Studying synchrony between interacting subjects

Comparison of statistical methods to quantify synchrony between subjects

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Abstract

Understanding the functioning of the brain and how it relates to behavior is one of the primary objectives of neuroscience. The focus of neuroscience has evolved from a single brain to studying interactions between multiple brains. In several fields, synchrony in brain responses between individuals has been proven to positively influence psychological processes and lead to better outcomes.

Time-series data for each subject's behavior or modality are obtained by measuring synchrony. Comparative studies for synchrony methods have been carried out in order to gain some insight into the similarities and differences between many measures for evaluating the synchrony between subjects using such time-series data. The research only provides a partial picture of the performance of the synchrony methods in terms of capturing synchrony and the conditions in which these methods are optimal. It is still unknown how well the synchrony methods perform when changing other data characteristics.

The goal of this study is to evaluate the performance of several methods for capturing different types of synchrony between a pair of time series. Two mechanisms are used to generate a pair of time-series data with a known amount of synchrony between the time series (1) two unidirectionally connected Hénon maps, and (2) bivariate von Mises distribution. Correlations between the two time series are computed as another definition of true synchrony to provide a different perspective on true synchrony. In addition, a systematical evaluation of the performance of the synchrony methods on simulated data with various data characteristics is carried out.

For the generated data coherence and phase synchrony are the two best performing methods. Regarding the varied data characteristics, especially the amount of true synchrony has a large effect on recovery performance. These main effects between the data characteristics are qualified by several two-way and three-way interactions that almost always include the synchrony methods and the amount of true synchrony. Under all of the different data characteristics, no synchrony method is perfect, and all of the synchrony methods in this study are not always stable. As a result, using a combination of different synchrony methods to detect synchrony is recommended.

Keywords: synchrony methods, Hénon maps, bivariate von Mises distribution, data characteristics, time series, simulation study

Abbreviations

Table 1: Abbreviations

Symbol	Description
KL	Kullback-Leibler divergence
R(01)	Rényi divergence with α equal to 0.1
R(05)	Rényi divergence with α equal to 0.5
R(09)	Rényi divergence with α equal to 0.9
JS	Jensen-Shannon divergence
JR(2)	Jensen-Rényi divergence with α equal to 2
JR(6)	Jensen-Rényi divergence with α equal to 6
JR(10)	Jensen-Rényi divergence with α equal to 10
MI	Mutual information

Chapter 1

Introduction

One of the main goals of neuroscience is to understand the functioning of the brain and how this relates to behavior. Previously, the study of brain functioning only focused on investigating a single brain of one subject. More recently, it is acknowledged that several important psychological processes, like, for example, emotions, are influenced by the interaction between subjects. Neuroscience therefore shifted its focus from a single brain to the study of the interactions between several brains. An important concept in this regard is brain synchrony. Brain synchrony is divided into intra-brain synchrony and inter-brain synchrony. Intra-brain synchrony refers to the coordinated neural activity or neural coupling between brain regions of the same individual, whereas inter-brain synchrony refers to the neural coupling of brain regions between individuals (Basso, Satyal, & Rugh, 2021). Hyperscanning measures the inter-brain synchrony by simultaneously recording the brain activity between two or more interacting individuals (Kinreich, Djalovski, Kraus, Louzoun, & Feldman, 2017). Synchrony between brain signals is somewhat related to the concept of synchronization that was originally introduced by Christiaan Huygens in his study monitoring the interplay of two pendulum clocks in 1665 (Quiroga, Kraskov, Kreuz, & Grassberger, 2002). Since the 1990s, the study of synchronization between chaotic systems has captured people's curiosity (Pikovsky, Rosenblum, & Kurths, 2002). Returning back to neuroscience, brain synchrony is measured in hyperscanning studies in which the synchrony of, for example, electroencephalographic (EEG) signals between subjects is investigated (Quiroga et al., 2002). Synchrony in brain responses between individuals has been shown to positively influence psychological processes and to lead to better outcomes in several fields. Synchrony, for example, might help the patient and therapist to create a bond (Koole & Tschacher, 2016). By building shared languages, emotional sharing, and affective co-regulation between the patient and the therapist, synchrony improves self-regulatory skills of patients and leads to a better therapeutic outcome. Another example is that students who interact well with one another in a group (i.e., are in sync) tend to perform better in group work than those who do not (Dikker et al., 2017).

Measuring synchrony yields time-series data (e.g., EEG data) for each behavior or modality (e.g., physiology, brain activity, language, movement) of each subject (Koole &

Tschacher, 2016). In the literature, many methods (e.g., coherence, state-space modeling, phase synchrony) have been applied to quantify the synchrony between the subjects from such time-series data. In order to get some insights into similarities and differences between several synchrony measures, comparative studies for the synchrony methods have been conducted. A first line of research focused on surrogate data testing, which has been applied in some comparative studies to examine whether the synchrony detected by the synchrony methods is significantly different from trivial (amounts of) synchrony that play at the background level (Bakhshayesh, Fitzgibbon, Janani, Grummett, & Pope, 2019; Lancaster, Iatsenko, Pidde, Ticcinelli, & Stefanovska, 2018; Vindiola, Vettel, Gordon, Franaszczuk, & McDowell, 2014). The lowest level of true synchrony at which synchrony is detected is used to evaluate the sensitivity of the different synchrony methods (Bakhshayesh et al., 2019). However, this line of research does not give insights into which methods can best capture the true amount or the changes over time in the true amount of synchrony underlying the data. Another line of research, therefore, has compared synchrony estimates obtained from different synchrony methods with the true synchrony in order to directly assess the performance of the synchrony methods regarding capturing true synchrony (Burgess, 2013; Wendling, Ansari-Asl, Bartolomei, & Senhadji, 2009; Kreuz et al., 2007). This line of research shows that there is no synchrony method that outperforms all the other ones in all studied situations. Indeed, the optimal synchrony method depends on the characteristics of the studied data set. Which synchrony method to use should be chosen based on the quality and type of data. However, the data settings that were manipulated in these studies were rather limited. For example, Burgess (2013) only manipulated the concentrations (i.e., one feature of the time series generated from bivariate von Mises distributions) and the true synchrony level in his simulation study. In Kreuz et al. (2007) the synchrony methods are examined on simulated time series with only different levels of noise and different degrees of true synchrony. These studies only yield a partial view on the performance of the methods regarding capturing synchrony and the conditions under which these methods are optimal. To our knowledge, the performance of the synchrony methods when manipulating other characteristics, such as time length and time lag, is yet unknown.

This study aims at examining the performance of certain methods for measuring synchrony between time series. It is investigated which synchrony methods are best for capturing the degree of synchrony presented in a pair of time series. It is also explored how the performance of the synchrony methods changes when data characteristics vary, such as the amount of noise in the data and the length of the time series. Finally, it is assessed whether the results are influenced by the mechanisms used to generate the data, which determine the type of synchrony that is present in the data (and can be captured by the synchrony methods). The following synchrony methods, which possess different features and therefore aim at capturing different types of synchrony, are studied in this thesis: (1) Coherence which focuses on linear relationships between time series, (2) phase synchrony which is based on the Hilbert transform and studies synchrony between the phases of two time series, and (3) information-theoretic measures, which are employed after a continuous wavelet transform (CWT) and use spatial-temporal information from the time series to determine synchrony.

To address the research aims of this study, two mechanisms are employed to generate a pair of time-series data with a known amount of synchrony between the time series: (1) two unidirectionally coupled Hénon maps (Botella-Soler, Castelo, Oteo, & Ros, 2011; Papana, Kyrtsou, Kugiumtzis, & Diks, 2013; Pica, 2020; Pijn, Van Neerven, Noest, & da Silva, 1991), and (2) bivariate von Mises distribution (Burgess, 2013). Apart from the given amount of (true) synchrony, correlations between the two time series are computed as another definition of true synchrony (see Section 3.3.1). Further, a systematic evaluation of the performance of the synchrony methods on simulated data with different data characteristics is carried out. It is discovered which methods are most sensitive in capturing the (changes in the) amount of synchrony among two time series. By assessing the synchrony methods on many time series generated by manipulating the data characteristics, the suitability of the synchrony methods for data with different characteristics is examined. Besides, knowledge will be gained to which extent the performance results can be generalized to different data generating mechanisms. As a result, a better grasp of the strengths and weaknesses of the synchrony methods under varied data characteristics and data generating mechanisms is gained. Based on the results, recommendations regarding which methods best to use in which data setting are formulated.

The thesis is outlined as follows: in Chapter 2, the synchrony methods that will be compared to each other are introduced. In Chapter 3, the design and procedure for the simulation study are sketched, along with the discussion of the two data generating mechanisms and the outcome measures that are used. The results of the simulation study are presented in Chapter 4. Finally, in Chapter 5, the main results are summarized and discussed, followed by a presentation of the limitations of the study and suggestions for further research.

Chapter 2

Methods

2.1 Phase synchrony

Phase synchrony measures the relationship between the phases of the signals above the relationship between amplitudes of the signals that may be present (Quiroga, 2009). To compute the phase of signal x, the Hilbert transform of x is computed:

$$\widetilde{x}(t) = \frac{1}{\pi}x(t). \tag{2.1}$$

The instantaneous phase of x is then extracted by:

$$P_x^H(t) = \arg[x(t) + i\tilde{x}(t)]. \tag{2.2}$$

The phase difference between the two signals is defined as:

$$P_{xy}(t) = nP^H(t)_x - mP^H(t)_y. \tag{2.3}$$

The phase synchrony index between the signals x and y is given by:

$$\text{Synchrony index} = \sqrt{\langle\cos(P_{xy}(t))^2\rangle_t + \langle\sin(P_{xy}(t))^2\rangle_t}. \tag{2.4}$$

The phase synchrony index ranges from 0 to 1. The angle brackets represent the average over time. The coefficients m and n are generally set to 1. The synchrony index is 1 when the phase difference is a constant, which indicates that both time series are very much synchronizing. Synchrony is low when the index is close to zero.

