerations. The results obtained with the MDS are consistent with the MCS results, given that the response time was faster for decelerations than accelerations in the musical condition but not in the monotonal condition. We conclude that the MDS is a sensitive tool for investigating slight tempo variations.

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THIS article addresses the question of sensitivity to time between events. The traditional psychophysical perspective on time perception has emphasized very simple experimental conditions, involving the categorization or discrimination of single intervals (see Allan & Kristofferson, 1974; Grondin, 2001; or Nakajima, 1987). Much research has been done recently on duration discrimination in contexts using sequences of events, which have more ecological validity than sequences of sounds, which are present, for instance, in speech or music (Jones & Boltz, 1989; ten Hoopen et al., 1994, 1995).

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Some fundamental ideas exist about the basis of sensitivity for discriminating intervals embedded in series of signals. One is that there is an internal clock device that operates via an oscillating process (Barnes & Jones, 2000; Large & Jones, 1999; McAuley & Jones, 2003). Some authors report that such an oscillating device would have a fundamental internal periodicity (Vos, van Assen, & Franek, 1997). Another fundamental idea about sensitivity to time and to tempo variations is that every individual, when asked to spontaneously produce a tempo with a series of digital taps, for example, will have a preferred tempo, the so-called spontaneous motor tempo (Drake, Jones, & Baruch, 2000; Fraisse, 1984).

The general aim of this article is to develop a tool that could eventually serve for investigating the presence of a fundamental frequency. This fundamental frequency is argued to correspond to a point where there would be no difference between the ease with which acceleration and deceleration are detected (Vos et al., 1997). The literature indicates that such a frequency could exist within the indifference interval (Barnes & Jones, 2000; Fraisse, 1984; Vos et al., 1997). More specifically, this interval corresponds to a range of durations circa 1.45 to 2.0 Hz, that is, to conditions where there are 500 to 700 ms between events. Since this indifference interval is fairly large, developing a new method would make it possible to locate a fundamental frequency within the interval more precisely.

Vos et al. (1997) have proposed an approach for studying the fundamental frequency. When stimuli used in experimental contexts are close to this frequency value, sensitivity to tempo variations should be maximal (Vos et al., 1997). In other words, subtle temporal differences would be perceivable for a very narrow range of frequencies, and there would be no bias regarding relative sensitivity to accelerations versus decelerations. Preference for acceleration or deceleration would depend on the fact that the initial frequency of initial sounds is faster or slower than the fundamental frequency of an internal clock. For instance, if a tempo is faster than the fundamental frequency, the tempo of a listener's internal beats is inclined to decelerate, relative to the stimulus, and the listener will be biased toward acceleration responses (Vos et al., 1997; Figure 1).

Precise exploration of such a fundamental frequency, or of a narrow range of critical event frequencies where no bias would be found, requires a sensitive tool that would allow many trials to be carried out in various experimental conditions in a time-effective manner. This article aims to propose such a method, a method that is original in that it emphasizes the continuity of changes.

The general strategy adopted here involves contrasting the results of a new method, the *method of dynamic stimuli* (MDS), with those obtained using the *conventional method of constant stimuli* (MCS). The MCS is known to be a very reliable psychophysical procedure, but also a time-consuming one. Typically, estimating a single threshold for one participant

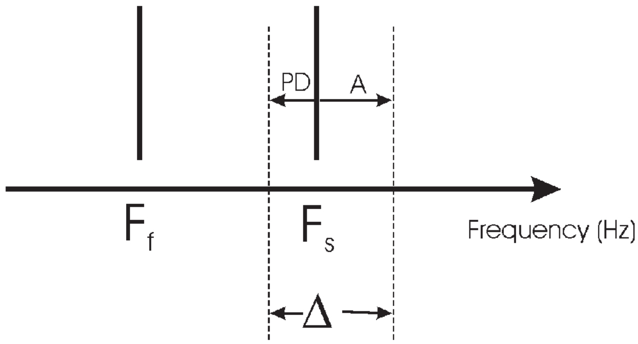

Fig. 1. Hypothesis regarding the relative facility for detecting acceleration and deceleration. If a tempo (at a starting frequency F_S) is faster than a so-called fundamental frequency (F_f), then a listener is biased toward acceleration responses (A) because the internal beat is prone to deceleration (PD) relative to the stimuli. This results in a greater perceptual difference (Δ).

