Psychological Research (2004) 69: 115–123
DOI 10.1007/s00426-003-0164-3

ORIGINAL ARTICLE

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Aspects of temporal information processing: A dimensional analysis

Received: 26 May 2003 / Accepted: 8 October 2003 / Published online: 31 January 2004

Abstract A major controversy in the field of prospective temporal information processing refers to the question of whether performance in various temporal tasks can be accounted for by the general assumption of an internal clock rather than by distinct, task-specific timing mechanisms. Therefore, the present study was designed to identify dimensions of temporal information processing. For this purpose, 120 subjects performed eight psychophysical temporal tasks. Correlational and principal factor analyses suggested a common pacemaker-based interval timing mechanism involved in duration discrimination, temporal generalization, and temporal order judgment. On the other hand, rhythm perception and perceived simultaneity/successiveness appeared to be controlled by task-specific processes unrelated to interval-based timing.

Introduction

A major controversy in research into prospective temporal information processing refers to the question of whether psychological time represents a unitary concept or consists of distinct elementary temporal experiences. While the latter view implies different mechanisms underlying specific temporal experiences, a unitary concept of temporal processing would be consistent with the general idea that temporal information processing may depend on a universal timing mechanism referred to as a 'master clock.' The present study was designed to investigate whether the notion of a single master clock or the assumption of several independent timing mechanisms provides a more valid account for various aspects of prospective temporal processing.

Within the framework of prospective human timing, the idea of different elementary time experiences such as simultaneity and successiveness, temporal order judgment, rhythm perception, or interval timing has been put forward by several authors (Block, 1990; Fraisse, 1984; Friedman, 1990; Pöppel, 1978). This notion has been accompanied by the assumption that these elementary time experiences are associated with distinct timing mechanisms. In the following, the above-mentioned elementary time experiences will be briefly characterized.

Investigations into *simultaneity* and *successiveness* are concerned with the size of the temporal interval between two events that is required for them to be perceived as two separate events (successiveness) rather than fused as one event (simultaneity; for a concise review see Fraisse, 1984). Auditory or visual fusion thresholds, for example, represent an indicator of this type of temporal resolving power.

Temporal order judgment (TOJ) refers to the question of how much time must intervene between the onsets of two different stimuli for their order to be perceived correctly. Models of TOJ basically assume that processing of temporal order depends on specific aspects of temporal resolution (e.g., Sternberg & Knoll, 1973; Ulrich, 1987).

Rhythm perception refers to the subjective grouping of objectively separate events (Demany, McKenzie, & Vurpillot, 1977) or discrimination processes in serial temporal patterns (ten Hoopen et al., 1995). Typically, in psychophysical rhythm perception tasks, the subject is presented with a click pattern, devoid of any pitch, timbre, or dynamic variations to avoid possible confounding influences on perceived rhythm. The subject's task is to detect a deviation from regular, periodic click-to-click intervals. The perception of temporal deviations

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in isochronous patterns may be accounted for by an interval-based (Keele, Nicoletti, Ivry, & Pokorny, 1989; Pashler, 2001) or beat-based (McAuley & Kidd, 1998; Povel & Essens, 1985) timing mechanism.

Interval timing and *duration discrimination* are often explained by the general assumption of a hypothetical internal clock based on neural counting (e.g., Creelman, 1962; Gibbon, 1977; Killeen & Weiss, 1987; Rammsayer & Ulrich, 2001; Treisman, Faulkner, Naish, & Brogan, 1990). This means that a neural pacemaker generates pulses and that the number of pulses relating to a physical time interval is recorded by an accumulator. Thus, the number of pulses counted during a given time interval is the internal representation of the interval. Although the concept of neural counting has been a central feature of many theoretical accounts of interval timing, several factors influencing timing performance argue against the general validity of this assumption. For example, there are two types of stimuli used in duration discrimination studies; one type is the filled interval and the other type is the empty interval. In filled intervals, the onset and the offset of a continuous signal serve as markers, whereas an empty interval is a silent duration marked by an onset and an offset signal with no stimulus present during the interval itself. Experimental evidence suggests that interval timing is affected by stimulus type and, thus, temporal processing of filled intervals may be functionally different from processing of empty ones (Craig, 1973). Furthermore, interval timing and duration discrimination are also influenced by cognitive factors such as attention (e.g., Brown, 1997; Grondin & Macar, 1992; Zakay & Block, 1996) and memory processes (e.g., Fortin & Breton, 1995; McCormack, Brown, Maylor, Richardson, & Darby, 2002). Since cognitive influences were shown to be more pronounced for intervals longer than approximately 500 ms, it has been proposed that temporal processing of longer intervals is cognitively mediated (Michon, 1985; Rammsayer & Lima, 1991) while temporal processing of extremely brief intervals is explained by the assumption of an internal timing mechanism not accessible to cognitive control (Rammsayer, 1999).

It should be noted, however, that during the last four decades, a considerable number of studies, not directly related to interval timing, put forward the notion of a hypothetical master clock controlling information processing. Since many perceptual tasks similarly require processing changes in information over time, Surwillo (1968) introduced the idea that an internal timing mechanism in the brain is responsible for coordination of different neural activities. More recently, Burle and Bonnet (1997, 1999) also provided experimental evidence of the existence of some kind of master clock in the human information processing system. Also, in the field of human interval timing, several studies supported the notion of a common timing mechanism involved in both perception and production of temporal intervals (e.g., Ivry & Hazeltine, 1995; Keele, Pokorny, Corcos, & Ivry, 1985; Pashler, 2001; Treisman, Faulkner, & Naish, 1992). These studies, however, exclusively focused on time perception and production. On the other hand, two recent correlational studies (Robertson et al., 1999; Zelaznik, Spencer, & Doffin, 2000) suggested that different mechanisms are involved in the timing of discrete and continuous actions.

