Elucidating the Internal Structure of Psychophysical Timing Performance in the Sub-second and Second Range by Utilizing Confirmatory Factor Analysis

Thomas H. Rammsayer and Stefan J. Troche

Abstract

The most influential theoretical account in time psychophysics assumes the existence of a unitary internal clock based on neural counting. The distinct timing hypothesis, on the other hand, suggests an automatic timing mechanism for processing of durations in the sub-second range and a cognitively controlled timing mechanism for processing of durations in the range of seconds. Although several psychophysical approaches can be applied for identifying the internal structure of interval timing in the second and sub-second range, the existing data provide a puzzling picture of rather inconsistent results. In the present chapter, we introduce confirmatory factor analysis (CFA) to further elucidate the internal structure of interval timing performance in the sub-second and second range. More specifically, we investigated whether CFA would rather support the notion of a unitary timing mechanism or of distinct timing mechanisms underlying interval timing in the sub-second and second range, respectively. The assumption of two distinct timing mechanisms which are completely independent of each other was not supported by our data. The model assuming a unitary timing mechanism underlying interval timing in both the sub-second and second range fitted the empirical data much better. Eventually, we also tested a third model assuming two distinct, but functionally related mechanisms. The correlation between the two latent variables representing the hypothesized timing mechanisms was rather high and comparison of fit indices indicated that the assumption of two associated timing mechanisms described the observed data better than only one latent variable. Models are discussed in the light of the existing psychophysical and neurophysiological data.

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Introduction

Within the field of psychophysical research on timing and time perception, there are two competing major theoretical accounts on the mechanisms underlying the temporal processing of intervals in the range of seconds and milliseconds referred to as the *distinct timing hypothesis* and the *common timing hypothesis*. The distinct timing hypothesis acts on the assumption that processing of temporal information in the sub-second range depends upon a qualitatively different mechanism than processing of temporal information in the second range. The common timing hypothesis, on the other hand, acts on the assumption of a single, central timing mechanism. As depicted in the first chapter, over the past 50 years psychophysical research on time perception has been guided by the notion of a common timing mechanism underlying temporal processing of intervals irrespective of interval duration (cf. [1, 2]). Although such internal clock models based on neural counting provide a useful heuristic for explaining human and animal performance on timing of brief intervals, there is increasing empirical evidence challenging the assumption of a common, unitary timing mechanism (for a review see: first chapter of this volume; [2–4]). Over the past two decades, psychophysical research on interval timing has been in the search of a definite answer on whether a common timing mechanism or two distinct timing mechanisms account for the timing of intervals in the second and sub-second range.

In the present chapter, we will acquaint the reader with the basic assumptions of both the common and distinct timing hypotheses. Furthermore, we will provide a concise overview of the basic findings of psychophysical studies designed to experimentally dissociate the two timing mechanisms implied by the distinct timing hypothesis. As we will see, the available psychophysical studies, so far, failed to provide unambiguous experimental evidence against or in favour of either of the two competing hypotheses. Therefore, we will introduce a novel methodological approach, based on confirmatory factor analysis, for investigating the internal structure of psychophysical timing performance in the sub-second and second range.

The Common Timing Hypothesis: A Unitary Timing Mechanism Based on Neural Counting

To date, the most popular conception in time psychophysics represents the notion of a common timing mechanism underlying temporal processing of intervals in the sub-second and second range. This highly influential theoretical account of human and animal timing and time perception assumes the existence of a single internal clock based on neural counting (e.g., [2, 5–11]). The main features of such an internal-clock mechanism are a pacemaker and an accumulator. The neural pacemaker generates pulses, and the number of pulses relating to a physical time interval is recorded by the accumulator. Thus, the number of pulses counted during a given time interval indexes the perceived duration of this interval. Hence, the higher the clock rate of the neural pacemaker the finer the temporal resolution of the internal clock will be, which is equivalent to more accuracy and better performance on timing tasks.

The assumption of a unitary internal-clock mechanisms based on neural counting also represents the established explanation for the Scalar Expectancy Theory (SET) introduced by Gibbon [7, 12]. SET is one of the currently most prominent theoretical accounts of human and animal timing. According to SET, when estimating the duration of a given standard interval, a participant's responses follow a normal distribution around the interval duration. The width of this response distribution is predicted to be proportional to the standard duration. This linear covariation of the mean and the standard deviation of the response distribution across different standard durations, referred to as the scalar property of interval timing, is also asserted by Weber's law [9, 13].

Although direct experimental evidence for the notion of a single, common timing mechanism underlying temporal processing in the sub-second and second range is hard to obtain, some indirect psychophysical evidence can be derived from the failure to detect so-called 'break points' in the precision of interval timing across interval durations ranging from 68 ms to 16.7 min [14]. Such break points would be the expected outcome if different timing mechanisms, with different levels of absolute precision of timing, were used for measuring intervals of different durations [15, 16]. At the same time, however, the scalar property of interval timing for brief durations is seriously questioned by psychophysical research in humans (see Chapter 1; [8, 17]) and animals (e.g., [18]).