with the MCS may require hundreds of trials. Moreover, another disadvantage of this method is that it requires using trials in which there is only one change between a standard stimulus and a comparison stimulus. In other words, changes from the presentation of a standard stimulus to the presentation of the comparison stimulus are abrupt and the comparison stimulus is kept constant.

In the context of music perception, for instance, the capacity of detecting gradual tempo changes is fundamental. The main feature of the MDS is that it uses gradual tempo changes. We propose to use gradual and continuous tempo variations after presenting the standard stimulus, and to employ response time as a measure for estimating relative sensitivity (bias) to accelerations and decelerations. Technically, this means that, with a single trial, we can estimate a sensitivity threshold, that is, a point, as estimated by the response time, where a participant becomes capable of detecting the change. Of course, the response time will depend on the abruptness of the series of tempo changes. That is the reason why several slopes of changes will be adopted in the experiment proposed next.

In the present experiment, these two methods will be used with a 100 beats per minute (bpm) standard tempo (or 1.667 Hz), which is argued to reflect the presence of a fundamental frequency (Vos et al., 1997), and in two different contexts, one musical and the other monotonal. In the musical context, a musical excerpt is presented, while, in the monotonal context, a simple series of piano notes is presented. Not very many experiments comparing tempo sensitivity in musical versus monotonal contexts are available in the rhythm literature. However, such comparisons are most relevant, as it is known, for example, that musicians can be particularly sensitive to tempo decelerations in musical performances (Madsen, 1979; Madsen, Duke, & Geringer, 1984). Tempo bias for acceleration versus deceleration in monotonic contexts versus musical ones may well be different. If so, using an MCS should reveal different performance estimates for the two contexts. If the MDS is valid, any difference observed with the MCS should also be observed with the MDS.

The main purpose of the present experiment is to test a new method, the MDS, for estimating sensitivity for detecting tempo changes. The results obtained with this method will be compared to those obtained with a more classical method, the MCS. More specifically, this comparison will be made in a context where relative sensitivity to accelerations and decelerations is tested. This relative sensitivity is argued to be related to the fundamental frequency of some oscillating process (Vos et al., 1997). If the MCS reveals a bias toward detecting one direction of change more easily than the opposite direction, this same bias should also be revealed with the MDS if this new method is valid. Moreover, whether or not a preference for accelerations versus decelerations is observed might depend on the nature (monotonal vs. musical) of the sequence of stimuli. This issue will be part of the present study and, at the same time, will provide a new opportunity to directly compare relative sensitivity to tempo changes in musical versus monotonal contexts.

Method

PARTICIPANTS

Twenty participants with normal audition—8 men and 12 women between 17 and 40 years of age (mean = 22.95)—took part in all conditions of the experiment.

APPARATUS

A Pentium III running Windows 98 SE without any networking connection was used for the tests with a program written in C++ by the first author. This program, which employs DirectX version 8 (multimedia programming interface with a ±5 ms accuracy), made it possible to present sequences composed of audio and MIDI files, and to store the information related to the stimuli and response time. The sound source was composed of amplified speakers connected to the computer audio output from a Sound Blaster Live soundcard. The stimuli were presented at a comfortable auditory level of about 55 dB. The monotonal stimuli were a series of C_4 notes using the same piano sound as the musical stimuli. All stimuli were generated by MIDI files with a duration of 167 ms at a tempo of 100 bpm.