To our knowledge, no data seem to be available that may help to elucidate the dimensional structure of temporal performance obtained with a wider variety of different elementary temporal tasks. Therefore, the primary goal of the present experiment was to investigate whether there is evidence of a hypothetical master clock providing a task-independent general processing system for various aspects of temporal information. For this purpose, a sample of 120 participants was tested on eight temporal tasks.

There are two major methodological approaches to investigating whether tasks that require precise timing are dependent on a common mechanism. The correlational approach is based on the assumption that if the same timing mechanism is involved in two tasks, the performance or timing variability of both tasks should be highly correlated. An alternative approach represents the slope analysis method (Ivry & Hazeltine, 1995) derived from Getty's (1975) generalization of Weber's law. Basically, within the framework of slope analysis, changes in variability as a function of the standard duration can be compared across tasks. If the slope of the variability functions of two tasks is equivalent, a common timing mechanism for both tasks is inferred. Since this elegant approach necessitates systematic variation of the standard duration, its applicability is restricted to temporal tasks based on interval timing such as duration discrimination or production tasks. Thus, for temporal tasks, such as TOJ and simultaneity/successiveness tasks, that are primarily associated with temporal resolving power rather than the timing of an interval itself, slope analysis is not applicable. Therefore, in the present study, we applied a correlational, factor-analytic approach. Exploratory principal factor analysis (PFA) was used to analyze a set of eight temporal tasks. In PFA, the common variance of the eight temporal tasks is analyzed, while error and unique variance is excluded. Therefore, the first principal factor obtained by PFA represents a feasible way of determining the degree to which each of the temporal tasks is correlated with a latent dimension that is common to all analyzed tasks (cf., Jensen, 1998; Tabachnick & Fidell, 2001).

Materials and methods

Participants

Participants were 58 male and 62 female volunteers ranging in age from 18 to 51 years (mean and standard deviation of age: 26.0 ± 7.5 years). All participants had normal hearing and normal or corrected-to-normal sight. Furthermore, all participants reported that they had never played any musical instruments nor were they especially interested in music.

Duration discrimination tasks

Because interval timing may be influenced by type of interval (filled vs. empty) and base duration, the duration discrimination task consisted of one block of filled and one block of empty intervals with a base duration of 50 ms each, as well as one block of filled intervals with a base duration of 1,000 ms.

Stimuli

Filled intervals were white-noise bursts from a computer-controlled sound generator (Phylab Model 1), presented binaurally through headphones (Vivanco SR85) at an intensity of 67 dB SPL. The empty intervals were marked by onset and offset clicks of 3 ms duration, with an intensity of 88 dB. These intensity levels were chosen on the basis of the results of a prior pilot experiment in which 12 participants were asked to adjust the volume of a 3-ms click until it matched that of a 1,000-ms white noise signal.

Procedure

The order of blocks was counterbalanced across participants. Each block consisted of 64 trials, and each trial consisted of one standard interval (= base duration) and one comparison interval. The duration of the comparison interval varied according to an adaptive rule (Kaernbach, 1991) to estimate *x.25* and *x.75* of the individual psychometric function, i.e., the two comparison intervals at which the response "longer" was given with a probability of .25 and .75 respectively. In each experimental block, one series of 32 trials converging to *x.75* and one series of 32 trials converging to *x.25* were presented. Within each series, the order of presentation for the standard interval and the comparison interval was randomized and balanced, with each interval being presented first in 50% of the trials. Trials from both series were randomly interleaved within a block.

Within each trial, the two intervals were presented with an interstimulus interval (ISI) of 900 ms. The participant's task was to decide which of the two intervals was longer and to indicate his or her decision by pressing one of two designated response keys. After each response, visual feedback ("+," i.e., correct; "–," i.e., false) was displayed on the computer screen. The next trial started 900 ms after the feedback. As an indicator of discrimination performance, half the interquartile ranges [(75%-threshold value–25%-threshold value)/2], representing the difference limen (DL; Luce & Galanter, 1963), was determined for each duration discrimination task.

In previous studies performed to evaluate the sensitivity of assessment, Cronbach's coefficients were shown to range from .82 to .99 for the duration discrimination tasks (Brandler & Rammsayer, 1999; Rammsayer, 1994; Rammsayer & Brandler, 2001).

Temporal generalization tasks

In addition to the duration discrimination tasks, two temporal generalization tasks were used with base durations of 75 and 1,000 ms respectively. Unlike duration discrimination, temporal generalization relies on long-term memory as well as timing processes (McCormack et al., 2002). This is because, with the latter task, participants are presented with a reference duration during a pre-exposure phase and are required to judge whether the durations presented during the test phase are the same as the reference duration that they have encountered earlier.

Stimuli

The stimuli were sine wave tones presented through headphones at an intensity of 67 dB SPL. In the range of seconds, the standard stimulus duration was 1,000 ms and the nonstandard durations were 700, 800, 900, 1,100, 1,200, and 1,300 ms. In the range of milliseconds, the nonstandard stimulus durations were 42, 53, 64, 86, 97, and 108 ms and the standard duration was 75 ms.