2.2 Coherence

Coherence is a linear method in the frequency domain for measuring the synchrony between two signals. Signals x and y are divided in to segments of equal lengths. The cross spectrum between x and y is computed by averaging across these segments (Bakhshayesh et al., 2019):

$$C_{xy}(f) = E[X(f)Y^*(f)]. \tag{2.5}$$

$X(f)$ is the Fourier transform of x. Y^* is the complex conjugate of the complex number Y. The coherence value is computed as:

$$c(f) = \frac{|C_{xy}(f)|^2}{C_{xx}(f)C_{yy}(f)}. \tag{2.6}$$

The synchrony estimates obtained from coherence are in the [0,1] interval, with a larger value representing a larger degree of synchrony.

2.3 Information-theoretic measures

2.3.1 Continuous wavelet transform

By performing the continuous wavelet transform (CWT), the signals x and y are transformed to the time-frequency domain (Dauwels, Vialatte, Musha, & Cichocki, 2010):

$$X(k, f) = \sum_{l=1}^{K} x(l)M^*(\frac{l-k}{s}). \tag{2.7}$$

$M(k)$ is the 'mother' wavelet, chosen as the complex Morlet wavelet in this study. The total number of the time points is K, and k denotes the kth time point. f is the central frequency, and it can be computed by dividing the central frequency of the 'mother' wavelet by the scaling factor s. The different information-theoretic measures are derived from the CWT of signals x and y.

2.3.2 Kullback-Leibler divergence

The Kullback-Leibler divergence measures the dissimilarity between signals, and its range is $[0, 1]$. When the values obtained from Kullback-Leibler divergence become larger, a lower degree of synchrony between the signals is detected. Thus, the observed synchrony is obtained by using 1 minus the values obtained from Kullback-Leibler divergence. The Kullback-Leibler divergence is measured as (Dauwels et al., 2010):

$$K(C_x; C_y) = \frac{1}{2}(K(C_x, C_y) + K(C_y, C_x)), \tag{2.8}$$

where

$$K(C_x, C_y) = \sum_{k,f} C_x(k, f)\log\frac{C_x(k, f)}{C_y(k, f)}, \tag{2.9}$$

where $C_x(k,f)$ is the normalized spectrogram and can be obtained by (Dauwels et al., 2010):

$$C_x(k,f) = \frac{|X(k,f)|^2}{\sum_{k,f}|X(k,f)|^2}. \tag{2.10}$$

2.3.3 Rényi divergence

Rényi divergence is another method for measuring dissimilarity of time series. It is generalized from Kullback-Leibler divergence (Dauwels et al., 2010). Its formula is:

$$D_\alpha(C_x, C_y) = \frac{1}{\alpha - 1}\log\sum_{k,f}|C_x(k,f)|^\alpha|C_y(k,f)|^{1-\alpha}. \tag{2.11}$$

Its order α is in the interval $[0,1]$ (Van Erven & Harremos, 2014). When $\alpha \in [0,1]$ the Rényi divergence is in [0,1]. $D_\alpha(C_x, C_y)$ converges to the Kullback-Leibler divergence as $\alpha \to 1$ (Liuni, Röbel, Romito, & Rodet, 2011). In this study, α is set to 0.10, 0.50 and 0.90. It is investigated how the changes of α affect the performance of Rényi divergence. A value of 0 of Rényi divergence implies the signals are highly synchronized, and a value that is close to 1 of Rényi divergence indicates a very low degree of synchrony. Therefore, the observed synchrony is obtained by using 1 minus the values obtained from Rényi divergence.

2.3.4 Jensen-Shannon divergence

The Jensen-Shannon divergence is also derived from the Kullback-Leibler divergence. Its range is in $[0,1]$. When the value obtained from Jensen-Shannon divergence becomes larger, the detected synchrony is considered lower, since it quantifies dissimilarity between time series (Aviyente, 2007; Endres & Schindelin, 2003). Therefore, the observed synchrony is obtained by using 1 minus the values obtained from Jensen-Shannon divergence. The formula for Jensen-Shannon divergence is:

$$J(C_x, C_y) = S(\frac{C_x + C_y}{2}) - \frac{S(C_x) + S(C_y)}{2}, \tag{2.12}$$

where

$$S(C_x) = -\sum_{k,f} C_x(k,f)\log C_x(k,f), \tag{2.13}$$

where $S(C_x)$ is Shannon entropy of $C_x(k,f)$ (Dauwels et al., 2010).

2.3.5 Jensen-Rényi divergence

Jensen-Rényi divergence extends Jensen-Shannon divergence by measuring the distance between the time series with the geometric mean instead of the arithmetic mean for Jensen-Shannon divergence. Rényi entropy is given by (Bakhshayesh et al., 2019):

$$R_\alpha(C_x) = \frac{1}{1-\alpha}\log\sum_{k,f}(C_x(k,f))^\alpha. \tag{2.14}$$

Then Rényi entropy R is employed to obtain Jensen-Rényi divergence (Dauwels et al., 2010):

$$J_\alpha(C_x, C_y) = R_\alpha(\sqrt{C_x(k,f)C_y(k,f)}) - \frac{R_\alpha(C_x) + R_\alpha(C_y)}{2}. \tag{2.15}$$

Jensen-Rényi divergence is $\in [0,1]$ when α is larger than 1. A value of 0 implies a very large degree of synchrony between the signals, and a value of 1 indicates no synchrony between the signals. Therefore, the observed synchrony is obtained by using 1 minus the values obtained from Jensen-Rényi divergence. In this study, the following α values are used: 2, 6, 10. As such, the effect of different α values on the performance of Jensen-Rényi divergence is explored.

2.3.6 Mutual information

Different from the information-theoretic measures above, mutual information measures the shared information between signals and this implies that larger mutual information values represent a larger degree of synchrony. Its results are in the range $[0, +\infty)$. The mutual information is given by Dauwels et al. (2010):

$$\mathrm{MI} = \sum_{k,f} C_{xy}(k,f)\log\frac{C_{xy}(k,f)}{C_x(k,f)C_y(k,f)}, \tag{2.16}$$

where $C_x(k,f)$ is the normalized spectrogram (Dauwels et al., 2010):

$$C_x(k,f) = \frac{|X(k,f)|^2}{\sum_{k,f}|X(k,f)|^2}. \tag{2.17}$$

$C_{xy}(k,f)$ is the normalized cross time-frequency distribution of x and y (Dauwels et al., 2010):

$$C_{xy}(k,f) = \frac{|X(k,f)Y^*(k,f)|}{\sum_{k,f}|X(k,f)Y^*(k,f)|}, \tag{2.18}$$

where Y^* is the complex conjugate of the complex number Y.

Chapter 3

Simulation study

In this chapter, in Section 3.1, the two data generating mechanisms are introduced. Next, in Section 3.2, the design and procedure of the simulation study are sketched, herewith also presenting the data characteristics that will be manipulated. Finally, in Section 3.3, the evaluation measures used to quantify the performance of the synchrony methods are introduced.

3.1 Data generating mechanisms

Two data generating mechanisms will be used in the simulation study: (1) Hénon maps, and (2) bivariate von Mises distributions. Both will be explained in detail below.

3.1.1 Hénon maps

Research has shown that EEG signals are generated from random processes or nonlinear dynamic systems that demonstrate chaotic behavior (Pijn et al., 1991). Two unidirectionally coupled Hénon maps is a nonlinear dynamic system, by which signals x and y are generated:

$$\begin{aligned} x(k+1) &= a + bx(k-1) - x^2(k), \\ y(k+1) &= a + dy(k-1) - [\mu x(k) + (1-\mu)y(k)]y(k). \end{aligned} \tag{3.1}$$

The features of Hénon maps depend on the control parameters a, b, d and μ. μ is the coupling strength, which manipulates the synchrony degree (Quiroga, Arnhold, & Grassberger, 2000). b and d are control parameters for generating data with identical systems or nonidentical systems. For classical Hénon maps, $a = 1.4$, and $b = d = 0.3$, and this exhibits chaotic behavior (Botella-Soler et al., 2011; Pica, 2020). Thus, we set $a = 1.4$, as in many previous studies (Papana et al., 2013; Junge & Parlitz, 2001). Therefore, the

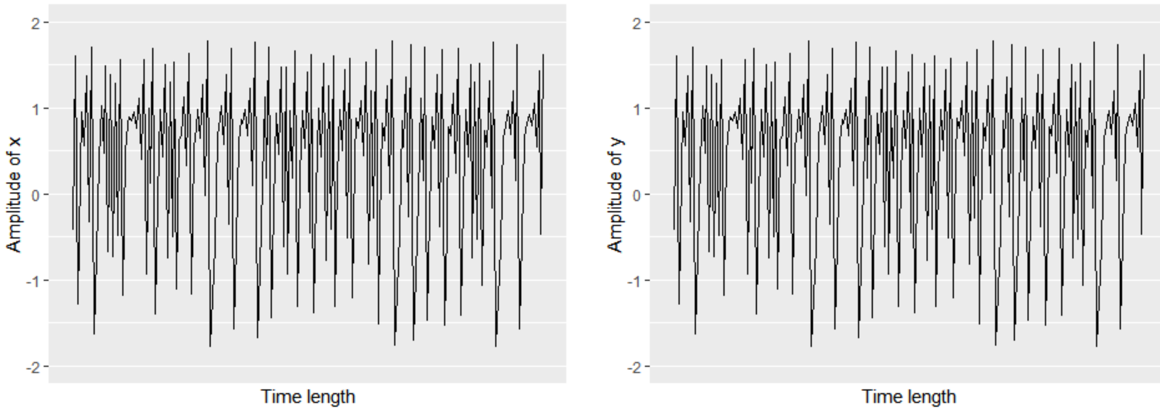


Figure 3.1: A pair of time series x (left panel) and y (right panel) generated from Hénon maps. The given true synchrony is 0.6.

equation becomes:

$$\begin{aligned} x(k+1) &= 1.4 + bx(k-1) - x^2(k), \\ y(k+1) &= 1.4 + dy(k-1) - [\mu x(k) + (1-\mu)y(k)]y(k). \end{aligned} \tag{3.2}$$

Figure 3.1 shows the amplitude of a pair of time series x and y against the time points. In this study, for all data generated from Hénon maps, the first 10000 time points are discarded to avoid transient effects.