PROCEDURE

The procedure was essentially the same for both MCS and MDS conditions: only the comparison stimuli were different (Figure 2). The initial tempo—the standard—was 100 bpm (1.667 Hz). The MCS test had 10 abrupt variations (5 accelerations and 5 decelera-

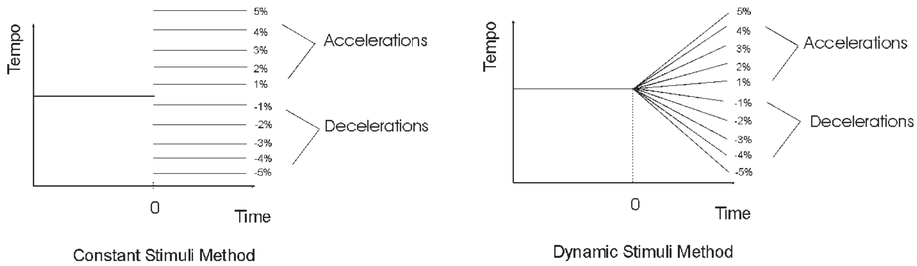

Fig. 2. Illustration of the constant method (left panel) with abrupt steps and of the dynamic stimuli method (right panel) with gradual changes. With the dynamic stimuli method, the 1% change is reached after 2 s.

tions) that ranged from 1% to 5% from the initial tempo, with 1% steps. The MDS test had 10 gradual variations (5 accelerations and 5 decelerations), which consisted of a 1%, 2%, 3%, 4%, or 5% change per 2 s, in comparison with the initial tempo. There was no 0% change condition, or catch trial, because this type of trial would not have led to a response. Therefore, there would not have been any response time, which is the dependent variable for the MDS. The tempo variation (i.e., the end of the standard presentation) occurred randomly at the 8th or at the 10th tempo event (4.2 s, 6 s) for all conditions. The musical content was either a monotonal piano note (middle C) (monotonal condition) or a portion of Chopin's Prelude in E Minor, Opus 28, No. 4, which has a constant rhythm with subtle changes on the left hand while the right hand is playing a very simple melody with very little rhythm (musical condition). Each version of the stimuli was presented 3 times (2 onsets × 2 monotonal/musical × 10 variations of tempo × 3 trials), for a total of 120 trials for both the MCS and the MDS.

The experimental trials were separated into 4 blocks: MCS–Monotonal, MCS–Musical, MDS–Monotonal, and MDS–Musical. Participants were randomly assigned to one of two orders of method presentation: half started with the MCS and the other half with the MDS. In both cases, the monotonal block was used first, followed by the musical excerpt block. The monotonal versus musical block was not randomized because pilot trials had shown that participants starting with the musical excerpt had severe problems performing the task: participants apparently understood more easily the concept of tempo changes in the monotonal context.

Participants were given instructions via audio files and text screens on the computer for each part of the test. In both cases, the practice trials consisted of four auditory stimuli presented successively with feedback, which indicated whether or not participants had given the correct response. Feedback was used to make sure they understood the procedure and the tempo concept in both the monotonal and musical contexts. Participants were instructed to first make sure they detected a change before stopping the sequence. Second, they were told to react as quickly as possible. When ready, they hit the space bar once to play an auditory stimulus and left their index finger on the space bar. When a tempo change was detected, they hit the space bar and thereby interrupted the stimulus. The recorded response time included the movement time. Participants were then asked via a display screen if they had perceived an acceleration or a deceleration. They entered the result on the numeric keypad, tapping on the plus sign to indicate an acceleration and on the minus sign to indicate a deceleration. They hit the spacebar when they were ready for the next trial. A practice run with feedback was available for each test to make sure that participants understood the procedure.

The order of presentation of other factors (length of the standard, difficulty level, and acceleration vs. deceleration) was randomized within each monotonal or musical condition for the MCS and MDS.