Performance

Performance in temporal generalization was assessed separately for intervals in the range of milliseconds and seconds. The order of the two temporal generalization tasks was randomized and balanced across participants. Participants were required to identify the standard stimulus among the six nonstandard stimuli. In the first part of the experiment, participants were instructed to memorize the standard stimulus duration. For this purpose, the standard interval was presented five times accompanied by the display "This is the standard duration." Then participants were asked to start the test. The test task consisted of eight blocks. Within each block, the standard duration was presented twice, while each of the six nonstandard intervals was presented once. All duration stimuli were presented in randomized order.

In each test trial, one duration stimulus was presented. Participants were instructed to decide whether or not the presented stimulus was of the same duration as the standard stimulus stored in memory. Immediately after presentation of a stimulus, the display "Was this the standard duration?" appeared on the screen, requesting the participant to respond by pressing one of two designated response keys. Each response was followed by a visual feedback. As a quantitative measure of performance on temporal generalization an individual index of response dispersion (Wearden, 1992) was determined. For this purpose, the proportion of total "yes" responses to the standard duration and the two nonstandard durations immediately adjacent (e.g., 900, 1,000, and 1,100 ms) was determined. This measurement would approach 1.0 if all "yes" responses were clustered closely around the standard duration.

Although many recent studies of human timing have used temporal generalization tasks, to our knowledge, the reliability of this type of task has not yet been evaluated.

Rhythm perception task

Stimuli

The stimuli consisted of 3-ms clicks presented binaurally through headphones at an intensity of 88 dB.

Procedure

Participants were presented with auditory rhythmic patterns, each consisting of a sequence of six 3-ms clicks marking five beat-to-beat intervals. Four of these intervals were of a constant duration of 150 ms, while one interval was variable (150 ms + x). The magnitude of x changed from trial to trial depending on the participant's previous response according to the weighted up-down procedure (Kaernbach, 1991), which converged on a probability of hits of .75. Correct responding resulted in a decrease in x and incorrect responses made the task easier by increasing the value of x. Thus, the weighted up-down procedure was used to determine the 75% threshold as an indicator of performance of rhythm perception. A total of 64 experimental trials were grouped in two independent series of 32 trials each. In Series 1, the third beat-to-beat interval was the deviant interval, while in Series 2 the fourth beat-to-beat interval was the deviant interval. Trials from both series were randomly interleaved.

The participant's task was to decide whether the presented rhythmic pattern was perceived as "regular" (i.e., all beat-to-beat intervals appeared to be of the same duration) or "irregular" (i.e., one beat-to-beat interval was perceived as deviant). Participants indicated their decision by pressing one of two designated response keys. No feedback was given, as there were no perfectly isochronous ("regular") patterns presented. In a previous study (Brandler & Rammsayer, 2000), a reliability coefficient of $r = .87$ was obtained in the rhythm perception task.

Temporal order judgment task

Stimuli

For the TOJ task, visual as well as auditory stimuli were employed. Visual stimuli were generated by a red light-emitting diode (LED) in a black viewer box. The LED was located at about 1 m in front of the participant, subtending a visual angle of .58°. Auditory stimuli were 1,000-Hz square waves presented binaurally via headphones at an intensity of 67 dB.

Procedure

The TOJ task was divided into two independent series of 32 trials each. In Series 1, the tone was preceded by the light, while in Series 2, the tone was presented first. Trials from both series were presented randomly. Within each series, the duration of SOA varied from trial to trial depending on the participant's previous response according to the weighted up-down procedure (Kaernbach, 1991), which converged on a level of 75% correct responses. Presentation of both stimuli was simultaneously terminated 200 ms after the onset of the second stimulus. Participants were required to decide whether the onset of the tone or the onset of the light occurred first and to indicate their decision by pressing one of two designated response keys. As an indicator of TOJ performance, DL was determined. In a pilot study with 12 participants, a test-retest reliability coefficient of $r = .73$ was obtained for the TOJ task.

Auditory flutter fusion task

Stimuli

The stimuli consisted of 25-ms noise bursts presented binaurally through headphones at an intensity of 88 dB.

Procedure

Auditory flutter fusion (AFF) threshold estimation consisted of 12 trials, and each trial consisted of two noise bursts separated by a variable ISI ranging from 1 to 40 ms. After each trial, the participant's task was to indicate by pressing one of two designated response keys whether he or she perceived the two successive noise bursts as one tone or two separate tones. The ISI was changed using an adaptive rule based on the Best PEST procedure (Pentland, 1980) to estimate the 75% fusion threshold. To enhance reliability of measurement, two AFF threshold estimates were obtained for each participant. Thus, final individual threshold values represented the mean across both measurements. In a pilot study with 55 participants, a test-retest reliability coefficient of $r = .87$ was obtained for the AFF task.

Time course of the experiment

All experiments were carried out in a sound-attenuated room. The experiment was initiated by the three duration discrimination tasks followed by TOJ, rhythm perception, the two temporal generalization tasks, and the AFF task. The experimental trials of all temporal tasks were preceded by practice trials to ensure that the participants understood the instructions and to familiarize them with the stimuli. An experimental session lasted for approximately 75 min.