The Distinct Timing Hypothesis: Interval Timing in the Second and Sub-second Range Is Based on Two Distinct Timing Mechanisms

As early as 1889, Münsterberg [19] put forward the idea of two distinct timing mechanisms underlying temporal information processing. He assumed that durations less than one third of a second can be directly perceived whereas longer durations need to be (re-)constructed by higher mental processes. More recently, Michon [20] argued that temporal processing of intervals longer than approximately 500 ms is cognitively mediated while temporal processing of shorter intervals is supposedly "of a highly perceptual nature, fast, parallel and not accessible to cognitive control" [20, p. 40]. More recent studies, pursuing Michon's [20] conception, provided converging evidence that the transition from sensory/automatic to cognitively mediated timing might lie closer to 250 ms than to 500 ms [21, 22].

In a first attempt to provide direct experimental evidence for the validity of the distinct timing hypothesis, Rammsayer and Lima [23] applied a dual-task paradigm guided by the following considerations: If, as suggested by Michon [20], temporal discrimination of intervals longer than approximately 500 ms is cognitively mediated, one would expect that temporal discrimination under relatively high cognitive load would be more difficult than temporal discrimination under lower cognitive load. On the other hand, if discrimination of extremely brief intervals is based upon an automatic, sensory mechanism, performing a concurrent nontemporal cognitive task should produce no deleterious effect on temporal discrimination of intervals in the range of milliseconds. To test these predictions, a dual-task procedure was used with duration discrimination as the primary task and word learning as a secondary nontemporal cognitive task. Results from the dual-task conditions were compared with results from single-task conditions. If two tasks compete for the same pool of cognitive resources then simultaneous performance on both tasks should be impaired compared to performance on one task alone. With this approach, Rammsayer and Lima [23] found that temporal discrimination of intervals ranging from 50 to 100 ms is unaffected by a secondary cognitive task whereas duration discrimination of intervals in the range of seconds is markedly impaired by the same secondary task. The likely conclusion was that timing of intervals in the sub-second range is based on an automatic, sensory mechanism while timing of intervals in the second range is cognitively mediated.

To further test the distinct timing hypothesis, Rammsayer and Ulrich [4] investigated the effects of maintenance and elaborative rehearsal as a secondary task on temporal discrimination of intervals in the sub-second and second range. Unlike mere maintenance rehearsal, elaborative rehearsal as a secondary task involved transfer of information from working memory to long-term memory and elaboration of information to enhance storage in long-term memory. Temporal discrimination of brief intervals was not affected by a secondary cognitive task that required either maintenance or elaborative rehearsal. Concurrent elaborative rehearsal, however, reliably impaired temporal discrimination of intervals in the second range as compared to maintenance rehearsal and a control condition with no secondary task.

These findings support the notion of two distinct timing mechanisms involved in temporal processing of intervals in the sub-second and second range. While temporal processing of intervals in the second range demands cognitive resources, temporal processing of intervals in the sub-second range appears to be highly sensory in nature and beyond cognitive control.

The distinct timing hypothesis is also supported by neuropharmacological and neuroimaging studies on temporal information processing. Findings from neuroimaging studies are consistent with the notion of an automatic timing system for measuring brief intervals in the sub-second range and a cognitively controlled system, depending on the right dorsolateral prefrontal cortex, for temporal processing of intervals in the suprasecond range (for reviews see [24–26]). Similarly, neuropharmacological timing studies also suggest the existence of a prefrontal cognitive system for the processing of temporal information in the second range and a subcortical automatic system controlled by mesostriatal dopaminergic activity for temporal processing in the range of milliseconds (for reviews see [27–29]).

Statistical Approaches for Identifying the Internal Structure of Psychophysical Timing Performance

In the face of the rather ambiguous experimental findings with regard to the common timing and distinct timing hypotheses, additional statistical approaches became increasingly important. There are at least two basic statistical approaches to investigating whether tasks that require fine temporal resolution and precise timing depend upon a unitary timing mechanism. The *method of slope analysis* is derived from Getty's [30] generalization of Weber's law. With this approach, changes in timing variability as a function of timescale (e.g., sub-second vs. second range) can be compared across tasks. If the slope of the variability functions of two tasks is equivalent, a common timing mechanism underlying both tasks is inferred (for more information see [31]).

The *correlational approach* is based on the general assumption that if the same timing mechanism is involved in two tasks, the performance or timing variability of the two tasks should be highly correlated. Common forms of the correlational approach to the identification of the internal structure of psychophysical timing performance represent correlational analyses (e.g., [32]), exploratory factor analysis (e.g., [33]), and multiple linear regression [34].

In an attempt to apply the correlational approach to elucidate the dimensional properties of temporal information processing in the sub-second and second range, Rammsayer and Brandler [33] used exploratory factor analysis to analyse eight psychophysical temporal tasks in the sub-second (temporal-order judgment, and rhythm perception) and second range (temporal discrimination and generalization of filled intervals). Their main finding was that the first principle factor accounted for 31.5 % of the total variance of the eight different temporal tasks. More specifically, all the various temporal tasks, except rhythm perception and auditory fusion, showed substantial loadings on this factor. Rammsayer and Brandler [33] interpreted this outcome as evidence for a common, unitary timing mechanism involved in the timing of intervals in the sub-second and second range.

Confirmatory Factor Analysis: An Alternative, Theory-Driven Methodological Approach for Identifying the Internal Structure of Psychophysical Timing Performance

Confirmatory factor analysis (CFA) represents a methodological approach more sensitive to theoretical assumptions and given hypotheses than the exploratory factor analysis applied by Rammsayer and Brandler [33]. Similar to the exploratory factor analysis, CFA is based on the correlations (or actually unstandardized correlations, i.e. covariances) of a set of measurements. While exploratory factor analysis makes a proposal for the number of latent variables underlying a given covariance matrix without any theoretical assumptions, CFA probes whether theoretically

predefined latent variables can be derived from the pattern of correlations.