3.1.2 Bivariate von Mises distribution

Another data generating mechanism for EEG data is bivariate von Mises distribution. The density function of bivariate von Mises distribution is given by (Burgess, 2013):

$$f(\phi, \psi) = \frac{1}{C} e^{[\kappa_\phi \cos[(\phi-\mu_\phi)] + \kappa_\psi \cos[(\psi-\mu_\psi)] + \lambda \sin[(\phi-\mu_\phi)] \sin[(\psi-\mu_\psi)]]}, \tag{3.3}$$

where ϕ and ψ are two random variables, and κ_ϕ and κ_ψ are the concentrations for ϕ and ψ and represent (more or less) the variance for ϕ and ψ, respectively (Mardia, Taylor, & Subramaniam, 2007). μ_ϕ and μ_ψ represent the mean for ϕ and ψ. λ is related to the correlation between ϕ and ψ, and $\lambda \in (-\infty, \infty)$(Singh, Hnizdo, & Demchuk, 2002). $\lambda = 0$ represents that there is no correlation between ϕ and ψ. Larger $|\lambda|$ represents stronger dependence between ϕ and ψ.

To simulate a pair of time series, $[\phi_1, \phi_2, \phi_3, ..., \phi_n]$ and $[\psi_1, \psi_2, \psi_3, ..., \psi_n]$ are generated from a bivariate von Mises distribution, with the true amount of synchrony controlled by λ. The phase series $[0, 2\pi, 3\pi, ..., n\pi]$ is added to the two phase series respectively, and $[0+\phi_1, 2\pi+\phi_2, 3\pi+\phi_3, ..., n\pi+\phi_n]$ and $[0+\psi_1, 2\pi+\psi_2, 3\pi+\psi_3, ..., n\pi+\psi_n]$ are obtained. The simulated signals are alpha rhythms with a mean frequency $f = 10$ Hz (Burgess,

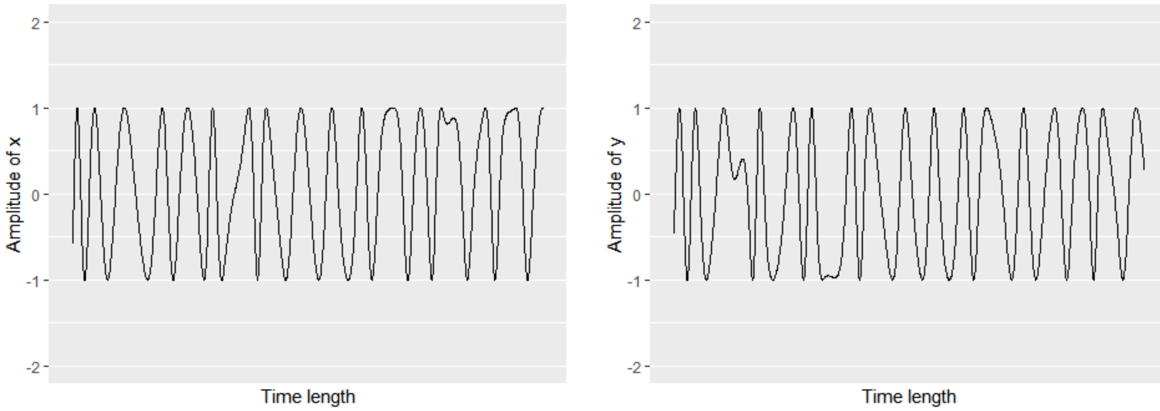


Figure 3.2: A pair of time series x (left panel) and y (right panel) generated from the bivariate von Mises distribution. The given true synchrony is 0.6.

2013). Then the spline interpolation is implemented, where the interval is $1/\omega$, $\omega = 2\pi f$ seconds. To get the time series x or y, the last step is to take the sine of the obtained phase series.

Figure 3.2 shows the amplitude of a pair of time series x and y against time, which are generated from the bivariate von Mises distribution.

3.2 Design and procedure

3.2.1 Design

The data characteristics that will be manipulated in the simulation study are introduced in this section. The manipulated data characteristics are 1) synchrony level, 2) the control parameters of the two data generating mechanisms b, d and κ (κ_ϕ and κ_ψ), 3) time lag, 4) time length, 5) amount of noise, 6) type of noise. The values of these factors are specified below.

True synchrony level

Values representing low synchrony (0.20), average synchrony (0.50) and high synchrony (0.80) are set. In order to create variability in the generated true amounts of synchrony, the true synchrony values for these three levels are sampled uniformly from symmetric intervals with a width of 0.10 around these three values. In other words, the three intervals are [0.1, 0.3], [0.4, 0.6] and [0.7, 0.9], from which the low synchrony, average synchrony and high synchrony values are sampled.

One definition for the true synchrony between the generated signals x and y is based on the parameter of the data generating mechanisms, through which the amount of synchrony between x and y can be controlled. For Hénon maps, the coupling strength μ represents the true synchrony. For data generated from bivariate von Mises distribution, parameter λ is related to the correlation between x and y. However, λ cannot be used as the amount of true synchrony directly, and a transformation is needed. Since λ is in $[0, \infty)$ when the relationship between x and y is positive, a Fisher z-transformation $z = 0.5 \cdot \log\frac{1+r}{1-r}$ is applied to transform the true synchrony from [0, 1] to the range $[0, \infty)$, where r is defined as the true synchrony between the time series generated from bivariate von Mises distribution. In this case, λ is z.

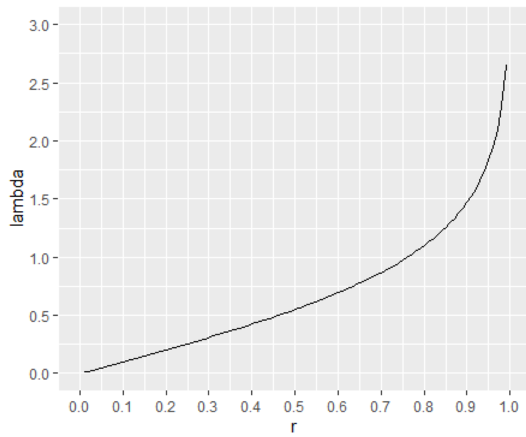


Figure 3.3: The relationship between λ and r when applying the Fisher z-transformation. $r \in [0.01, 0.99]$.

From Figure 3.3, it can be seen that when r is 0.99, λ is smaller than 3. However, this is not the appropriate scale. λ should be able to be greater than 10 so that the true amount between x and y can be large (Hnizdo, Tan, Killian, & Gilson, 2008).

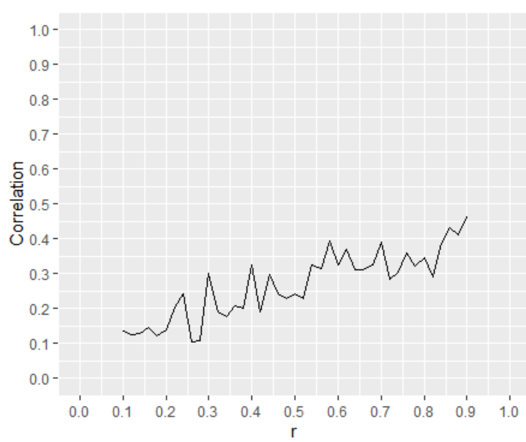


Figure 3.4: Correlation between x and y against r when applying the Fisher z-transformation.

To see if the transformation works properly, noise-free data with $r = [0.1, 0.2, \ldots, 0.9]$

is generated. The time length is 10054. From Figure 3.4, it can be seen that the correlation between x and y are low even when r takes high values. Thus, the scale needs to be adjusted.

In this case, z is multiplied by 4 and this value is taken as the value of λ, and the procedure above generating the data is repeated. It can be seen from Figure 3.5 that the transformation makes more sense as now the correlation takes the whole [0, 1] range.

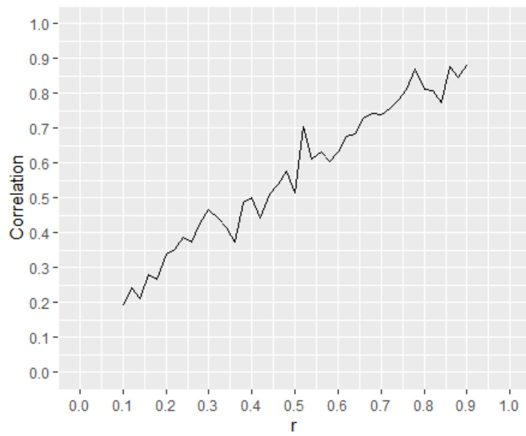


Figure 3.5: Correlation between x and y against r when z is multiplied by 4

Control parameters b, d and κ

Other parameters than the amount of synchrony of the two data generating mechanisms are varied. The parameters are (1) b and d for Hénon maps and (2) the concentrations κ (κ_ϕ and κ_ψ) for the bivariate von Mises distributions (Botella-Soler et al., 2011). The parameters b and d define whether systems are identical ($b = d = 0.3$) or not ($b \neq d$). For identical systems, the choice of 0.3 is a classical choice. For nonidentical systems, we set $b = 0.3$ and $d = 0.1$, which is used in many previous studies (Krakovská, Jakubík, Budáčová, & Holecyová, 2015; Quiroga et al., 2000; Bakhshayesh et al., 2019). Regarding the parameters for the bivariate von Mises distributions, the concentrations $(\kappa_\phi, \kappa_\psi)$ are set as $(0.5, 0.5)$, $(1, 1)$ and $(2, 2)$, where the values of the concentrations represent anti-variance, which indicates that data with larger values of $(\kappa_\phi, \kappa_\psi)$ has a larger degree of concentrations. A larger degree of concentrations may lead to a larger degree of detected synchrony when the true amount of synchrony is 0.

Time lag

The time lags at which the true synchrony is presented (i.e., synchrony could exist between a time series and a lagged version of the other time series) are set as 0, and 2 units. For data generated from Hénon maps, the time lag is implemented by shifting one of both time series 0 (i.e., no shifting) or 2 time units/points. For data generated from the bivariate von Mises distribution, to obtain a pair of time-lagged time series, $n + 2$

independent samples were drawn, which are $[\phi_1, \phi_2, \phi_3, ..., \phi_{n+2}]$ and $[\psi_1, \psi_2, \psi_3, ..., \psi_{n+2}]$. The phase series $[0, 2\pi, 3\pi, ..., n\pi]$ is added to the two phase series respectively, and $[0 + \phi_1, 2\pi + \phi_2, 3\pi + \phi_3, ..., n\pi + \phi_n]$ and $[0 + \psi_3, 2\pi + \psi_4, 3\pi + \psi_5, ..., n\pi + \psi_{n+2}]$ are obtained (Burgess, 2013). Other procedure is the same as generating the time series with no time lag.