Results

Table 1 reports means and standard error of the means of all eight temporal tasks. The interrelationship between the various tasks is presented in Table 2. Since there was a wide age range in the present sample, correlations between age and performance in the eight temporal tasks were also computed. The index of response dispersion obtained with the temporal generalization tasks is positively related to performance, i.e., better performance is indicated by higher values of response dispersion, while the other psychophysical measures based on threshold estimates are negatively associated with temporal performance, i.e., better performance is reflected by lower threshold values and DLs. To enhance the clarity of data presentation, the sign (+ or −) of the correlation coefficients presented in Table 2 has been adjusted in a way that positive correlation coefficients indicate a positive covariation of performance in respective temporal tasks.

As can be seen from this table, most performance measures were significantly correlated with each other. Thus, the pattern of results can be described as a positive manifold (cf., Carroll, 1993). Only AFF and rhythm perception exhibited lower and mainly nonsignificant correlations with the other aspects of temporal performance. Scattergram analyses revealed that the observed significant correlations cannot be attributed to outliers. Furthermore, the absence of statistically significant correlations with age indicated that timing performance was not affected by participants' age.

In the next step, exploratory PFA was performed to elucidate the dimensional structure of temporal performance. The observed positive manifold as well as inspection of the anti-image correlation matrix and Kaiser's (1974) measure of sampling adequacy indicated that the correlation matrix is legitimately factorable. Some researchers prefer principal components analysis (PCA) to PFA because PCA provides an empirical summary of the correlation matrix (cf., Tabachnick & Fidell, 2001). However, when there are no definite

Table 1 Mean performance (± SEM) on eight different temporal tasks. *DD1* duration discrimination of filled intervals, base duration = 50 ms; *DD2* duration discrimination of empty intervals, base duration = 50 ms; *DD3* duration discrimination of filled intervals, base duration = 1,000 ms; *TG1* temporal generalization, base duration = 75 ms; *TG2* temporal generalization, base duration = 1,000 ms; *RP* rhythm perception; *TOJ* temporal-order judgment; *AFF* auditory flutter fusion; *DL* difference limen

Temporal task	Indicator of performance	Mean	SEM
DD1	DL (ms)	9.2	.31
DD2	DL (ms)	19.1	.83
DD3	DL (ms)	136	5.38
TG1	Response dispersion	.76	.13
TG2	Response dispersion	.74	.13
RP	75% threshold (ms)	53.0	1.76
TOJ	DL (ms)	89.6	2.97
AFF	75% threshold (ms)	7.3	.49

Table 2 Intercorrelations among performance measures of eight different temporal task and age

	DD1	DD2	DD3	TG1	TG2	RP	TOJ	AFF
DD2	.52***							
DD3	.38***	.41***						
TG1	.34***	.56***	.30**					
TG2	.32***	.47***	.38***	.47***				
RP	.13	.30**	.14	.10	.03			
TOJ	.44***	.37***	.40***	.39***	.44***	.15		
AFF	.12	.20*	-.04	.20*	.15	.19*	.19*	
Age	.10	.05	.02	.02	.10	-.13	.04	.05

*p < .05; **p < .01; ***p < .001 (two-tailed)

hypotheses about the factor structure of the set of tasks, as in the present study, PFA is preferable to PCA (Jensen, 1998). Therefore, to further analyze the dimensional structure underlying the eight temporal tasks, an exploratory PFA was performed. This analysis resulted in two factors with eigenvalues greater than unity, whereas the scree plot (Cattell, 1966) indicated that there is only one factor. Being unsure of the number of factors, we performed PFAs for one- and two-factor solutions and examined the respective residual correlation matrices.

When extracting one factor, the residual correlations were quite high. Of the 28 residual correlation coefficients, five of them were greater than (absolute value of) .10. This relatively high number of large residuals may point to the presence of another factor. After extraction of a second factor, only two of the 28 residual correlations were greater than (absolute value of) .10.

With the first factor, duration discrimination, temporal generalization and TOJ tasks loaded highest, while rhythm perception and AFF showed no substantial loadings on this factor (see Table 3). The second factor was defined exclusively by rhythm perception. Neither the one- nor the two-factor solution revealed substantial AFF loadings.

A good factor analysis, however, should capture fairly high, significant correlations between variables. Furthermore, interpreting a factor requires that at least three variables load on it; if only one variable loads highly on a factor, the factor is poorly defined (cf., Gorsuch, 1983; Tabachnick & Fidell, 2001). Both these criteria were not met by the second factor; therefore, it seemed reasonable to retain the one-factor solution. Table 3 shows the factor loadings of all temporal tasks, eigenvalues, and total explained variance for the one-factor PFA. This one-factor solution accounted for 31.54% of total variance.

Table 3 Results of the principal-factors analysis: Factor loadings, eigenvalue, and explained variance for the one-factor solution

	Factor 1
DD1	.61
DD2	.75
DD3	.54
TG1	.64
TG2	.63
RP	.24
TOJ	.62
AFF	.22
Eigenvalue	2.52
Percentage of explained variance	31.54

Discussion

The main finding of the present study was that one factor accounted for approximately 32% of the total variance of eight different temporal tasks. While this finding argues against the notion of distinct, highly task-specific timing mechanisms, rhythm perception and AFF showed only marginal loadings on this factor. As will be pointed out in the following, the overall pattern of results suggests a common timing mechanism involved in duration discrimination, temporal generalization, and TOJ tasks. Although the very nature of the common timing mechanism is still unknown, we will provide some preliminary evidence for the notion of a pacemaker-based interval timing process.