Assume, for example, that 100 participants performed on three timing tasks in the second range and three other timing tasks in the sub-second range. You compute the correlations among the six tasks and, hence, you produce an empirical correlation matrix. As a supporter of the distinct timing hypothesis, you expect statistically significant correlations between the three timing tasks in the second range. Because you assume that a specific timing mechanism for intervals in the second range accounts for these significant correlations, you derive a factor (i.e., a latent variable) from the three timing tasks in the second range which represents the timing mechanism for the second range. You also expect significant correlations between the three timing tasks in the sub-second range. As for the second range, these significant correlations suggest a timing mechanism specific to processing of temporal information in the sub-second range which is, consequently, represented by a factor (latent variable) derived from these sub-second timing tasks. In addition, you expect the pair-wise correlations between a given timing tasks in the second range, on the one hand, and a given timing tasks in the sub-second range, on the other hand, to be statistically non-significant. This is because the distinct timing hypothesis assumes different distinct mechanisms to underlie timing in the second and in the sub-second range, respectively. If the correlations between timing tasks in the second and the sub-second range are non-significant, also the correlation between the latent variables representing the timing mechanism in the second and sub-second range, respectively, should be low. Thus, a latent variable model derived from the basic assumption of the distinct timing hypothesis should contain a latent variable for timing in the second range and another latent variable for timing in the sub-second range with a non-significant correlation between these two latent variables.

In case, however, that you are a follower of the common timing hypothesis, you would expect that individual differences in one timing task go with individual differences in any other timing task—regardless of whether these tasks use stimulus durations in the second or sub-second range. As a consequence, there should be significant correlations among performances of all tasks (irrespective of the stimulus duration) suggesting a common latent variable which accounts for these relationships.

Thus, the two alternative timing hypotheses result in different predictions of how a correlation matrix of tasks in the second and in the sub-second range should look like. CFA compares the respective predicted correlation matrix with the empirically observed correlation matrix and, thus, provides indices of how accurately the expected matrix fits the observed matrix. These indices are, therefore, called fit indices and will be described in more detail below. On the basis of these model fit indices, it can then be decided which of the two models describes the observed data better and should be preferred. It should be noted, however, that CFA does actually not analyze the correlations but the covariances, i.e., the unstandardized correlations. Therefore, we will refer to "covariance" and "covariance matrix" in the following paragraphs.

Applying Confirmatory Factor Analysis for Identifying the Internal Structure of Psychophysical Timing Performance: An Example of Use

We will demonstrate the application of CFA by means of a study that was designed to probe whether covariances of interval timing tasks in the second and sub-second range can be described by the assumption of either one or two latent variables supporting the common or distinct timing hypothesis, respectively. In order to obtain a sufficient number of behavioral data for the CFA approach, a rather large sample of 130 participants (69 males and 61 females ranging in age from 18 to 33 years) had been tested.

Psychophysical Assessment of Interval Timing Performance

For psychophysical assessment of performance on interval timing, three temporal discrimination
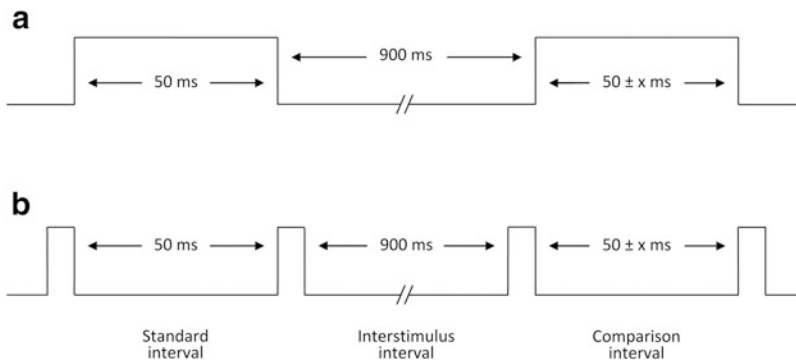
Fig. 1 Schematic diagram of the time course of an experimental trial of the temporal discrimination task with filled (Panel A) and empty (Panel B) intervals in the sub-second range. In filled intervals, a white-noise burst is presented continuously throughout the interval, whereas in empty intervals only the onset and the offset are marked by brief 3-ms white-noise burst. Thus, in empty intervals, there is no stimulus present during the interval itself. On each trial, the participant is presented with two intervals a constant 50-ms standard interval and a variable comparison interval ($50 \pm x$ ms). The participant's task is to decide which of the two intervals was longer. The duration of the comparison interval varied from trial to trial depending on the participant's previous response. Correct responding resulted in a smaller duration difference between the standard and the comparison interval, whereas incorrect responses made the task easier by increasing the difference in duration between the standard and the comparison interval

tasks and two temporal generalization tasks were used. Because the auditory system has the finest temporal resolution of all senses (for reviews see [35, 36]), auditory intervals were presented in all tasks.