Time length

The time length of the time series is manipulated at 2 levels: around 1000 and 10000 units, where the unit is the time point. Note that spline interpolation is conducted during the process of generating data from the bivariate von Mises distribution. This indicates that it is tricky to generate a time series with a given time length. The time length of the generated data can only be around the given time length. In this case, the data is first generated by the bivariate von Mises distribution method, and Hénon maps is used to generate time series with the same time length as the time length of the data generated using the bivariate von Mises distribution. As a result, the two levels of time length are 1006 and 10054. It should be noted that for Hénon maps time series with 11006 and 20054 are generated and then the first 10000 time points are discarded to avoid transient effects.

Amount of noise

Noise is added to the time series. In particular, white noise generated from a Gaussian distribution and temporally autocorrelated noise generated by using different AR correlation values are considered. The amount of noise is manipulated at the following 2 levels: 20% and 50%. The amount of noise can be measured by the signal-to-noise ratio, which is the ratio of the signal power to the noise power, where the power of a signal is computed by its mean squared value. For signal (noise) with zero mean, the mean squared values of the signal (noise) are equal to the variance of the signal (noise) (Alyasseri, Khader, Al-Betar, Abasi, & Makhadmeh, 2019; Hassani & Karami, 2015):

$$\text{SNR} = \frac{\text{1-noise\%}}{\text{noise\%}} = \frac{\sum \text{signal}^2}{\sum \text{noise}^2} = \frac{\text{VAR}_{\text{signal}}}{\text{VAR}_{\text{noise}}}. \tag{3.4}$$

The variance of the signals and SNR are known. From Equation 3.4, it can be seen that the variance of the noise can be computed by $\frac{\text{VAR}_{\text{signal}}}{\text{SNR}}$. In this way, the information required to generate the noise is obtained. The noise has the same length as the signals, and is added to the signals x and y respectively.

Type of noise

White noise is generated from a Gaussian distribution, where the mean is 0 and the variance is computed as mentioned before. The noise value at each time point is uncorrelated with the noise value at the previous time point.

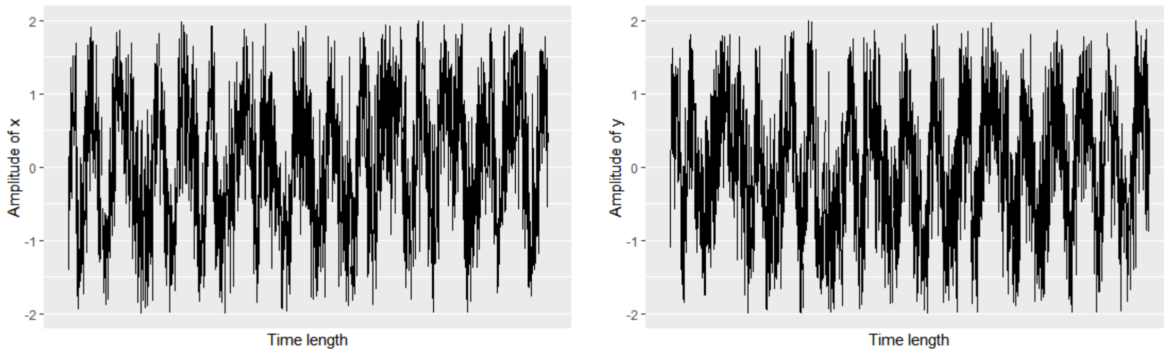


Figure 3.6: A pair of time series x (left panel) and y (left panel) generated from the bivariate von Mises distribution after adding white noise. The given true synchrony is 0.6, and the noise level is 0.5.

Temporally autocorrelated noise is generated by the R Package 'colorednoise'. The temporally autocorrelated noise is given by (Pilowsky & Dahlgren, 2020):

$$\begin{aligned} \nu_1 &= w_1, \\ \nu_{t+1} &= \beta\nu_t + w_{t+1}\sqrt{1-\beta^2}, t > 1. \end{aligned} \tag{3.5}$$

ν_t is the temporally autocorrelated noise at time point t. w_t is the white noise at time point t. β is the temporal autocorrelation, where $-1 \leq \beta \leq 1$. If $\beta = 0$, the model generates white noise rather than temporally autocorrelated noise. In this study, β is set as 0.5. A positive β implies the time points are positively correlated with the previous ones.

Figure 3.6 shows the amplitude of a pair of time series against the time length. This time series is obtained by adding white noise to the time series x and y presented in Figure 3.2.

3.2.2 Procedure

Both for the simulation with Hénon maps and with bivariate von Mises distribution, the following parameters will be manipulated:

1) amount of synchrony: low (0.20), average (0.50) and high synchrony (0.80);

2) other parameters of the two data generating mechanisms: b, d (for Hénon maps, manipulated at two values) and κ (for bivariate von Mises distribution, manipulated at three levels);

3) the time lags at which true synchrony is present: 0 and 2 units;

4) the time length of the time series: 1006 and 10054 units;

5) amount of noise: 20% and 50%;

6) type of noise: Gaussian and temporally autocorrelated (with 0.50 as autocorrelation).

For each cell of the design, 20 replicate data sets will be generated.

The data generated from Hénon maps has 96 conditions (i.e., 3 synchrony × 2 other parameters × 2 lags × 2 time serie lengths × 2 noise amounts × 2 noise types), and there are 20 replicates in each condition, which gives 1920 datasets in total. To each of the 1920 datasets, 11 different synchrony methods are applied. The data generated from the bivariate von Mises distribution has 144 conditions (i.e., 3 synchrony × 3 other parameters × 2 lags × 2 time serie lengths × 2 noise amounts × 2 noise types), and there are 20 replicates in each condition, which gives 2880 datasets in total. To each of the 2880 datasets, 11 different synchrony methods are applied.

The 20 values for the true synchrony score are sampled from the given interval (see above). This value is taken by μ (for Hénon maps) and r (for bivariate von Mises distribution). λ is obtained by the transformation mentioned in Section 3.2.1. Then the values of the manipulated factors except the noise level and the noise type are specified, and the two signals x and y are generated from the data generating mechanisms. Noise with different characteristics mentioned in Section 3.2.1 (i.e., noise level and noise type) is generated and added to the time series respectively. The synchrony methods are applied on the simulated data, and the synchrony estimates are obtained.

3.3 Evaluation measures

3.3.1 Another definition for true synchrony

The values of μ and r can describe the true amount of true synchrony to some extent. However, there is no guarantee that the true level of synchrony is accurately represented by these value. Therefore, another definition for true synchrony is computed as a complement to provide a different perspective on true synchrony. One of the most well-known synchrony values is the Pearson correlation coefficient between time series. To measure the true synchrony in this manner, data with manipulated characteristics other than noise and time lag are first generated. The true synchrony is calculated for each dataset using the correlation between the two time series (to which no noise is yet added). Then noise and time lag are added to the data. The other steps are the same as in Section 3.3.1. One drawback is that synchrony methods that function similarly to the correlation coefficient may have an advantage over other methods when using this correlation as the true synchrony measure.

The correlation coefficient between x and y is given by (Dauwels et al., 2010):

$$r = \frac{1}{N}\sum_{k=1}^{N}\frac{(x(k)-\bar{x})}{\sigma_x}\frac{y(k)-\bar{y}}{\sigma_y}, \tag{3.6}$$

where $-1 \leq r \leq 1$. A larger $|r|$ indicates a larger degree of synchrony. The sign of the correlation coefficient values represents the direction of the relationship. Negative values of r indicate a negative relationship between the two signals, and positive values of r represent a positive relationship between the two signals. There is a debate in the literature about whether negative synchrony should be considered on the same level as positive synchrony. Interestingly in this regard is that a good conversation is characterized by subjects speaking and listening in alternating turns, which implies a negative correlation between the subjects (i.e., when one subject talks, the other one is silent and vice versa). As such, negative synchrony seems to be valuable to study and seems to be at the same level as positive synchrony.

3.3.2 Performance measures

To determine the extent to which measures are capable of detecting varying levels of true synchrony, the mean squared error (MSE), which is the average squared difference between the estimated synchrony and the true synchrony, is computed. Furthermore, as not all synchrony methods produce estimates on a 0-1 scale, also the correlation between the given synchrony and the synchrony estimates are calculated. It should be noted that there are two definitions for the true synchrony, so we have two MSEs and two correlations for data generated from each data generation mechanism. We use symbols in Table 3.1 to represent the measures of the performance.

The MSE between the 20 pairs of true synchrony and obtained synchrony result in one value of MSE as the MSE is averaged across these 20 pairs. Computing the correlation between the 20 pairs of true synchrony and obtained synchrony results in one value of the correlation. For each condition formed by the data characteristics, the process of simulating 20 data sets are implemented 20 times (i.e., repetitions of the design) and the corresponding MSEs and correlations are obtained. We use the symbols explained in Table 3.1 to represent the measures of the performance of the synchrony methods.

Table 3.1: Symbols for the performance measures for the two data generating mechanisms with different definitions for true synchrony

Symbol	Measure	Data generating mechanism	Definition for true synchrony
$\mathrm{MSE}_{h\mu}$	MSE	Hénon maps	μ
MSE_{hc}	MSE	Hénon maps	Correlation
$\mathrm{Cor}_{h\mu}$	Correlation	Hénon maps	μ
Cor_{hc}	Correlation	Hénon maps	Correlation
MSE_{br}	MSE	bivariate von Mises distribution	r
MSE_{bc}	MSE	bivariate von Mises distribution	Correlation
Cor_{br}	Correlation	bivariate von Mises distribution	r
Cor_{bc}	Correlation	bivariate von Mises distribution	Correlation

Chapter 4

Results

In this chapter, the results of the simulation study are presented. First, the results are presented for the simulation with Hénon maps (Section 4.1) and next the results for the data generated from a bivariate von Mises distribution (Section 4.2). For each simulation study, we first show the overall results of the performance measures (i.e., mean values) in order to determine the best performing method in general. To this end, the methods are ranked based on the mean performance value (Section 4.1.1 and 4.2.1). Next, the main effects for the manipulated data characteristics are presented, through which the influence of the data characteristics can be evaluated (Section 4.1.2 and 4.2.2). Finally, the results of the mixed ANOVA are discussed in which the performance measure is used as the dependent variable (Section 4.1.3 and 4.2.3). In order to focus on the most important results, only the significant main and interaction effects with a generalized effect size (ges) that is larger than some certain determined value are presented and interpreted.