Results

METHOD OF CONSTANT STIMULI

A 10-point psychometric function was traced for each experimental condition (grouped data), with the 10 comparison tempo variations (from slower to faster) plotted on the *x*-axis and the probability of responding "faster" on the *y*-axis. The *cumulative normal distribution* was fitted to the resulting curves. The proportion of variance accounted for, or the R^2 parameter, was used to estimate the goodness-of-fit. R^2 values were .995 and .978 for the musical and monotonal conditions, respectively, in the short standard condition, and .968 and .929 in the long standard condition. (Figure 3).

On each psychometric function, the critical dependent variable in the present analysis is the point of subjective equality (PSE). The PSE is

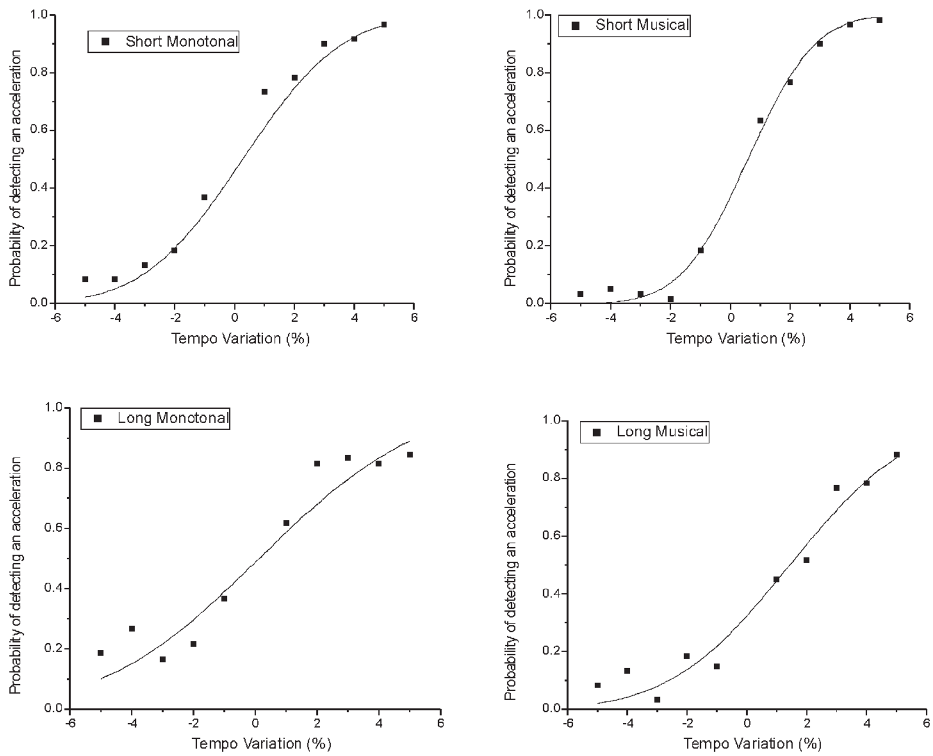

Fig. 3. Psychometric functions in the monotonal and musical conditions in each standard-length condition (top panels: short; bottom panels: long) with the constant method. Each data point on the functions is a mean result for all participants. Functions are based on the cumulative normal distribution.

defined as the *x* value that corresponds to the 0.50 probability of "faster" responses on the *y*-axis. In both standard conditions, there is an important difference between the musical and monotonal conditions. In the short standard condition, the PSE equals 0.59 and 0.28 bpm in the musical and monotonal conditions, respectively; and, in the long standard condition, 1.44 and 0.13 bpm, respectively. In other words, in each standard condition, the PSE is clearly higher in the musical condition, which means that far more "deceleration" responses were delivered by participants.

Finally, although response time is not as critical with the MCS as it is with the MDS, it should be noted that it varied, in the ±5% to ±1% change conditions respectively, from 1.33 to 3.67 s (short standard) and from 1.2 to 3.59 s (long standard) in the monotonal condition; and, in the music condition, from 1.54 to 4.76 s (short standard) and from 1.45 to 4.01 s (long condition).