On each trial of a typical *temporal discrimination task*, the participant is presented with two intervals and his/her task is to decide which of the two intervals was longer. There are two types of intervals commonly employed in temporal discrimination tasks. One type is the *filled* interval and the other type is the *empty* (silent) interval. In filled auditory intervals, a tone or noise burst is presented continuously throughout the interval, whereas in auditorily marked empty intervals only the onset and the offset are marked by clicks (see Fig. 1). Thus, in empty intervals, there is no auditory stimulus present during the interval itself. Most importantly, type of interval appears to affect temporal discrimination of auditory intervals in the range of tens of milliseconds. For such extremely brief intervals, performance on temporal discrimination was found to be reliably better with filled than with empty intervals. This effect seems to be limited to intervals shorter than approximately 100 ms and is no longer detectable for longer intervals [37].

Based on these considerations, our participants performed one block of filled and one block of empty intervals with a standard duration of 50 ms each, as well as one block of filled intervals with a standard duration of 1,000 ms. Order of blocks was counterbalanced across participants. Each block consisted of 64 trials, and each trial consisted of one standard interval and one comparison interval. The duration of the comparison interval varied according to an adaptive rule [38] to estimate *x*.25 and *x*.75 of the individual psychometric function, that is, the two comparison intervals at which the response "longer" was given with a probability of 0.25 and 0.75, respectively. Generally speaking 'adaptive' means that stimulus presentation on any given trial is determined by the preceding set of stimuli and responses. Therefore, the comparison interval is varied in duration from trial to trial depending on the participant's previous response. Correct responding resulted in a smaller duration difference between the constant standard and the variable comparison interval, whereas incorrect responses made the task easier by increasing the difference in duration between the standard and the comparison interval (for more details see [39]). As an indicator of

discrimination performance, the difference limen, *DL* [40], was determined for each temporal discrimination task.

In addition to the temporal discrimination tasks, two *temporal generalization tasks* (see first chapter) were employed with standard durations of 75 and 1,000 ms for the sub-second and second range, respectively. Like temporal discrimination, temporal generalization relies on timing processes but additionally on a reference memory of sorts [41, 42]. This is because in the first part of this task, participants are 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 the test phase began. On each trial of the test phase, one duration stimulus was presented. Participants had to decide whether or not the presented stimulus was of the same duration as the standard stimulus stored in memory. The test phase consisted of eight blocks. Within each block, the standard duration was presented twice, while each of the six nonstandard intervals was presented once. 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. All duration stimuli were presented in randomized order. As a quantitative measure of performance on temporal generalization an individual index of response dispersion [43] 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 in the case of temporal generalization in the second range) was determined. This measure would approach 1.0 if all "yes"-responses were clustered closely around the standard duration.

The standard durations of the interval timing tasks for the sub-second and second range were selected because the hypothetical shift from one timing mechanism to the other may be found at an interval duration somewhere between 100 and 500 ms [20–22, 44, 45]. Furthermore, when participants are asked to compare time intervals, many of them adopt a counting strategy. Since explicit counting becomes a useful timing strategy for intervals longer than approximately 1,200 ms [46, 47], the long standard duration was chosen not to exceed this critical value.

Statistical Analyses Based on Confirmatory Factor Analysis: Different Indices for Evaluation of Model Fit

The two models investigated by means of CFA are schematically presented in Fig. 2. Proceeding from the common timing hypothesis, Model 1 assumes that one common latent variable underlies performance on all five interval timing tasks (see Fig. 2, model on the left). Model 2 refers to the distinct timing hypothesis assuming two distinct latent variables. One latent variable underlies performance on the timing tasks in the sub-second range, i.e., the temporal generalization and the two duration discrimination tasks with stimuli in the sub-second range. A second latent variable underlies performance on the temporal generalization and the duration discrimination tasks with stimuli in the second range. According to the distinct timing hypothesis, these two latent variables are not correlated with each other (see Fig. 2, model on the right). Since CFA provides an evaluation of how well a theoretical model describes the observed data, the comparison of so-called *model fit indices* helps to decide whether the unitary or the distinct timing hypothesis better predicts the empirical data.

In order to test whether the empirical data are well described by given theoretical assumptions, the observed covariance matrix is compared with the theoretically implied matrix. The dissimilarity can be tested for significance by the χ^2 *test* [48]. A significant χ^2 value requires rejecting the null hypothesis which says that the observed and implied covariance matrices are identical and differences are just due to sampling error. A non-significant χ^2 value, on the contrary, indicates that the theoretical model is not proven to be incorrect and that the empirical data fit the
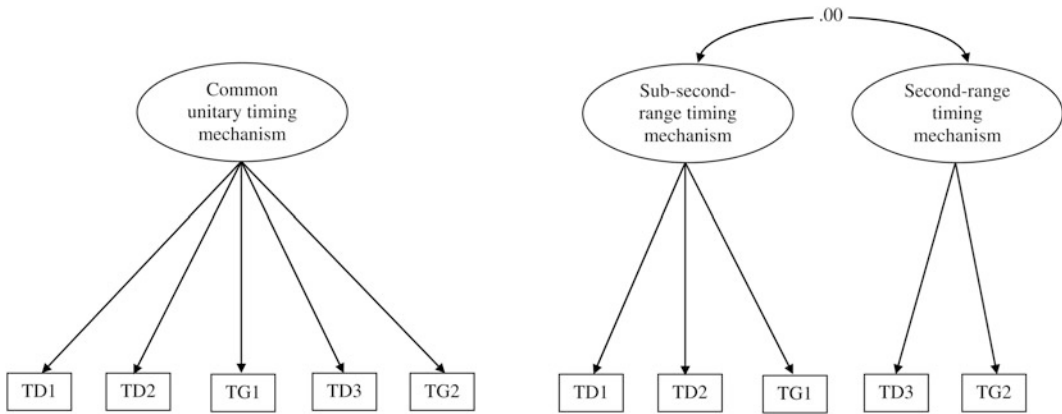
Fig. 2 Two models reflecting the common timing hypothesis (model on the *left*) and the distinct timing hypothesis (model on the *right*), respectively. The common timing hypothesis assumes correlational relationships among the five interval timing tasks, irrespective of interval duration, which can be explained by a common latent variable. The distinct timing hypothesis suggests that performances on the three interval timing tasks in sub-second range are highly correlated with each other and that these correlations are due to a specific mechanism for the timing of intervals in the sub-second range. Similarly, also performances on the two interval timing tasks for the second range are expected

