Travelling Through Pitch Space Speeds up Musical Time

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Several models of time estimation have been developed in psychology; a few have been applied to music. In the present study, we assess the influence of the distances travelled through pitch space on retrospective time estimation. Participants listened to an isochronous chord sequence of 20-s duration. They were unexpectedly asked to reproduce the time interval of the sequence. The harmonic structure of the stimulus was manipulated so that the sequence either remained in the same key (CC) or travelled through a closely related key (CFC) or distant key (CGbC). Estimated times were shortened when the sequence modulated to a very distant key. This finding is discussed in light of Lerdahl's Tonal Pitch Space Theory (2001), Firmino and Bueno's Expected Development Fraction Model (in press), and models of time estimation.

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In subjective time research, there are two main procedural paradigms for the study of time estimation behavior, prospective or retrospective: respectively, the participant is warned about the time estimation task before or after the stimulus presentation (Zakay, 1990). Since the present study approaches large music structures—such as tonality and modulation—supposedly implying tacit high order cognitive structures, the retrospective (unexpected) paradigm seemed appropriate (Firmino & Bueno, in press; see also Poynter, 1983). Music stimuli or conditions are very useful for experimental time perception questions once music theory has abundant parametrical descriptions of compositional structures (Bailey & Areni, 2006; Boltz, 1989; Bueno & Ramos, 2007; Bueno, Firmino, & Engelmann, 2002; Schmuckler & Boltz, 1994).

Several models have been used to explain subjective time estimation (see Block, 1990, for a review). The storage size model (Ornstein, 1969) states that a large amount and high complexity of information require a large space in memory, and thus produce long time estimations. The attention model (Hicks, Miller, Gaes, & Bierman, 1976) considers that the more the attention demanded by a task, the more the mental effort would be demanded in storing temporal information in memory, and hence, the longer the time estimation would be. The contextual change model (Block & Reed, 1978) claims that the remembered duration involves a cognitive reconstruction of the environmental information that surrounds the stimulus: more recalled contextual changes cause longer time estimations. An expectation model (Jones & Boltz, 1989) relates subjective time to the patterns of events. The model predicts that a sequence of events ending at the "right time" would confirm expectations and would elicit quasi-precise estimations ("zero-contrast"). A sequence of events ending later than expected would seem longer and would elicit overestimations ("positive-contrast"). A sequence of events ending earlier than expected would elicit underestimations ("negative-contrast").

Several experiments carried out by Boltz and collaborators support the contrast model (Boltz, 1991, 1993a, 1993b, 1995). This model emphasizes the temporal and rhythmic properties of musical sequences as well as the contribution of Western pitch structure at the level of tones (Boltz, 1989) or chords (Schmuckler & Boltz, 1994) in musical time estimation. As far as we know, the importance of a higher level of Western pitch structure, such as the tonality level, has not yet been investigated in time estimation studies. This is surprising, since excursions to different keys are typically utilized as tools to achieve extended musical discourse or development and aesthetic expressiveness (Schenker, 1935/1979). Tonal modulation articulates temporal features by reference to the original and destination keys, and by key change per se. Music cognition studies have usually approached tonality and modulation as an almost static domain, in the sense that these pitch structures should be only tangentially related to the temporal dimension of music (Krumhansl, 1990, 2000; Shepard, 1982; Tillmann, Bharucha, & Bigand, 2000). As a consequence, the

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importance of modulation for musical time estimation remains an uninvestigated issue.

When taken in combination with Lerdahl and Jackendoff's Generative Theory of Tonal Music (1983; hereafter GTTM), the theory of Tonal Pitch Space (hereafter TPS) by Lerdahl (1988, 2001) offers an interesting perspective on this issue. Both models imply harmonic structures as dynamic (Bigand, 2003). In TPS, Western pitch structure is represented in the form of a three-dimensional space for pitches (and pitch classes), and four-dimensional space for chords and keys (regions). The distance between two events may be computed by considering their places in the musical context in which they occurred. Harmonic structures may thus be formalized in the shape of a *journey through pitch space*, each step of this journey being quantified precisely by a combination of both GTTM and TPS. A core principle for this computation is that of the "shortest path": the distances between two events are calculated as their smallest possible value. When the path is also understood regarding its unfolded corresponding time, the concept of *velocity* appears (Firmino & Bueno, in press): for an equal unit of time, long paths through pitch space would imply greater velocities than short paths. In this sense, TPS may be used to predict the specific effect of tonal modulations on musical time estimation. A chord sequence would induce a feeling of shorter time when it modulates to a distant key than when it moves to a closely related key or remains in the same key.