METHOD OF DYNAMIC STIMULI

Only valid entries, that is, those without anticipation and without error in identifying acceleration or deceleration, were kept for the final analysis of response times (90.0% of responses were correct). Figure 4 shows the mean response time, for each level of difficulty for acceleration and deceleration, in the musical and the monotonal conditions. Response times were asymmetric for accelerations and decelerations in the musical condition, but not in the monotonal condition.

A 5 (difficulty level, ±1%, ±2%, ±3%, ±4%, ±5%) × 2 (standard length) × 2 (mono/music) × 2 (accel./decel.) repeated-measures analysis of variance was used to analyze the response time data (with the Greenhouse-Geisser correction when required). The difference between response times for the various difficulty levels was significant ($p < .01$), with greater difficulty leading to increased response times. The difference between response times for acceleration and deceleration was also significant ($p < .05$), with decelerations showing the shortest response times. Most importantly, this acceleration/deceleration effect interacted significantly with the mono/music effect ($p < .01$). Moreover, the triple interaction involving the mono/music, difficulty level, and accel/decel effects was significant ($p < .01$). A post-hoc analysis, using repeated *t*-tests (with *p* levels adjusted) for comparing the acceleration versus deceleration conditions, indicated that, for all difficulty levels, participants responded faster in the deceleration condition with musical stimuli, but did not do so with monotonal stimuli. The triple interaction highlighted differences of limited interest in the present context: for decelerations, there was a significant difference between the musical and monotonal conditions at 1% but not with other percentages, whereas, for accelerations, there was no signifi-

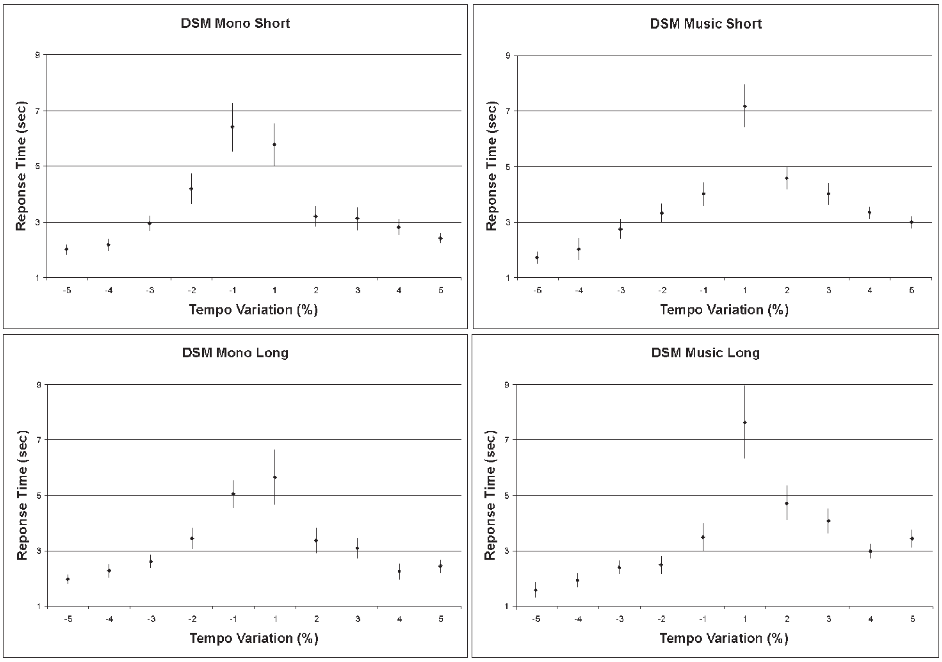

Fig. 4. Mean response time for each acceleration and deceleration condition in each standard-length condition (upper panels: short; lower panels: long) with the dynamic stimuli method (bars are standard errors).

cant difference between the musical and monotonal conditions at 1%, although the differences were significant for other percentages.