to correlate with each other due to a specific mechanism underlying the timing of intervals in the second range. Both these mechanisms, however, are conceptualized to be completely independent from each other as indicated by the correlation coefficient of $r = 0.00$. Note. TD1: temporal discrimination of filled intervals in the sub-second range; TD2: temporal discrimination of empty intervals in the sub-second range; TD3: temporal discrimination of filled intervals in the second range; TG1: temporal generalization of filled intervals in the sub-second range; TG2: temporal generalization of filled intervals in the second range

theoretical expectations. The χ^2 value, however, depends on the sample size and easily yields significance with large sample sizes which are required for the computation of CFA. Therefore, to avoid that models are rejected just because of too large sample sizes, further model fit indices are usually computed [49]. In the following, the most common and widely-used additional fit indices will be briefly introduced.

The *Comparative Fit Index* (CFI) estimates how much better a given model describes the empirical data compared to a null model with all variables assumed to be uncorrelated. The CFI varies between 0 and 1 and a value of more than 0.95 is acceptable [50].

The *Akaike Information Criterion* (AIC) is an explicit index of the parsimony of a model. This is important as it is required that models should be as parsimonious (i.e., as less complex) as possible. The AIC charges the χ^2 value against model complexity in terms of degrees of freedom. The lower the AIC, the more parsimonious is the model.

The *Root Mean Square Error of Approximation* (RMSEA) is relatively independent of sample size and tests the discrepancy between observed and

implied covariance matrices. Furthermore, the RMSEA considers the complexity of a model so that higher parsimony is reinforced by this fit index. To indicate a good model, the RMSEA should be smaller than 0.05 but also values between 0.05 and 0.08 are considered acceptable [51]. Another advantage of the RMSEA is that a confidence interval can be computed which should include 0 to approximate a perfect model fit.

Eventually, the *Standardized Root Mean Square Residual* (SRMR) represents an index of the covariance residuals as the difference between empirical and implied covariances which should be smaller than 0.10 [52].

Model Evaluation by Means of Confirmatory Factor Analysis: Preliminary Considerations

The two models, depicted in Fig. 2, were evaluated based on the previously described model fit indices. Model 1 constitutes the common timing hypothesis, while Model 2 illustrates a schematic representation of the distinct timing hypothesis

suggesting two distinct timing mechanisms for processing of temporal information in the sub-second and second range, respectively. In this context, it is important to note that the finding of a non-significant χ^2 value for one model and a significant χ^2 value for the other model does not necessarily mean that the first model describes the data *significantly* better than the second model. Therefore, the general rule for comparing different theoretical models is to test whether differences of the model fits are substantial. In the case that two models are in a hierarchical (or nested) relationship, the difference between their χ^2 values and their degrees of freedom can be calculated and this difference value can be tested for statistical significance.

This, however, is only possible when the two models to be compared are in a nested relationship. A nested relationship means that one or more *paths* are freely estimated in one model, but fixed in the other one. In the present study, an example for a *path* refers to the correlation between the two latent variables in Model 2. In this case, the correlation between the two latent variables is fixed to zero because the distinct timing hypothesis predicts two independent mechanisms for interval timing in the second and in the sub-second range. In Model 1, the same correlation can be seen as being fixed to 1 indicating that the two latent variables in Model 2 are virtually identical or represent one and the same latent variable, i.e. one common timing mechanism irrespective of interval duration. Therefore, Model 1 and Model 2 are not nested models because they have the same number of degrees of freedom.

If, however, an alternative third model would imply a freely estimated correlation between the two latent variables of Model 2 (i.e., the assumed correlation coefficient is not theoretically fixed to a certain value of 1 [as in Model 1], or 0 [as in Model 2]), this alternative Model 3 can be considered a nested model compared to Model 1 and Model 2. This is because fixing this correlation in Model 3 to 1 would result in Model 1 and fixing the correlation in Model 3 to 0 would result in Model 2. Thus, the hypothesized Models 1 and 2 can be directly compared to Model 3 by means of a χ^2 difference test.

Our Models 1 and 2, as already pointed out, are not nested. Because non-nested models cannot be compared by χ^2 differences, this type of model has to be compared by their parsimony in terms of the AIC value (see above). As already explicated above, a difference in the AIC values indicates that the model with the lower AIC describes the data more parsimoniously and, therefore, better than the model with the higher AIC. Thus, it is the AIC which has to be used to directly compare Model 1 and Model 2 in the present study.