For very brief auditory intervals, discrimination has been shown to be better with filled than with empty intervals (cf., Grondin, 2001), as has been found in the present study. In his review article, Grondin (2001) introduced several theoretical propositions to explain why the finding of superior performance with extremely brief filled rather than empty intervals is consistent with the assumption of a master-clock perspective. For example, better performance in filled than in empty intervals can be envisioned as an increase in neural firing rate due to the presence of a perceivable physical stimulus in the case of filled intervals. This higher firing rate will result in finer temporal resolution and, thus, less uncertainty about interval duration in filled than in empty intervals. Furthermore, since each empty interval is bounded by an onset and an offset marker, processing of a series of two empty intervals may produce larger timing variability due to enhanced attentional demands than filled intervals.

From an information processing point of view, Michon (1985) argued that timing of intervals longer than approximately 500 ms is cognitively mediated whereas processing of shorter intervals is supposedly "of a highly perceptual nature, fast, parallel and not accessible to cognitive control" (p. 40). The significance of cognitive mediation for the timing of longer intervals in the range of seconds has been demonstrated in a large number of psychophysical studies applying a dual-task paradigm (e.g., Brown, 1997; Fortin & Breton, 1995; Zakay, 1993). In an attempt to provide experimental evidence of two distinct timing mechanisms as a function of base duration, Rammsayer and Lima (1991) showed that duration discrimination of 1,000-ms auditory intervals was markedly impaired by an increased working memory load whereas duration discrimination of 50-ms intervals was unaffected by the same cognitive task. The notion of different mechanisms underlying the timing of long and very brief intervals was also supported by several neuropharmacological studies (cf., Rammsayer, 1999). The outcome of these studies suggest that drug-induced impairment of working memory processes results in reduced performance of duration discrimination of longer intervals but leaves the temporal processing of extremely brief intervals in the range of milliseconds unaffected.

These data seem at variance with our finding that, regardless of the base duration, all duration discrimination and temporal generalization tasks showed substantial loadings on the first factor. However, there is first evidence from human studies (Rammsayer & Ulrich, 2001; Rousseau, Picard, & Pitre, 1984; Treisman et al., 1990) supporting the notion deduced from animal timing that the pulse rate of the internal timing mechanism varies proportionately with the base duration of the intervals being timed (Killeen & Fetterman, 1988). A generalized counting model with a base duration-dependent pulse rate has been shown to account for temporal discriminations of intervals with base durations of 50 as well as 1,000 ms (Rammsayer & Ulrich, 2001). Furthermore, another line of research focusing on discrimination and comparison processes (Hellström & Rammsayer, 2003), and reanalyzing and reinterpreting the available neuropharmacological data on duration discrimination (Hellström & Rammsayer, 2002), proposed a hybrid timing model. According to the hybrid model, there are two clock mechanisms: A sensory one, based on neural counting, and a more cognitive one. While the timing of extremely brief intervals exclusively depends on the sensory internal clock mechanism, the sensory and cognitive mechanisms are weighted together for the timing of longer intervals. Both the generalized counting model as well as the hybrid model of timing would be consistent with the substantial loadings on the first factor found for all three duration discrimination tasks.

Unlike the duration discrimination tasks applied in the present study, temporal generalization relies on memory processes in addition to internal clock processes. This is because the intervals to be judged during the test phase have to be compared with the standard interval presented during the preceding pre-exposure phase. Thus, to successfully perform the temporal generalization task, memory presentations of the standard interval formed from the output of the internal clock have to be stored in reference or long-term memory (McCormack et al., 2002). From this perspective, the significant correlations between performance of duration discrimination and temporal generalization tasks as well as their substantial factor loadings on the same factor most likely reflect the involvement of a common, interval-based timing mechanism underlying both types of timing tasks.

Within the framework of so-called threshold models of TOJ, imperfect TOJs are attributed to the variability of the arrival latencies as well as the length of the interval between the central arrival times (Sternberg & Knoll, 1973; Ulrich, 1987). For example, according to the perceptual moment hypothesis of TOJ (Pöppel, 1978; Stroud, 1955), two sensory events can be ordered only if they fall in different perceptual moments. Furthermore, it is assumed that the duration of the perceptual moment depends on internal clock speed, with higher clock speeds producing shorter perceptual moments and, thus, better performance on TOJ. The outcome of the correlational and factor-analytic analyses supports the view that internal clock processes associated with interval timing and duration discrimination may also be relevant for the processing of TOJ information.

It may be disputed that the interpretation of the revealed factor as a temporal dimension representing an interval-based internal timing mechanism is somewhat arbitrary. However, alternative interpretations of this factor, such as attentional or memory processes, appear to be highly unlikely. Differential involvement of attentional and memory processes has been shown for duration discrimination, with temporal processing of intervals longer than approximately 500 ms being more susceptible to such cognitive influences. Furthermore, temporal generalization relied much more on the representation of the standard interval in reference memory than the duration discrimination tasks. Despite all the differences in base duration, structure of interval, psychophysical method, and type of task, performance of the three duration discrimination tasks, the two temporal generalization tasks, and the TOJ task constituted a strong common factor accounting for approximately 32% of total variance. Thus, the largest common denominator of all these temporal tasks appears to be interval-based timing performance rather than cognitive or attentional task demands.