Method

Participants

The participants were 45 college students (men = 22; women = 23), aged between 17 and 30 years, from University of São Paulo at Ribeirão Preto. All participants reported having normal hearing; none reported specific training in music.

Stimuli and Apparatus

The stimuli consisted of three sequences of 29 isochronous chords, following the basic rules of harmony as found in standard texts (Piston & DeVoto, 1987; Schoenberg, 1922/1974). All chords were major or minor triads with no omission or doubling of any note. In accordance with prescriptions by Shepard (1964) and Krumhansl, Bharucha, and Kessler (1982), each tone was a complex sound composed of five partials in perfect octaves (2:1). Thus, each chord formed a sound pulse with 15 different partials. In the "nonmodulation" condition, the sequence remained in C major. In the "near key condition," the sequence started at C major, modulated to F major (pitch distance of 5 relative to C major, in Lerdahl's TPS), and then came back to C major. In the "distant key condition," the sequence started at C major, modulated to Gb major (pitch distance of 31, in Lerdahl's TPS), and then returned to C major. These musical stimuli were 20-s long. Each chord was 0.689-s long, except the last chord that was 0.708-s long. The experiment was carried out in a quiet room with an IBM-PC notebook microcomputer with an extra keyboard, using WaveSurfer software for task monitoring and response and reproduction time storage.

Procedure

Participants listened with headphones to one of the three sequences. At the end, they were unexpectedly requested to reproduce the duration of the listened music (retrospective paradigm). Participants subsequently pressed the "initiate" and the "finish" keys of the extra keyboard, marking with beeps the beginning and ending of a silent time interval, which had to correspond to the listened music duration. Thus, the following instructions were presented to the participants: (a) before the listening: "You have to push the play-key to listen to very simple music through the headphones. When the music finishes, you take off the headphones, and I give you the next instructions. Put on the headphones in a comfortable way and you can start whenever you want." (b) after the listening: "You push the initiate-key and you let the time pass by. When you think that the time that is passing by is the same as the time of the listened music, you push the finish-key. Put on the headphones and start whenever you want." The different key (tonal region) distances defined the between-group variables.

Results

Table 1 displays the means and standard deviations of time reproductions for each group of participants relative to modulating sequences. There was an overall tendency for time overestimation regarding the 20-s of the stimuli. Overestimations were the highest for the nonmodulating sequences and, to a lesser extent, for the closely related key condition. An ANOVA confirmed a significant effect of modulation on time estimation, $F(2, 42) = 9.85$ $p < 0.05$ ($MSE = 192.32$). Posthoc analysis using the Duncan test indicated that the longest distance modulation elicited the shortest time estimation.

TABLE 1. Means and Standard Deviations of Retrospective Time Estimations for Three Modulating Chord Sequences (20-s each)

	Mean (s)	Standard Deviation (s)
CC	26.28	4.92
CFC	25.05	4.21
CGbC	19.56	4.08

Discussion

The influence of tonal modulation has been demonstrated with tasks such as probe tone ratings (Krumhansl & Kessler, 1982; see also Bharucha 1987), tension relaxation measurements (Bigand & Parncutt, 1999; Lerdahl & Krumhansl, 2007), or priming tasks (see Bigand & Poulin-Charronat, 2006, for a review.). Bigand, Parncutt, and Lerdahl (1996) showed that the feeling of musical tension was correlated with the distance travelled through pitch space, with more tension for progressions such as CGbC than for CFC or CCC. The present data demonstrate that travelling to a distant key (CGbC) results in a shorter estimated time than travelling to a related key or nonmodulation. This finding is consistent with Firmino and Bueno (in press), who showed time underestimation for chord sequences exhibiting a sudden modulation at the end of the sequence (CGb). Interestingly, the authors found that the effect of modulation on time estimation was reduced when the modulation was achieved progressively (CEbGb). The present study confirms that bias in time estimation is not strictly caused by the occurrence of a specific event that occurs on time—early or late—at the end of a musical sequence (Boltz, 1989). In the present case, the sequence exhibited a progressive modulation in the middle section that moved from the main key. This change had no effect on estimated time when music moved toward a closely related key, but it had an effect when the new key was distant.