Model Evaluation by Means of Confirmatory Factor Analysis: Results of the Present Study

Descriptive statistics and intercorrelations of the five interval timing tasks are given in Table 1. In order to contrast the common with the distinct timing hypothesis, we computed CFAs on the two models presented in Fig. 2. Model 1 proceeded from the assumption of a common, unitary timing mechanism so that covariances among performance on all five psychophysical timing tasks were explained by one latent variable. This model, depicted in Fig. 3, explained the data well as can be seen from a non-significant χ^2 test [$\chi^2(5) = 6.27$; $p = 0.28$] as well as from CFI (0.99) which exceeded the requested limit of 0.95. Also the RMSEA was smaller than 0.08 (RMSEA = 0.04) and the 90 % confidence interval included zero (ranging from 0.00 to 0.14). The AIC was 2,396.0 and the SRMR = 0.03. Thus, the assumption of a common unitary timing mechanism is supported by our finding that the empirical data were well described by the theoretical assumption of a single latent variable underlying performance on interval timing tasks in both the sub-second and the second range.

Nevertheless, the finding of a model, that describes the empirical data quite well, does not necessarily mean that there are no other models which describe the empirical data even better. Therefore, we tested the distinct timing hypothesis by deriving a first latent variable from the

Table 1 Mean performance scores (M) and standard deviations (SD) as well as intercorrelations for the five interval timing tasks

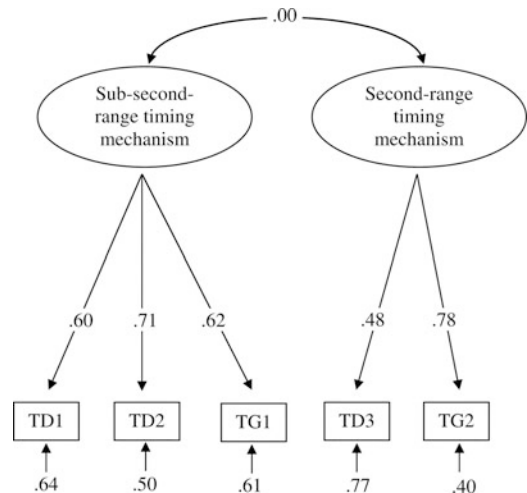|		M	SD	Sub-second range		Second range	
	Indicator of performance			TD2	TG1	TD3	TG2
Sub-second range							
TD1	DL (ms)	7.7	2.7	0.43 ***	0.38 ***	0.20 *	0.36 ***
TD2	DL (ms)	16.0	6.7		0.44 ***	0.36 ***	0.41 ***
TG1	Response dispersion	0.38	0.12			0.19 *	0.37 ***
Second range							
TD3	DL (ms)	118.9	42.0				0.37 ***
TG2	Response dispersion	0.37	0.13				

Note: *TD1* temporal discrimination of filled intervals in the sub-second range, *TD2* temporal discrimination of empty intervals in the sub-second range, *TD3* temporal discrimination of filled intervals in the second range, *TG1* temporal generalization of filled intervals in the sub-second range, *TG2* temporal generalization of filled intervals in the second range

*p < 0.05 (two-tailed); ***p < 0.001 (two-tailed)
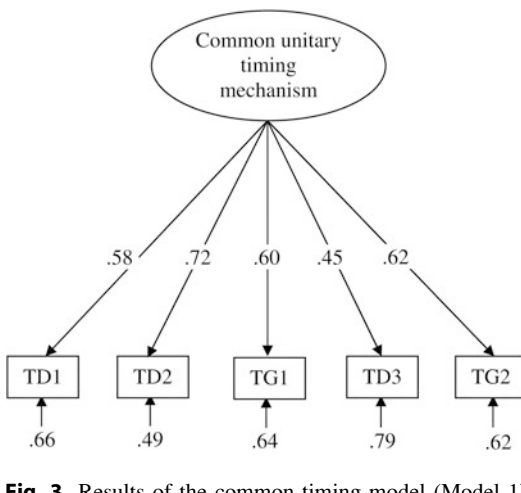
Fig. 3 Results of the common timing model (Model 1) with the assumption of one common latent variable underlying individual differences in all five interval timing tasks irrespective of interval duration. The model fit indices suggest a good model fit [$\chi^2(5) = 6.27$; $p = 0.28$; CFI = 0.99; RMSEA = 0.04; AIC = 2,396.0; SRMR = 0.03]. Presented are completely standardized factor loadings as well as residual variances of the five interval timing tasks. For abbreviations see Table 1