4.1 Results for data generated from Hénon maps

4.1.1 General results

The overall performance (i.e., averaged across all generated data sets) of the synchrony methods in terms of the mean MSE (Table 4.1) and correlation (Table 4.2) values is shown in Table 4.1 and 4.2. The general results shown in these two tables pertain to the data under all the manipulated conditions (see Section 3.2). Note that larger values for $\text{Cor}_{h\mu}$ (left part of Table 4.2) and Cor_{hc} (right part of Table 4.2), and lower values of $\text{MSE}_{h\mu}$ (left part of Table 4.1) and MSE_{hc} (right part of Table 4.1) indicate better recovery performance. Remember that $\text{MSE}_{h\mu}$ and $\text{Cor}_{h\mu}$ refer to the results when the synchrony parameter μ from Hénon maps is used as true synchrony score, whereas MSE_{hc} and Cor_{hc} pertain to the mean of the correlations between the given synchrony (i.e., the true synchrony estimated as the average correlation between pairs of time series) and the synchrony estimates. Indeed, the MSEs between the obtained synchrony and the true synchrony score reflect the (raw) difference between the synchrony estimate and true synchrony (i.e., including some offset or bias term). The correlation between the obtained synchrony and the true synchrony score captures how well the obtained synchrony score picks up changes in the true amount of synchrony, irrespective of some offset or bias terms. In general, as the true synchrony increases, the synchrony estimates should increase overall. Lower mean values of MSEs do not always necessarily indicate a better performance, since it can be that overall the MSEs are lower (due to a small offset term), but the synchrony estimates do not capture well the changes in the true synchrony score. Larger MSEs could be caused by an offset (bias) in the obtained synchrony score, which could be linked to the scale used for the obtained synchrony score and maybe could be corrected for. For example, when the obtained synchrony score is always 0.20 above the true synchrony score, the MSE will indicate a poor recovery (i.e., large MSE), whereas the correlation would indicate a good recovery (i.e., a correlation close to 1). By subtracting 0.20 from the obtained synchrony score, an overall very good performing method could be obtained in this case.

From this perspective, we first evaluate the performance of the synchrony methods based on the correlations ($\mathrm{Cor}_{h\mu}$ and Cor_{hc}) and next we look at the MSEs ($\mathrm{MSE}_{h\mu}$ and MSE_{hc}). When the mean values of the correlations of two synchrony methods are close to each other, we can look at the MSEs to determine which synchrony method is the best one of the two. When the correlations are low for some synchrony methods, even although MSEs are low, we do not consider this synchrony method performing well.

From Table 4.1 and 4.2, it can be seen that coherence is the best synchrony method both in terms of the MSEs (Table 4.1) and the correlation (Table 4.2). The phase synchrony is the second best performing synchrony method when using MSE_{hc}, $\mathrm{Cor}_{h\mu}$ and Cor_{hc} as the performance measure. The correlations for the information-theoretic measures (i.e., MI, KL, R(01), R(05), R(09), JS, JR(2), JR(6), JR(10)) are much lower than coherence and phase synchrony. In this case, we consider phase synchrony as the second best performing method for data generated from Hénon maps regardless that the $\mathrm{MSE}_{h\mu}$ of phase synchrony is larger than most other synchrony methods. When we look at $\mathrm{Cor}_{h\mu}$ and Cor_{hc}, there are no large differences between the performance of the information-theoretic measures, except for Jensen-Rényi divergence with α equal to 10 (JR(10)), which performs a bit worse than the other information-theoretic measures. When looking at MSEs, JR10 ranks in the middle, but since $\mathrm{Cor}_{h\mu}$ and Cor_{hc} weight more and $\mathrm{Cor}_{h\mu}$ and Cor_{hc} of JR(10) are much lower than these of other information-theoretic measures, we consider JR(10) performing much worse than the other information-theoretic measures. Thus, $\alpha = 10$ seems a bit large in this case.

Table 4.1: Overall performance of the synchrony methods ranked according to $\text{MSE}_{h\mu}$ (left part of the table) and MSE_{hc} (right part of the table)

Method	Mean of $\text{MSE}_{h\mu}$	Method	Mean of MSE_{hc}
coherence	0.09	coherence	0.10
KL	0.10	phase synchrony	0.22
R(09)	0.12	KL	0.23
JR(10)	0.13	R(09)	0.25
JR(2)	0.14	JR(10)	0.27
JR(6)	0.14	JR(2)	0.28
R(05)	0.19	JR(6)	0.28
phase synchrony	0.23	R(05)	0.35
JS	0.25	JS	0.43
R(01)	0.28	R(01)	0.47
MI	103.22	MI	105.23

Table 4.2: Overall performance of the synchrony methods ranked according to $\text{Cor}_{h\mu}$(left part of the table) and Cor_{hc} (right part of the table)

Method	Mean of $\text{Cor}_{h\mu}$	Method	Mean of Cor_{hc}
coherence	0.53	coherence	0.48
phase synchrony	0.33	phase synchrony	0.43
JR(2)	0.21	JR(2)	0.19
JS	0.2	JS	0.18
R(05)	0.2	R(05)	0.18
KL	0.2	KL	0.18
R(01)	0.2	R(01)	0.18
R(09)	0.2	R(09)	0.18
MI	0.19	MI	0.18
JR(6)	0.18	JR(6)	0.17
JR(10)	0.14	JR(10)	0.12

4.1.2 Overall influence of the manipulated characteristics

The mean performance measures $\text{MSE}_{h\mu}$ (Table 4.3), MSE_{hc} (Table 4.4), $\text{Cor}_{h\mu}$ (Table 4.5) and Cor_{hc} (Table 4.6) for the different synchrony methods (in the columns) as a function of the different values of the manipulated data characteristics (in the rows) are presented in Tables 4.3-4.6. As such, these tables can be used to evaluate the main effects of the manipulated data characteristics for the different synchrony methods.

From Table 4.3, it can be seen that the change of the true synchrony level has the largest influence on the performance of the synchrony methods, with larger true synchrony values in general leading to larger observed synchrony for the different synchrony methods. Time lag has a greater impact on phase synchrony than on the other synchrony methods. All the synchrony methods are not sensitive to the change of the type of noise, except the coherence for which the performance measures change slightly when the noise type changes. The change of time length has a substantial impact on mutual information (MI). Note that for MI, the MSEs are large in general (therefore, overall results in Tables 4.3-4.6 are presented with and without MI included). Coherence and phase synchrony are influenced by noise level, and information-theoretic measures are stable when the noise level changes.

Table 4.3: Overall influence of the data characteristics to the synchrony methods when using $\text{MSE}_{h\mu}$ as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall without MI	Overall with MI
true synchrony	low	0.01	0.04	0.26	0.60	0.43	0.29	0.54	0.33	0.33	0.31	108.39	0.31	10.14
true synchrony	average	0.10	0.21	0.05	0.23	0.13	0.06	0.19	0.08	0.08	0.08	102.76	0.12	9.45
true synchrony	high	0.18	0.43	0.01	0.03	0.01	0.00	0.02	0.00	0.00	0.00	98.53	0.68	9.02
b and d	0.3 and 0.3	0.10	0.23	0.10	0.29	0.19	0.12	0.25	0.14	0.14	0.13	102.90	0.17	9.51
b and d	0.3 and 0.1	0.09	0.23	0.11	0.29	0.19	0.12	0.25	0.14	0.14	0.13	103.55	0.17	9.57
time lag	0	0.09	0.18	0.10	0.28	0.19	0.12	0.25	0.14	0.14	0.13	103.23	0.17	9.53
time lag	2	0.09	0.28	0.11	0.29	0.19	0.12	0.25	0.14	0.14	0.13	103.22	0.17	9.54
time length	1006	0.09	0.23	0.11	0.28	0.19	0.12	0.25	0.14	0.14	0.13	81.64	0.17	7.57
time length	10054	0.09	0.23	0.10	0.29	0.19	0.12	0.25	0.14	0.14	0.13	124.82	0.17	11.5
noise level	0.2	0.06	0.19	0.11	0.29	0.20	0.12	0.25	0.14	0.14	0.14	103.96	0.16	9.60
noise level	0.5	0.13	0.27	0.10	0.29	0.19	0.12	0.25	0.13	0.13	0.13	102.50	0.17	9.48
noise type	ar	0.08	0.23	0.10	0.29	0.19	0.12	0.25	0.14	0.14	0.13	103.08	0.17	9.52
noise type	white	0.11	0.23	0.11	0.29	0.19	0.12	0.25	0.14	0.14	0.13	103.38	0.17	9.55
Overall		0.09	0.23	0.10	0.28	0.19	0.12	0.25	0.14	0.14	0.13	103.22	0.17	9.54

The results in Table 4.4 are very similar to the results in Table 4.3. The difference is that in Table 4.4 the MSE_{hc} slightly changes when the values of b and d (i.e., meta parameters of Hénon maps) change, whereas such a change in MSEs is not observed in Table 4.3.