Based on these considerations, our one-factor solution is consistent with the general assumption that millisecond timing involves a pacemaker-based interval timing process, in addition to other task-specific processes. These task-specific processes, however, may be the largest source of individual differences for some tasks, such as rhythm perception and AFF. Thus, while the factor identified by means of PFA seems to represent a dimension of temporal information processing strongly associated with interval timing, rhythm perception and simultaneity/successiveness judgments do not appear to be functionally related to the timing of intervals.

As an alternative to an interval-based internal clock mechanism involved in rhythm perception, Jones and Boltz (1989) put forward the idea of an ecological approach. According to these authors, internal capabilities for attending to external signals may help to capture environmental regularities in sensory events. It is these regularities that generate subjective expectations regarding the occurrence of future events in time. Similarly, the conception of beat-based timing (McAuley &

Kidd, 1998; Povel & Essens, 1985; Ross & Houtsma, 1994; Schulze, 1978) may also represent an alternative mechanism to account for performance of the rhythm perception task. According to this approach, an internal timing mechanism produces an isochronous beat pattern that corresponds to the temporal structure of the sequence to be judged. Thus, the distinction between the pacemaker-based interval timing process, as reflected by the one-factor solution of the PFA, and the major task-specific process associated with rhythm perception could perhaps be interpreted by contrasting intervals with points in time. Thus, the PFA factor may represent judgments of differences between intervals, whereas the crucial, task-specific process for rhythm perception involves judgments of (non)coincidence of time points. In the case of rhythm perception, that would be the difference between a temporal expectation and the actual time of occurrence of a sound, as proposed by Jones and colleagues (Barnes & Jones, 2000; Jones, 2001; Jones, Boltz, & Klein, 1993).

Furthermore, it is important to note, that PFA failed to identify a substantial factor loading of AFF. Temporal resolving power for simultaneity and successiveness as indicated by AFF threshold values appears to be different from all the potential timing mechanisms discussed so far. This conclusion is consistent with evidence suggesting that AFF depends primarily on characteristics of auditory processing and not on processing of duration per se (Florentine & Buus, 1984). Converging evidence for this notion can be derived from neuropharmacological studies where interval timing was reliably affected by the dopamine receptor blocker haloperidol, while AFF thresholds proved to be insensitive to changes in dopaminergic activity (Rammsayer, 1989). From this perspective, AFF may represent a distinct temporal task based on specific timing processes largely unrelated to all the other tasks.

Although the intercorrelations between temporal discrimination, temporal generalization, and TOJ were somewhat higher than those that occur for rhythm perception and the AFF task, the correlational analysis revealed a so-called positive manifold (Jensen, 1998) as indicated by a general, positive correlational relationship between all temporal tasks. This correlational pattern points to the conclusion that the eight temporal tasks overlap to varying degrees and are linked at a higher order level. This means that, from a neuropsychological perspective, different brain structures may be primarily responsible for different types of timing processes but these could be considered to be components of a larger over-arching system. Most recently, Ivry and Zelaznik (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003; Zelaznik, Spencer, & Ivry, 2002) proposed a shared timing process involved in different tasks, such as repetitive tapping, eye blink conditioning, temporal discrimination, and speech perception, which all involve explicit representation of the passage of time. Furthermore, these authors hypothesized that the cerebellum may provide this explicit form of temporal representation. From this perspective, the idea of a master clock and a set of specialized temporal mechanisms are not necessarily opposing viewpoints as they have been presented in the past literature. Another possible explanation for the observed positive manifold is that different temporal mechanisms were responsible for the performance of the different tasks but all the mechanisms are somehow synchronized or that all are characterized by a similar psychophysical function.

Clearly, further research is needed to support the notion of a common, interval-based timing mechanism that is involved in various timing tasks. In future studies, specific tasks with high attentional and/or memory demands, but unrelated to interval timing, should be additionally included in the analysis. This kind of study could provide discriminant evidence for the validity of the interval-based timing dimension if these supplementary, nontemporal tasks do not yield substantial factor loadings on the common factor constituted by the interval-based timing tasks. Furthermore, using only one duration discrimination task, one temporal generalization task, and the TOJ task, but adding two or more tasks that involve processes similar to those involved in rhythm perception and AFF respectively, may provide additional evidence for the existence of distinct temporal dimensions associated with those latter tasks.

Acknowledgements The authors would like to thank Richard A. Block, Bruno H. Repp, Howard N. Zelaznik, and two anonymous reviewers for helpful comments on an earlier draft of this manuscript. This work was supported by Deutsche Forschungsgemeinschaft Grant RA 450/14–1.

References

Barnes, R., & Jones, M. R. (2000). Expectancy, attention, and time. *Cognitive Psychology*, *41*, 254–311.

Block, R. A. (1990). *Cognitive models of psychological time*. Hillsdale, NJ: Lawrence Erlbaum.

Brandler, S., & Rammsayer, T. (1999). Differential effects in temporal discrimination: Timing performance as a function of base duration and psychophysical procedure. In P. R. Killeen & W. R. Uttal (Eds.), *Fechner Day 99. The end of the 20th century psychophysics* (pp. 228–233). Tempe, AZ: The International Society for Psychophysics.

Brandler, S., & Rammsayer, T. (2000). Temporal-order judgment and rhythmic acuity: Description and comparison of two psychophysical timing tasks. C. Bonnet (Ed.), *Fechner Day 2000. Proceedings of the Sixteenth Annual Meeting of the International Society for Psychophysics* (pp. 157–162). Strasbourg, France: The International Society for Psychophysics.

Brown, S. W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Perception & Psychophysics*, *59*, 1118–1140.