Discussion

The main purpose of the present experiment was to compare the results obtained with a new method for investigating tempo sensitivity, the MDS, with those obtained with a classical method, the MCS. Relative sensitivity to accelerations and decelerations was the critical basis of comparison, and this was tested in monotonal and musical conditions. The main finding of the experiment was the between-method consistency of the results for the acceleration versus deceleration issue. With both the MCS and the MDS, results differed according to whether monotonal or musical stimuli were used. In the monotonal conditions, the PSEs were close to 0 (0.28 and 0.13) with the MCS, while in the musical conditions, PSEs were closer to 1 (1.44 and 0.59). Strictly speaking, this means that the comparison intervals were generally perceived as being slower than the standard in the musical conditions. It also reveals that more correct responses were given for deceleration than for acceleration. This particular fact is actually consistent with the asymmetric results in the musical condition for acceleration versus deceleration conditions with the MDS (response times). Response times were faster for deceleration than for acceleration, but only in the musical condition; no difference was observed in the monotonal one.

The observation that the acceleration versus deceleration results obtained with the MDS are consistent with those obtained with the MCS opens the door to new possibilities for future investigations of tempo sensitivity. The new method proposed here has several advantages over the MCS. The MDS not only requires few trials for judging relative sensitivity to accelerations and decelerations, but also shows that relative sensitivity can be revealed with any of the levels (1% to 5%) investigated in the present experiment. In searching for the value of the fundamental frequency of an internal timekeeping system, that is, a value where there would be no preference for acceleration or deceleration, the possibility of rapidly detecting specific sensitivities to accelerations and decelerations is critical.

As regards this fundamental frequency issue, our results already reveal that using monotonal versus musical stimuli leads to different conclusions: No preference for accelerations or decelerations was observed when monotonal stimuli were used, but significant differences were noted with musical stimuli. Does the near lack of preferences for acceleration or deceleration in the monotonal condition mean that the 100-bpm range (IOI = 600 ms) represents the critical value of an internal clock? Obtaining a final answer to this question would require more investigation aimed at establishing, for intervals longer or shorter than 600 ms, exactly how limited the range of this nonpreference is. The MDS could be most helpful in providing a precise answer to this question. For now, our results are consistent with those of Vos et al. (1997), who also used monotonal sequences.

On the other hand, it remains to be determined why we found a difference between musical and monotonal conditions. Clues for answering this question should be discovered through a more precise assessment of performances with both musical and monotonal conditions. In the musical condition, a much wider range of standard values than the one used here (100 bpm), as well as a much wider variety of musical conditions (different excerpts) must be employed. Using monotonal conditions with different notes, and notes played with different instruments should also provide clues for painting a clearer picture of the internal timekeeping mechanism.

Finally, the fact that the protocol had to be implemented using the monotonal stimuli first raises some questions. This could mean that the results for the musical condition are specific to the protocol adopted. On the other hand, monotonal trials can make the tempo concept simpler for nonmusicians to understand and provide them with enough practice and knowledge to increase their ability to perform difficult tempo discrimination tasks. Another possibility is that the internal clock is set by monotonal trials. Using different tempi in the monotonal and the musical conditions, respectively, could eventually indicate which of these hypotheses is valid.

In conclusion, we believe that the method of dynamic stimuli is a sensitive tool for studying fundamental aspects of rhythm perception. Compared with the method of constant stimuli, it not only has the advantage of requiring fewer experimental trials to reach a verdict regarding relative sensitivity to acceleration and deceleration, but also provides a certain ecological validity, because it brings us closer to the continuity of signals normally used in contexts such as speech and music, where time is so critical. In addition, the new method offers a new tool for investigating the relative efficiency of musicians and nonmusicians for tempo sensitivity. Using a method based on gradual changes should magnify the sensitivity difference between musicians and nonmusicians (Grondin & Laforest, 2004). Such an investigation could now be done easily in a wide variety of tempo conditions.[1]

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