Table 4.4: Overall influence of the data characteristics to the synchrony methods when using MSE_{hc} as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall without MI	Overall with MI
true synchrony	low	0.02	0.00	0.48	0.92	0.71	0.52	0.85	0.57	0.57	0.55	112.26	0.52	10.68
true synchrony	average	0.03	0.09	0.19	0.46	0.33	0.21	0.42	0.25	0.25	0.24	106.70	0.25	9.92
true synchrony	high	0.26	0.56	0.03	0.02	0.01	0.02	0.01	0.02	0.01	0.02	96.71	0.10	8.88
b and d	0.3 and 0.3	0.09	0.19	0.18	0.41	0.30	0.20	0.37	0.23	0.23	0.22	104.73	0.24	9.74
b and d	0.3 and 0.1	0.12	0.24	0.28	0.52	0.40	0.30	0.48	0.33	0.33	0.32	105.71	0.33	9.91
time lag	0	0.10	0.15	0.23	0.47	0.35	0.25	0.42	0.28	0.28	0.27	105.24	0.28	9.82
time lag	2	0.10	0.28	0.23	0.47	0.35	0.25	0.43	0.28	0.28	0.27	105.20	0.29	9.83
time length	1006	0.10	0.22	0.24	0.47	0.35	0.26	0.43	0.28	0.28	0.27	83.44	0.29	7.85
time length	10054	0.10	0.22	0.23	0.47	0.35	0.25	0.42	0.28	0.28	0.26	127.00	0.29	11.81
noise level	0.2	0.07	0.18	0.23	0.47	0.35	0.26	0.43	0.28	0.28	0.27	105.95	0.28	9.89
noise level	0.5	0.14	0.26	0.23	0.47	0.35	0.25	0.42	0.28	0.27	0.26	104.49	0.29	9.77
noise type	ar	0.09	0.22	0.23	0.47	0.35	0.25	0.42	0.28	0.28	0.27	105.07	0.29	9.81
noise type	white	0.12	0.22	0.23	0.47	0.35	0.25	0.43	0.28	0.28	0.27	105.37	0.29	9.84
Overall		0.10	0.22	0.23	0.47	0.35	0.25	0.43	0.28	0.28	0.27	105.23	0.29	9.83

Table 4.5, which uses $\text{Cor}_{h\mu}$ as performance measure, shows that the manipulated data characteristics have a larger influence on the different synchrony methods when the correlation is used as performance measure. There is a large influence of the amount of true synchrony and this especially for the coherence and phase synchrony method. For these two methods, the largest correlation is observed for average amounts of synchrony. For the other methods, there is no difference between high and average amounts of true synchrony but both levels differ substantially from low synchrony, with low synchrony

yielding the lowest correlations. The change of the values of b and d influences the performance of all the synchrony methods, with this change being larger for coherence and phase synchrony than for the other synchrony methods. For time lag, almost no differences are encountered between no lag and a lag of two time units. Phase synchrony, however, here is an exception with no time lag yielding the largest correlations. All the synchrony methods perform much better when time length is 10054 compared to when time length is 1006, with, again, this difference being the largest for the coherence and phase synchrony method. The noise level affects all synchrony methods, although it has a greater impact on the information-theoretic and the coherence method than on the other methods. Noise type has no effect on phase synchrony but only slightly affects the other methods.

Table 4.5: Overall influence of the data characteristics to the synchrony methods when using $\mathrm{Cor}_{h\mu}$ as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall
true synchrony	low	0.37	0.22	0.06	0.06	0.06	0.06	0.06	0.07	0.09	0.08	0.05	0.11
true synchrony	average	0.76	0.70	0.26	0.26	0.26	0.26	0.27	0.27	0.23	0.16	0.25	0.33
true synchrony	high	0.45	0.09	0.28	0.28	0.28	0.27	0.28	0.28	0.24	0.16	0.27	0.26
b and d	0.3 and 0.3	0.68	0.46	0.27	0.27	0.27	0.27	0.27	0.28	0.25	0.18	0.26	0.31
b and d	0.3 and 0.1	0.38	0.21	0.13	0.13	0.13	0.13	0.13	0.14	0.12	0.09	0.12	0.16
time lag	0	0.54	0.46	0.18	0.19	0.18	0.18	0.19	0.20	0.19	0.14	0.17	0.23
time lag	2	0.51	0.21	0.22	0.21	0.22	0.22	0.22	0.22	0.18	0.13	0.21	0.23
time length	1006	0.41	0.26	0.13	0.12	0.13	0.13	0.13	0.13	0.11	0.08	0.11	0.16
time length	10054	0.64	0.41	0.28	0.28	0.28	0.27	0.28	0.29	0.26	0.19	0.26	0.31
noise level	0.2	0.61	0.36	0.30	0.30	0.30	0.30	0.30	0.31	0.26	0.19	0.28	0.32
noise level	0.5	0.45	0.30	0.10	0.10	0.10	0.10	0.10	0.11	0.10	0.08	0.09	0.15
noise type	ar	0.55	0.33	0.18	0.18	0.18	0.18	0.18	0.18	0.16	0.12	0.17	0.22
noise type	white	0.50	0.33	0.22	0.22	0.23	0.22	0.23	0.23	0.21	0.15	0.21	0.25
Overall		0.53	0.33	0.20	0.20	0.20	0.20	0.20	0.21	0.18	0.14	0.19	0.23

From Table 4.6, one can see that the results for the Cor_{hc} performance measure are very similar than for Cor_{hc}. Remarkably is that the time lag affects phase synchrony here considerably more than in Table 4.5.

Table 4.6: Overall influence of the data characteristics to the synchrony methods when using Cor_{hc} as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall
true synchrony	low	0.14	0.45	0.05	0.05	0.05	0.05	0.05	0.06	0.08	0.07	0.05	0.10
true synchrony	average	0.84	0.74	0.25	0.25	0.25	0.25	0.25	0.25	0.21	0.14	0.24	0.33
true synchrony	high	0.48	0.11	0.24	0.24	0.24	0.24	0.24	0.25	0.22	0.16	0.23	0.24
b and d	0.3 and 0.3	0.68	0.47	0.23	0.23	0.23	0.23	0.23	0.24	0.21	0.15	0.22	0.28
b and d	0.3 and 0.1	0.29	0.39	0.13	0.13	0.13	0.13	0.13	0.14	0.13	0.09	0.13	0.17
time lag	0	0.49	0.70	0.17	0.17	0.17	0.17	0.17	0.18	0.16	0.11	0.16	0.24
time lag	2	0.48	0.16	0.19	0.19	0.19	0.19	0.19	0.20	0.18	0.13	0.19	0.21
time length	1006	0.41	0.36	0.09	0.09	0.10	0.10	0.10	0.10	0.09	0.06	0.09	0.14
time length	10054	0.55	0.50	0.27	0.27	0.27	0.27	0.26	0.28	0.25	0.18	0.26	0.31
noise level	0.2	0.53	0.48	0.27	0.27	0.27	0.27	0.27	0.28	0.24	0.17	0.26	0.30
noise level	0.5	0.44	0.39	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.07	0.09	0.15
noise type	ar	0.51	0.43	0.16	0.16	0.16	0.16	0.16	0.17	0.15	0.11	0.15	0.21
noise type	white	0.46	0.43	0.20	0.20	0.20	0.20	0.20	0.21	0.19	0.13	0.20	0.24
Overall		0.48	0.43	0.18	0.18	0.18	0.18	0.18	0.19	0.17	0.12	0.18	0.22

4.1.3 Mixed ANOVA

To investigate main and interaction effects of the manipulated data characteristics on recovery performance, a mixed ANOVA was performed. In this mixed ANOVA, the manipulated data characteristics are the between-subjects factors and the synchrony methods are the within-subjects factor. The performance measures are used as dependent variables. A mixed ANOVA is fit separately for each performance measure (i.e., $\text{MSE}_{h\mu}$, MSE_{hc}, $\text{Cor}_{h\mu}$ and Cor_{hc}). Due to the relatively large sample size, most main and interaction effects are significant in the mixed ANOVA. In order to focus on the most relevant results, only significant main and interaction effects (p-values ≤ 0.05) with a substantial generalized effect size (ges) value are visualized and interpreted by interaction plots. When $\text{MSE}_{h\mu}$ and MSE_{hc} are the dependent variable, a ges value of 0.75 is considered substantial, whereas for $\text{Cor}_{h\mu}$ and Cor_{hc} a value of 0.2 is used. Note that to better meet the assumptions of mixed ANOVA, Johnson transformation is applied for $\text{Cor}_{h\mu}$ and Cor_{hc}. For other performance measures, the situation is not much improved by the transformation, so we do not transform other performance measures.

Table 4.7 presents the significant main and interaction effects with ges larger than 0.75 when the dependent variable is $\text{MSE}_{h\mu}$. It appears that for $\text{MSE}_{h\mu}$ there are three important two-way interaction effects between (1) time length and synchrony method, (2) true synchrony and synchrony method, and (3) noise level and synchrony method, and one important three-way interaction effect between true synchrony, synchrony method and noise level, in which the two-way interaction effects (2) and (3) are included. Thus, the two-way interaction effects (2) and (3) will not be discussed separately. The two-way interaction effect between time length and synchrony method, and the three-way interaction effect will now be visualized and interpreted.

Table 4.7: ANOVA table for $\text{MSE}_{h\mu}$ presenting significant effects with ges greater than 0.75.

Effect	DF	F-value	p-value	ges
synchrony method	10	3.02×10^{8}	<0.0001	1
time length×synchrony method	10	1.32×10^{7}	<0.0001	1
time length	1	8.21×10^{6}	<0.0001	1
true synchrony×synchrony method	20	2.23×10^{5}	<0.0001	0.99
true synchrony	2	2.26×10^{5}	<0.0001	0.97
noise level×synchrony method	10	1.53×10^{4}	<0.0001	0.88
true synchrony×noise level×synchrony method	20	3.78×10^{3}	<0.0001	0.78

Figure 4.1 shows one important two-way interaction effect with ges larger than 0.75 with $\text{MSE}_{h\mu}$ as the dependent variable. Because the results for mutual information are not on the same scale as the results for the other synchrony methods, and $\text{MSE}_{h\mu}$ for mutual information is considerably larger than the for the other synchrony methods, we plotted the two-way interaction including mutual information (left panel) and excluding mutual information (right panel). For the time length by synchrony method interaction, as can be seen in Figure 4.1, it appears that the gain in recovery for increasing time length

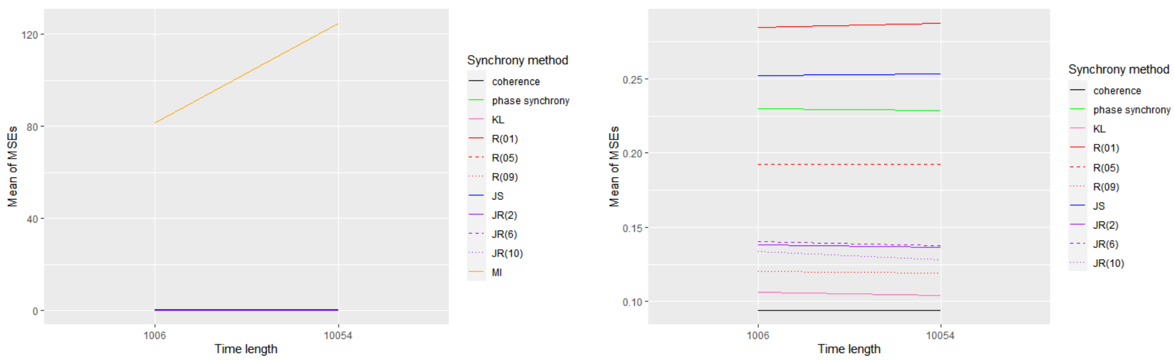


Figure 4.1: Significant two-way interaction effect between time length and synchrony method with ges larger than 0.75 when the performance measure is $\text{MSE}_{h\mu}$. Because mutual information is not on the same scale as other synchrony methods, to see the interaction effect more clearly, the figures are plotted with (left panel) and without mutual information (right panel).

is very small or even 0 for most of the synchrony methods. For MI and R(01), recovery even decreases for increasing time length, where MI is much more sensitive to the change of time length than other synchrony methods.