Burle, B., & Bonnet, M. (1997). Further argument for the existence of a pacemaker in the human information processing system. *Acta Psychologica*, *97*, 129–143.

Burle, B., & Bonnet, M. (1999). What's an internal clock for? From temporal information processing to temporal processing of information. *Behavioural Processes*, *45*, 59–72.

Carroll, J. B. (1993). *Human cognitive abilities. A survey of factor-analytical studies*. New York: Cambridge University Press.

Cattel, R. B. (1966). The scree test for the number of factors. *Multivariate Behavioral Research*, *1*, 245–276.

Craig, J. C. (1973). A constant error in the perception of brief temporal intervals. *Perception & Psychophysics*, *13*, 99–104.

Creelman, C. D. (1962). Human discrimination of auditory duration. *Journal of the Acoustical Society of America*, *34*, 582–593.

Demany, L., McKenzie, B., & Vurpillot, E. (1977). Rhythm perception in early infancy. *Nature*, *266*, 718–719.

Florentine, M., & Buus, S. (1984). Temporal gap detection in sensorineural and simulated hearing impairments. *Journal of Speech & Hearing Research*, *27*, 449–455.

Fortin, C., & Breton, R. (1995). Temporal interval production and processing in working memory. *Perception & Psychophysics*, *57*, 203–215.

Fraisse, P. (1984). Perception and estimation of time. *Annual Review of Psychology*, *35*, 1–36.

Friedman, W. J. (1990). *About time. Inventing the fourth dimension*. Cambridge, MA: MIT.

Getty, D. J. (1975). Discrimination of short temporal intervals: A comparison of two models. *Perception & Psychophysics*, *16*, 1–8.

Gibbon, J. (1977). Scalar expectancy theory and Weber's Law in animal timing. *Psychological Review*, *84*, 279–325.

Gorsuch, R. L. (1983). *Factor analysis*. Hillsdale, NJ: Lawrence Erlbaum.

Grondin, S. (2001). From physical time to the first and second moments of psychological time. *Psychological Bulletin*, *127*, 22–44.

Grondin, S., & Macar, F. (1992). Dividing attention between temporal and nontemporal tasks: A performance operating characteristic—POC—analysis. In F. Macar, V. Pouthas, & W. Friedman, (Eds.), *Time, action, cognition: Towards bridging the gap* (pp. 119–128). Dordrecht, The Netherlands: Kluwer.

Hellström, Å., & Rammsayer, T. (2002). Mechanisms behind discrimination of short and long auditory durations. In J. A. da Silva, E. H. Matsushima, & N. P. Ribeiro-Filho (Eds.), *Annual Meeting of the International Society for Psychophysics* (pp. 110–115). Rio de Janeiro, Brazil: The International Society for Psychophysics.

Hellström, Å., & Rammsayer, T. (2003). Effects of time-order, interstimulus interval, and feedback in duration discrimination of noise bursts in the 50- and 1000-millisecond ranges. Manuscript submitted for publication.

Ivry, R. B., & Hazeltine, R. E. (1995). Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 3–18.

Ivry, R. B., Spencer, R. M., Zelaznik, H. N., & Diedrichsen, J. (2002). The cerebellum and event timing. In S. M. Highstein & W. T. Thach (Eds.), *The cerebellum: Recent developments in cerebellar research*, Vol. 978 (pp. 302–317). New York: New York Academy of Sciences.

Jensen, A. R. (1998). *The g factor*. Westport, CT: Praeger.

Jones, M. R. (2001). Temporal expectancies, capture, and timing in auditory sequences. In C. L. Folk & B. S. Gibson (Eds.), Attraction, distraction and action: Multiple perspectives on attentional capture (pp. 191–229). Amsterdam: Elsevier.

Jones, M. R., & Boltz, M. G. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*, 459–491.

Jones, M-R., Boltz, M.G., & Klein, J.M. (1993). Expected endings and judged duration. *Memory & Cognition*, *21*, 646–665.

Kaernbach, C. (1991). Simple adaptive testing with the weighted up-down method. *Perception & Psychophysics*, *49*, 227–229.

Kaiser, H. F. (1974). An index of factorial simplicity. *Psychometrika*, *39*, 31–36.

Keele, S., Pokorny, R., Corcos, D., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. *Acta Psychologia*, *60*, 173–191.

Keele, S., Nicoletti, R., Ivry, R., & Pokorny, R. (1989). Mechanisms of perceptual timing: Beat-based or interval-based judgments? *Psychological Research*, *50*, 251–156.

Killeen, P. R., & Fetterman, J. G. (1988). A behavioral theory of timing. *Psychological Review*, *95*, 274–295.

Killeen, P. R., & Weiss, N. A. (1987). Optimal timing and the Weber function. *Psychological Review*, *94*, 455–468.

Luce, R. D., & Galanter, E. (1963). Discrimination. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology: Vol. 1* (pp. 191–243). New York: John Wiley.

McAuley, J. D., & Kidd, G. R. (1998). Effect of deviations from temporal expectations on tempo discrimination of isochronous tone sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1786–1800.

McCormack, T., Brown, G. D. A., Maylor, E. A., Richardson, L. B. N., & Darby, R. J. (2002). Effects of aging on absolute identification of duration. *Psychology and Aging*, *17*, 363–378.

Michon, J. A. (1985). The compleat time experiencer. In J. A. Michon & J. L. Jackson (Eds.), *Time, Mind, and Behavior* (pp. 21–52). Berlin Heidelberg New York: Springer.