Fig. 4 Results of the distinct timing model (Model 2) with the assumption of two completely independent latent variables underlying temporal processing of intervals in the sub-second and second range, respectively. The model fit indices suggest a poor model fit [$\chi^2(6) = 42.88$; $p < 0.001$; CFI = 0.67; RMSEA = 0.22; AIC = 2,430.63; SRMR = 0.18]. Presented are completely standardized factor loadings as well as residual variances of the five interval timing tasks. For abbreviations see Table 1

three temporal tasks with stimuli in the sub-second range and a second latent variable from the two timing tasks with stimuli in the second range. Furthermore, in order to represent two *independent* mechanisms, the correlation between the two latent variables was fixed to zero (see Fig. 4). As indicated by all model fit indices, this model did not yield a sufficient fit to

the data [$\chi^2(6) = 42.88$; $p < 0.001$; CFI = 0.67; RMSEA = 0.22; 90 %-confidence interval ranging from 0.16 to 0.28; AIC = 2,430.63; SRMR = 0.18]. Thus, the assumption of two distinct mechanisms underlying the processing of time intervals in the sub-second and second range
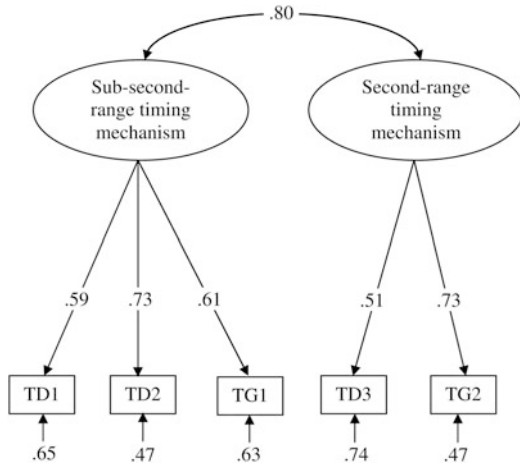
Fig. 5 Results of the third, rather exploratory, timing model (Model 3) assuming two dissociable but associated latent variables underlying the timing of intervals in the sub-second and second range, respectively. The model fit indices suggest a good model fit [$\chi^2(4) = 3.16$; $p = 0.53$; CFI = 1.00; RMSEA = 0.00; AIC = 2,394.9; SRMR = 0.02]. Presented are completely standardized factor loadings as well as residual variances of the five interval timing tasks. The correlation of $r = 0.80$ between the two latent variables is highly significant ($p < 0.001$). For abbreviations see Table 1

did not conform to the empirical data. Moreover, the AIC indicates that Model 1 is more parsimonious than Model 2 (despite more degrees of freedom in Model 2) suggesting that Model 1 describes the data better than Model 2.

It should be noted that Model 2 could only be computed when the factor loadings of the interval timing tasks in the second range were fixed. If not, the model parameters could not be estimated. This is sometimes the case if a latent variable is derived from only two manifest variables. The fact that we fixed this factor loading was the reason why the degrees of freedom of Model 2 do not equal the degrees of freedom of Model 1.

In a final step, we investigated whether temporal processing of intervals in the range of milliseconds may be dissociable from temporal processing of intervals in the second range even if the underlying processes are associated with each other. Therefore, in a third model, the correlation between the two latent variables of the distinct timing model was not fixed to zero but freely estimated. Without fixing this correlation,

Model 2 turned into Model 3 which fit the data well [$\chi^2(4) = 3.16$; $p = 0.53$; CFI = 1.00; RMSEA = 0.00; 90 %-confidence interval ranging from 0.00 to 0.12; AIC = 2,394.9; SRMR = 0.02]. As can be seen from Fig. 5, this model revealed a correlation of $r = 0.80$ ($p < 0.001$) between the two latent variables. As described above, Model 3 and Model 1 are in a hierarchical relationship so that their model fits can directly be compared by means of a χ^2-difference test. This test revealed that the model fits of Model 1 and Model 3 did not differ significantly from each other [$\Delta\chi^2(1) = 3.11$; $p = 0.08$]. The AIC value of Model 1, however, was larger than the AIC value of Model 3. Hence, Model 3, assuming two dissociable timing mechanisms which are highly related to each other, describes the data comparably well as Model 1 but more parsimoniously relative to the model fit and, thus, should be preferred over Model 1.

A Common Timing Mechanism or Two Functionally Related Timing Mechanisms?

In order to elucidate the internal structure of psychophysical timing performance in the sub-second and second range, we employed a CFA approach. More specifically, we investigated whether CFA would rather support the notion of a common unitary timing mechanism or of two distinct timing mechanisms underlying timing performance in the sub-second and second range, respectively. The assumption of two distinct timing mechanisms which are completely independent of each other, as represented by Model 2, was not supported by the present data. All fit indices indicated a poor model fit. On the other hand, Model 1 assuming a single common timing mechanism underlying timing performance in both the sub-second and second range did not only describe the data quite well but also better than Model 2. At this stage of our analysis, however, it would be premature to conclude that a unitary timing mechanism is the best explanation of our data. As an alternative model, we therefore introduced and examined Model 3. This model

assumes two distinct, but functionally related, mechanisms underlying timing performance in the sub-second and second range, respectively. As a matter of fact, Model 3 described the data also very well and even somewhat better than Model 1. Thus, although the correlation between the two latent variables was quite high, the comparison of fit indices indicated that the assumption of two closely associated latent variables described the observed data better than the assumption of only one latent variable.

The large portion of shared variance of approximately 64 % between the two latent variables in Model 3 can be interpreted in terms of a 'simple' functional relationship between the two timing mechanisms involved in the temporal processing of extremely brief intervals in the range of milliseconds and longer intervals in the range of seconds, respectively. Such an association may be due to some operations common to both timing mechanisms or due to 'external' factors, such as specific task demands or task characteristics (cf. [4]) that exert an effective influence on both timing mechanisms. An alternative interpretation of Model 3, however, points to a hierarchical structure for the processing of temporal information in the sub-second and second range. According to this latter account, at a first level, temporal information is processed by two distinct timing mechanisms as a function of interval duration; one mechanism for temporal processing of information in the range of milliseconds and the other one for processing of temporal information in the range of seconds. This initial stage of duration-specific temporal processing is controlled by a superordinate, duration-independent processing system at a higher level.