From Figure 4.2, in which one can see the three-way interaction effect between noise level, true synchrony and synchrony method, it appears that for coherence and phase synchrony, the decrease in recovery is larger for data with larger amounts of noise than for data with smaller amounts of noise, whereas for the other methods the recovery increases as the amount of true synchrony increases despite the amount of noise.

Table 4.8 presents the main and interaction significant effects with ges larger than 0.75 when the dependent variable is MSE_{hc}. Figure 4.3 and Figure 4.4 show the two-way and three-way interaction effects respectively. We will visualize the two-way interaction between noise level and synchrony method and the three-way interaction between (1) bd value (b and d), true synchrony and synchrony method, and (2) true synchrony, time length and synchrony method.

Table 4.8: ANOVA table for MSE_{hc} presenting significant effects with ges greater than 0.75.

Effect	DF	F-value	p-value	ges
synchrony method	10	2.31×10^8	<0.0001	1
time length×synchrony method	10	9.97×10^6	<0.0001	1
time length	1	4.90×10^6	<0.0001	1
true synchrony×synchrony method	20	4.16×10^5	<0.0001	1
true synchrony	2	3.40×10^5	<0.0001	0.98
true synchrony×bd×synchrony method	20	2.09×10^4	<0.0001	0.95
noise level×synchrony method	10	1.13×10^4	<0.0001	0.84
true synchrony×time length×synchrony method	20	3.36×10^3	<0.0001	0.75

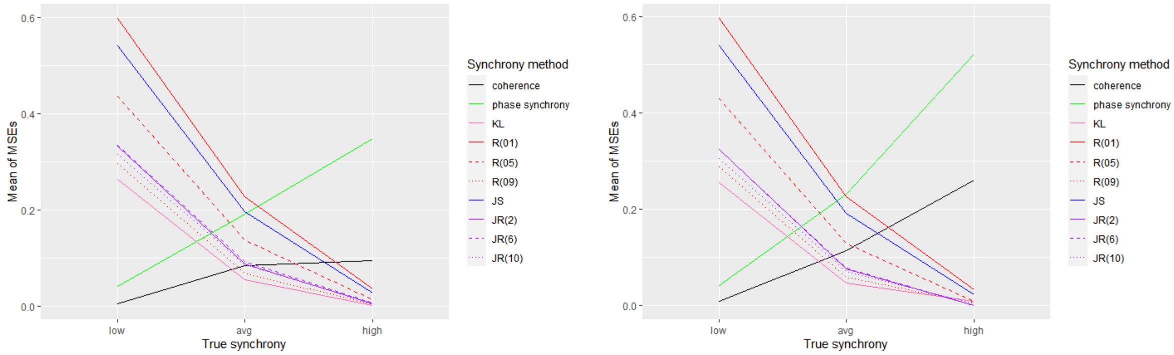


Figure 4.2: Significant three-way interaction effect between noise level, true synchrony and synchrony method with ges larger than 0.75 when the performance measure is $\text{MSE}_{h\mu}$. Because mutual information (MI) is not on the same scale as other synchrony methods, to see the interaction effect more clearly, MI is not displayed in the figures. The Interaction between true synchrony and synchrony method is displayed when the noise level is 0.2 (left panel) and 0.5 (right panel).

In Figure 4.3, which presents the two-way interaction between noise level and synchrony method, one can see that for coherence and phase synchrony larger amounts of noise lead to worse recovery, whereas the reverse is true for the other methods.

Figure 4.4 shows the two significant three-way interaction effects with ges larger than 0.75 when the dependent variable is MSE_{hc} (results for MI are not shown as MI has MSEs very different from the other methods). Regarding the bd value by true synchrony by synchrony method (top row in Figure 4.4), it appears that the two-way interaction between true synchrony and synchrony method (i.e., worse recovery with increasing true synchrony for coherence and phase synchrony and reverse pattern for the other methods) is more pronounced for equal b and d (top left panel) than for unequal b and d (top right panel). Regarding the time length by true synchrony by synchrony method interaction (bottom row in Figure 4.4), it appears that the recovery becomes worse with increasing true synchrony for coherence and phase synchrony and reverse pattern for the other methods. There is negligible change in patterns as time length changes. The patterns are expected to be remarkably different since the ges is a large value of 0.75. However, this is reasonable because the interaction effects has an impact on MI, which is substantially influenced by time length as shown in Table 4.4.

Table 4.9 presents the main and interaction significant effects with ges larger than 0.2 when the dependent variable is transformed $\text{Cor}_{h\mu}$ (by Johnson transformation). Besides the interaction between true synchrony and bd, there are only main effects of the synchrony methods, the time length and the noise level.

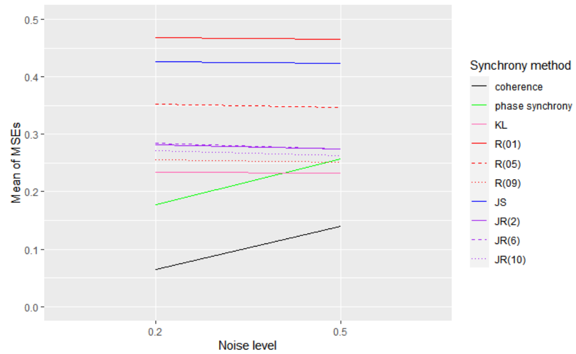


Figure 4.3: Significant two-way interaction effect between noise level and synchrony method with ges larger than 0.75 when the performance measure is MSE_{hc}. Because mutual information (MI) is not on the same scale as other synchrony methods, to see the interaction effects more clearly, MI is not displayed in the figures.

Table 4.9: ANOVA table for transformed $\mathrm{Cor}_{h\mu}$ presenting significant effects with ges greater than 0.2.

Effect	DF	F-value	p-value	ges
true synchrony×bd	2	1.06×10^3	<0.0001	0.41
synchrony method	10	2.49×10^3	<0.0001	0.35
true synchrony	2	5.01×10^2	<0.0001	0.25
noise level	1	8.62×10^2	<0.0001	0.22
time length	1	8.61×10^2	<0.0001	0.22

The two-way interaction between true synchrony and bd is displayed in Figure 4.5. From this figure, it appears that when the true synchrony is at the low and high synchrony level, the average $\mathrm{Cor}_{h\mu}$ across the synchrony methods is larger for equal bd than for unequal bd, and the reverse is true when it is the average synchrony level. Regarding the main effects, as can be seen in Table 4.5, the recovery increases when noise level decreases and when time length increases. When the amount of true synchrony increases from the low level to the average level and then to the high level, the recovery increases and then decreases.

Table 4.10 presents the main and interaction significant effects with ges larger than 0.2 when the dependent variable is transformed Cor_{hc} (by Johnson transformation). Three two-way interactions are relevant here: the interaction between (1) true synchrony and bd, and (2) true synchrony and synchrony method and (3) time lag and synchrony method.

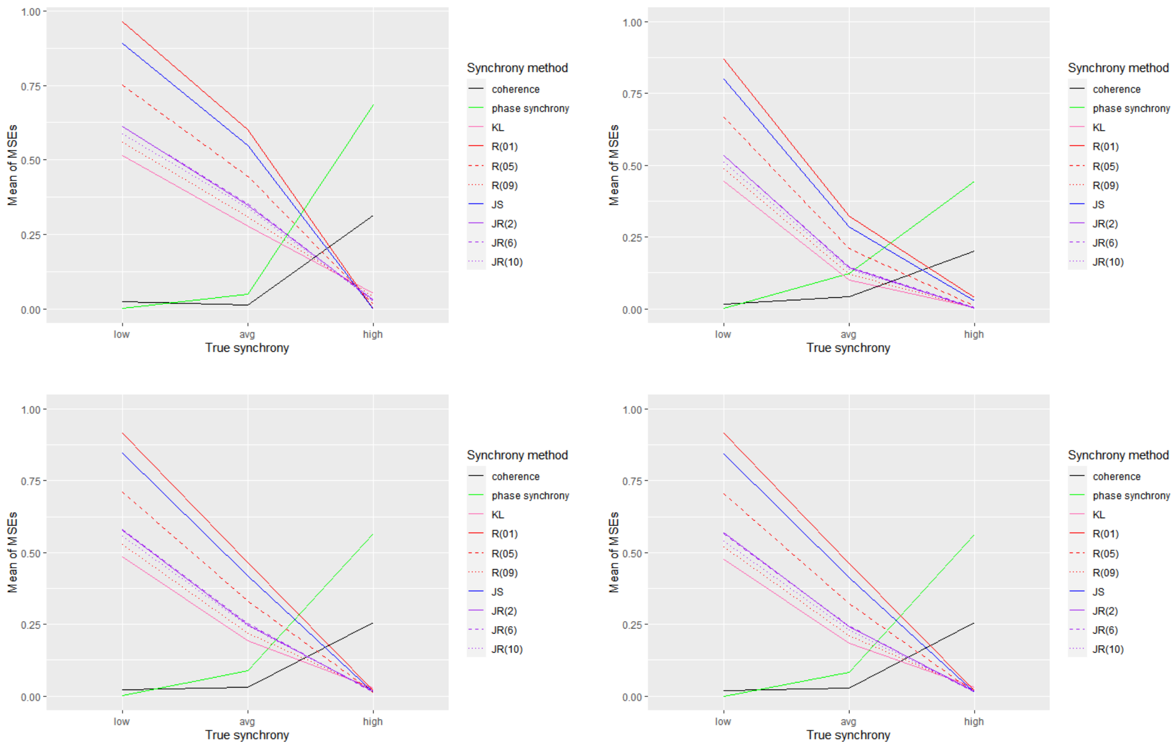


Figure 4.4: Significant three-way interaction effects between (1) bd, true synchrony and synchrony method (top panels) and (2) time length, true synchrony and synchrony method (bottom panels) with ges larger than 0.75 when the performance measure is MSE_{hc}. Because mutual information (MI) is not on the same scale as other synchrony methods, to see the interaction effect more clearly, MI is not displayed in the figures. The Interaction between true synchrony and synchrony method is displayed when $b = d = 0.3$ (top left) and $b = 0.3$ and $d = 0.1$ (top right). The Interaction between true synchrony and synchrony method is displayed when time length is 1006 (bottom left) and time length is 10054 (bottom right).