This finding demonstrates that tonal modulation is a relevant parameter that affects retrospective time estimation in music. This effect is difficult to account for in either the storage size or attention models (Hicks et al., 1976; Ornstein, 1969) of time estimation. All chord sequences provided an identically low level of stimulus (i.e., number of notes, rhythmic structure or even psychoacoustic features). If we suppose that modulation defined one unit of information at some abstract level, these models should anticipate time overestimation for modulating sequences in comparison to nonmodulating ones. The data of the present study show new evidence against this prediction (see also Firmino & Bueno, in press).

Modulation involves large-scale structures. To be perceived, information relative to the initial musical key still needs to be present in working memory when the modulation section occurs (Schacter & Tulving, 1994; for a debate in music, see Cook, 1987; see also Lalitte & Bigand, 2006). Thus, models of time estimation should necessarily contain a memory component to account for this effect. A working memory component is likely to play a considerable role in the retrospective time reproduction task. The present finding also shows that knowledge of Western tonal hierarchies influences musical time estimation in Western listeners. The term "tonal hierarchy" is used to designate a nontemporal schema of pitch regularities, specific to Western music, which is stored in long-term memory. It is nontemporal in the sense that it represents more or less permanent knowledge about the musical system, rather than being a response to a specific sequence of events. Accordingly, this high order musical knowledge of tonality relationships has some similarities to the concept of human semantic memory, since both are implicitly acquired by passive environmental exposure (Schacter & Tulving, 1994; Tillmann et al., 2000). Therefore, a relevant model of time estimation in music should involve two memory components: working memory and long term (or semantic) memory.

Firmino and Bueno (in press) proposed the Expected Development Fraction Model (EDF-model) that involves these two components. In this model, knowledge of Western musical hierarchies also includes knowledge of durations of travel in Western tonal pitch space. Implicit learning, occurring in everyday life, results in more than the storing of statistical regularities among tones, chords, and keys (Tillmann et al., 2000). Western listeners have also stored the average velocity of Western music in its travels through pitch space. This temporal information associated with tonal pitch space is activated when listening to Western music. The expected duration of a piece is compared to the experienced duration and stored in working memory. In the EDF-model, this comparison is expressed as a coefficient calculated by dividing the anticipated time duration mapped in semantic memory by the perceived duration stored in working memory. This temporal coefficient is applied to the working memory duration leading to time underestimation.

After participants are instructed to listen to a piece of music, an attentional process occurs relative to the music. The comparison between the temporal contents from both working and semantic memories occurs during the time reproduction task. The listened music (according to working memory) seems shorter than the expected music (according to semantic memory), so that a subsequent estimation of the music duration will analogously become shorter. The larger the travelled tonal pitch space is, the shorter the time estimation will be. There will be greater impact from sudden modulations (i.e., modulating within few chords) than from gradual ones (i.e., with intermediate keys and over several chords; Firmino & Bueno, in press).

To summarize, when gathered together, the EDF-model and TPS may explain the shorter duration estimation for the CGbC stimulus than for the CC and CFC stimuli. The key-change velocity concept is associated with time underestimations. Lerdahl's TPS offers quantified pitch/chord/key cognitive distances that extend such an idea. The EDF-model accounts for forward and reverse modulations concerning timing effects. Both models are being examined further through two experiments exploring other relevant key journeys; namely, the clockwise (CAF#) *versus* counterclockwise (CEbGb) sides of the cycle of fifths and the relative (CAmA) *versus* cycle of fifth paths (CGDA; Firmino, Bueno, & Bigand, 2008).

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