Empirical Findings Are Required to Validate the Findings Based on the Confirmatory Factor Analysis Approach

It is important to note that we cannot decide statistically on these two alternative interpretations of Model 3. For this reason, we will provide some empirical findings in the following that support the general validity of Model 3 and also address the two tentative interpretations derived from this model.

With the timing tasks applied in the present study, participants had to attend to the intervals to be judged, maintain the temporal information, categorize it, make a decision, and, eventually, perform a response. Although not directly involved in the genuine timing process per se, these mainly cognitive processes are essential for succeeding in interval timing independent of the range of interval duration. Therefore, it seems mandatory to take into account the involvement of cognitive processes irrespective of the interval duration to be timed. This view is consistent with the idea expressed by Model 3 that the timing mechanisms underlying temporal processing of intervals in the range of milliseconds and seconds are not completely independent of each other but may share some common processes [24, 53, 54]. The involvement of various non-temporal processes, and especially the failure to control for it across different studies, may also account for the inconsistent results obtained from the few studies applying a dual-task approach for testing the distinct timing hypothesis (cf. [4, 55]).

In a recent imaging study by Gooch et al. [56], voxel-based lesion-symptom mapping analysis revealed that the right pre-central gyrus as well as the right middle and inferior frontal gyri are involved in the timing of intervals in both the sub-second and second range. These findings are complemented by neuroimaging data from Lewis and Miall [57] showing consistent activity in the right hemispheric dorsolateral and ventrolateral prefrontal cortices and the anterior insula during the timing of both sub- and supra-second intervals. All these reports are consistent with several previous imaging (for a review see [58]) and clinical (e.g., [59, 60]) studies demonstrating that specific regions of the right frontal lobe play a crucial role in interval timing in the sub-second and second range. As these regions were activated regardless of the interval duration to be timed, these brain structures may be part of a core neural network mediating temporal information processing.

In the light of these findings, the two tentative interpretations of Model 3, outlined above, can be substantiated as follows. According to our first interpretation of Model 3, temporal information in the sub-second and second range is processed by two functionally related timing mechanisms. Both these timing mechanisms may operate largely independent of each other but draw upon some working memory processes required to successfully perform any given interval timing task irrespective of interval duration. Thus, the observed correlation between the two latent variables in Model 3 may originate from working memory functions shared by the two mechanisms underlying temporal processing in the sub-second and second range, respectively. It remains unclear, however, whether these shared memory functions can account as a single contributing factor for the strong functional relationship between the two latent variables.

Also compatible with Model 3 is the notion of a hierarchical structure of the timing mechanism. According to this account, temporal information is processed in a duration-specific way at an initial stage that is controlled by a common superordinate duration-independent component. This superordinate component can be tentatively interpreted as an overarching neural network for the processing of temporal information (cf. [61]). Most interestingly, in their most recent review on the neural basis of the perception and estimation of time, Merchant et al. [31] also put forward the idea of a partly distributed timing mechanism with a core timing system based on a cortico-thalamic-basal ganglia circuit.

At first sight, our CFA analyses clearly argued against the distinct timing hypothesis. From this perspective, a clear-cut distinction between sensory/automatic and cognitively mediated temporal processing appears to be too strict. Nevertheless, Model 3 does not inevitably rule out the existence of distinct mechanisms for the timing of intervals in the sub-second and second range, respectively. Apparently, a 'hard' boundary between a sensory/automatic and a cognitive mechanism for millisecond and second timing is unlikely to exist. Nevertheless, the assumption of a transition zone from one timing mechanism to the other with a significant degree of processing overlap [21, 53] would also be consistent with our Model 3. Within this transition zone, both mechanisms may operate simultaneously and their respective contributions to the outcome of the timing process would depend on the specific nature and duration range of a given temporal task [21, 53, 62]. If this is true, one would expect a decreasing correlational relationship between both latent variables in Model 3 when the difference is increased between the base durations of the interval timing tasks in the sub-second and second range. This is because the processing overlap should vanish with increasing dissimilarity between the base durations. To our knowledge, however, the transition zone hypothesis has not been empirically tested yet.

Conclusions

Taken together, application of a CFA approach for investigating the internal structure of interval timing performance in the sub-second and second range clearly argues against the validity of the distinct timing hypothesis that assumes two timing mechanisms completely independent of each other. Although the model of a common unitary timing mechanism fitted the empirical data much better than the model based on the distinct timing hypothesis, the outcome of our CFA analyses supported the basic idea of two *functionally related* timing mechanisms underlying interval timing in the sub-second and second range, respectively. Future research is required to identify the major constituents of both these mechanisms and to further elucidate their functional interaction.

Although CFA cannot always warrant clear-cut solutions, an extension of the traditional psychophysical methodology by incorporating a theory-driven statistical approach, such as CFA, proved to be a useful and highly feasible procedure. Let us consider Grondin's review of the literature (see first chapter) which revealed that there is actually no scalar property for timing and time perception. This finding calls for a re-examination of existing and highly popular models, such as

pacemaker-counter models or SET. In that case, statistical approaches, such as CFA, provide a promising tool for developing, testing, and validating new models even on the basis of psychophysical data already at hand.

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