Pashler, H. (2001). Perception and production of brief durations: Beat-based versus interval-based timing. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 485–493.

Pentland, A. (1980). Maximum likelihood estimation: The best PEST. *Perception & Psychophysics*, *28*, 377–379.

Pöppel, E. (1978). Time perception. In R. Held, H. W. Leibowitz, & H.-L. Teuber (Eds.), *Handbook of sensory physiology: Vol. 8* (pp. 713–729). Berlin Heidelberg New York: Springer.

Povel, D.-J., & Essens, P. (1985). Perception of temporal patterns. *Music Perception*, *2*, 411–440.

Rammsayer, T. (1989). Is there a common dopaminergic basis of time perception and reaction time? *Neuropsychobiology*, *21*, 37–42.

Rammsayer, T. H. (1994). Effects of practice and signal energy on duration discrimination of brief auditory intervals. *Perception & Psychophysics*, *55*, 454–464.

Rammsayer, T. H. (1999). Neuropharmacological evidence for different timing mechanisms in humans. *Quarterly Journal of Experimental Psychology, Section B: Comparative and Physiological Psychology*, *52*, 273–286.

Rammsayer, T., & Brandler, S. (2001). Internal consistency of indicators of performance on temporal discrimination and response times as obtained by adaptive psychophysical procedures. In E. Sommerfeld, R. Kompass, & T. Lachmann (Eds.), *Fechner Day 2001. Proceedings of the Seventeenth Annual Meeting of the International Society for Psychophysics* (pp. 565–570). Lengerich, Germany: Pabst.

Rammsayer, T. H., & Lima, S. D. (1991). Duration discrimination of filled and empty auditory intervals: Cognitive and perceptual factors. *Perception & Psychophysics*, *50*, 565–574.

Rammsayer, T., & Ulrich, R. (2001). Counting models of temporal discrimination. *Psychonomic Bulletin & Review*, *8*, 270–277.

Robertson, S. D., Zelaznik, H. N., Lantero, D. A., Bojczyk, K. G., Spencer, R. M., Doffin, J. G., & Schneidt, T. (1999). Correlations for timing consistency among tapping and drawing tasks: Evidence against a single timing process for motor control. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1316–1330.

Ross, J, & Houtsma, A. J. M. (1994). Discrimination of auditory temporal patterns. *Perception & Psychophysics*, *56*, 19–26.

Rousseau, R., Picard, D., & Pitre, E. (1984). An adaptive counter model for time estimation. In J. Gibbon & L. G. Allan (Eds.), *Timing and time perception* (Annals of the New York Academy of Sciences: Vol. 423, pp. 639–642. New York: New York Academy of Sciences.

Schulze, H. H. (1978). The detectability of local and global displacements in regular rhythmic patterns. *Psychological Research*, *40*, 172–181.

Spencer, R. M. C., Zelaznik, H. N., Diedrichsen, J., & Ivry, R. B. (2003). Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science*, *300*, 1437–1439.

Sternberg, S., & Knoll, R. L. (1973). The perception of temporal order: Fundamental issues and a general model. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 629–685). New York: Academic Press.

Stroud, J. M. (1955). The fine structure of psychological time. In H. Quastler (Ed.), *Information theory in psychology* (pp. 174–205). Glencoe, IL: Free Press.

Surwillo, W. W. (1968). Timing of behavior in senescence and the role of the central nervous system. In G. A. Talland (Ed.), *Human aging and behavior* (pp. 1–35). New York: Academic Press.

Tabachnik, B. G., & Fidell, L. S. (2001). *Using multivariate statistics*. Boston: Allyn & Bacon.

Ten Hoopen, G., Hartsuiker, R., Sasaki, T., Nakajima, Y., Tanaka, M., & Tsumura, T. (1995). Auditory isochrony: Time shrinking and temporal patterns. *Perception*, *24*, 577–593.

Treisman, M., Faulkner, A., Naish, P. L. N., & Brogan, D. (1990). The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception*, *19*, 705–743.

Treisman, M., Faulkner, A., & Naish, P. L. N. (1992). On the relationship between time perception and the timing of motor action: Evidence for a temporal oscillator controlling the timing of movement. *Quarterly Journal of Experimental Psychology*, *45A*, 235–263.

Ulrich, R. (1987). Threshold models of temporal-order judgments evaluated by a ternary response task. *Perception & Psychophysics*, *42*, 224–239.

Wearden, J. H. (1992). Temporal generalization in humans. *Journal of Experimental Psychology: Animal Behavior Processes*, *18*, 134–144.

Zakay, D. (1993). Time estimation methods—do they influence prospective duration estimates? *Perception*, *22*, 91–101.

Zakay, D., & Block, R. A. (1996). The role of attention in time estimation processes. In M. A. Pastor & J. Artieda (Eds.), *Time, internal clocks and movement* (pp. 143–164). Amsterdam: Elsevier.

Zelaznik, H. N., Spencer, R. M., & Doffin, J. G. (2000). Temporal precision in tapping and circle drawing movements at preferred rates is not correlated: Further evidence against timing as a general-purpose ability. *Journal of Motor Behavior*, *32*, 193–199.

Zelaznik, H. N., Spencer, R. M. C., & Ivry, R. B. (2002). Dissociation of explicit and implicit timing in repetitive tapping and drawing movements. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 575–588.