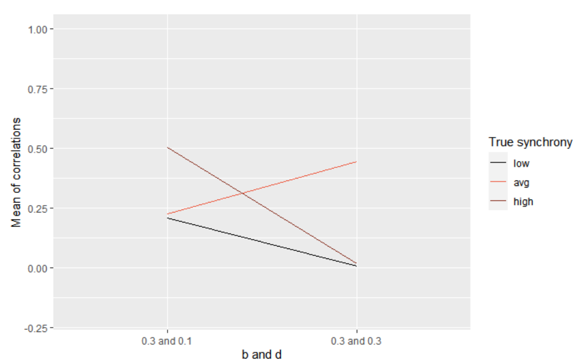


Figure 4.5: Significant two-way interaction effect between bd and true synchrony with ges larger than 0.2 when the performance measure is $\mathrm{Cor}_{h\mu}$.

Table 4.10: ANOVA table for transformed Cor_{hc} presenting significant effects with ges greater than 0.2.

Effect	DF	F-value	p-value	ges
true synchrony×bd	2	1.24×10^3	<0.0001	0.45
synchrony method	10	3.18×10^3	<0.0001	0.41
true synchrony×syncrhony method	20	1.05×10^3	<0.0001	0.32
true synchrony	2	5.70×10^2	<0.0001	0.27
time lag×synchrony method	10	1.50×10^3	<0.0001	0.25
time length	1	8.75×10^2	<0.0001	0.22

The three relevant two-way interactions are displayed in Figure 4.6, which shows the interaction effects with ges larger than 0.2. For the interaction between true synchrony and bd (top left), one can see the similar patterns as in Figure 4.5. Regarding the interaction between true synchrony and synchrony method (top right), it appears that when the amount of true synchrony increases from the low level to the average level, the recovery performance increases. When the amount of true synchrony increases from the average level to the high level, the decrease in recovery is much larger for coherence and phase synchrony than the changes in recovery for the other synchrony methods. Regarding the interaction between time lag and synchrony method (bottom panel), decrease in recovery is substantially larger as time lag increases for phase synchrony than for the other methods, and for the information-theoretic measures, recovery even increases as time lag increases from 0 to 2.

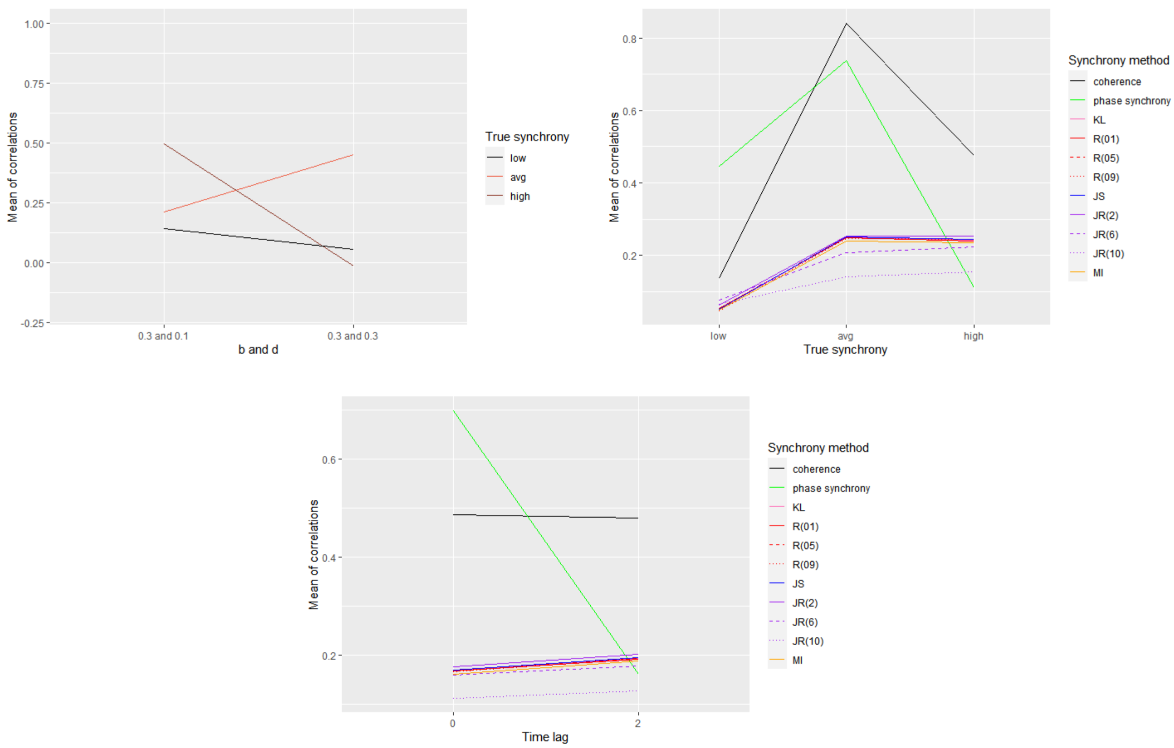


Figure 4.6: Significant two-way interaction effects between (1) true synchrony and bd (top left), (2) true synchrony and synchrony method (top right) and (3) time lag and synchrony method (bottom panel) with ges larger than 0.2 when the performance measure is Cor_{hc}.

4.2 Results for data generated from the bivariate von Mises distribution

4.2.1 General results

When inspecting, for the data generated with a bivariate von Mises distribution, the performance results for MSE, it appears that, as one can see in Table 4.11, Kullbach-Liebler divergence and Rényi divergence with α equal to 0.90 perform the best, with the Jensen-Rényi divergence methods (irrespective of the value of α) following at a very close distance. When using MSE_{br} as the performance measure, at a little bit further distance, one can find the coherence and phase synchrony methods, along with Rényi divergence with α equal to 0.50. At the furthest distance there are Jensen-Shannon divergence, Rényi divergence with α equal to 0.10 and the mutual information method. It is remarkable that the value of α has a large effect on the performance for Rényi divergence but not for Jensen-Rényi divergence. Note that the results for MSE_{br} (left part of Table 4.11) and MSE_{bc} (right part of Table 4.11) are very similar, except that coherence and phase synchrony switch the positions with Jensen-Shannon divergence and Rényi divergence with α equal to 0.10.

Table 4.11: Overall performance of the synchrony methods ranked according to MSE_{br} (left part of the table) and MSE_{bc} (right part of the table)

Method	Mean of MSE_{br}	Method	Mean of MSE_{bc}
KL	0.10	KL	0.04
R(09)	0.11	R(09)	0.05
JR(2)	0.13	JR(2)	0.05
JR(6)	0.14	JR(6)	0.06
JR(10)	0.14	JR(10)	0.06
R(05)	0.19	R(05)	0.08
Coherence	0.19	JS	0.12
Phase synchrony	0.20	R(01)	0.15
JS	0.25	coherence	0.29
R(01)	0.28	phase synchrony	0.29
MI	101.79	MI	98.98

When looking at Table 4.12, which shows the general performance results for Cor_{br} and Cor_{bc}, the best two synchrony methods are coherence and phase synchrony, although the correlation is small in general when Cor_{br} is used as the performance measure (i.e., around 0.20). When taking Cor_{bc} as performance measure, for the phase synchrony, the correlation is substantially large (0.47), and the correlation for coherence increases to 0.28. Phase synchrony thus outperforms coherence when the performance measure is Cor_{bc}, whereas coherence and phase synchrony show almost the same performance when the performance measure is Cor_{br}. For all the other synchrony methods, the correlation is around zero, which implies that these methods do not at all capture changes in the true synchrony. Indeed, for these methods, there is no relationship between the obtained synchrony and the true synchrony value. Thus, there is no need to compare the information-theoretic measures with the other two synchrony methods based on the MSEs (MSE_{br} and MSE_{bc}), and the information-theoretic measures are all considered bad performing. It can be concluded that phase synchrony is the best performing method, and coherence is second best. The performance of all the other methods is very disappointing.

Table 4.12: Overall performance of the synchrony methods ranked according to Cor_{br} (left part of the table) and Cor_{bc} (right part of the table)

Method	Mean of Cor_{br}	Method	Mean of Cor_{bc}
coherence	0.18	phase synchrony	0.47
phase synchrony	0.15	coherence	0.28
JR(10)	0.02	JR(10)	0.04
JR(6)	0.02	JR(6)	0.04
JR(02)	0.01	JR(2)	0.03
R(09)	0.01	MI	0.02
KL	0.01	JS	0.02
R(05)	0.01	KL	0.02
JS	0.01	R(05)	0.02
R(01)	0.01	R(09)	0.02
MI	0.00	R(01)	0.02

4.2.2 Overall influence of the manipulated characteristics

Table 4.13, 4.14, 4.15 and 4.16 show the overall influence of the data characteristics on the synchrony methods. The common information we can obtain from the four tables is that time lag has, except for MSE_{bc}, a substantial impact on phase synchrony. There is a considerable variation between the results in the four tables, which indicates that the two definitions for the true synchrony work quite differently for data generated from the bivariate von Mises distribution.

In Table 4.13, which presents the results for MSE_{br}, one can see that true synchrony exerts the largest influence. For coherence and phase synchrony, performance becomes better when the amount of true synchrony decreases, whereas the reverse pattern is observed for the other methods. Noise level and time lag only seem to change performance for the phase synchrony method, with lower noise and no time lag showing the best results. Time length (except for MI), κ and noise type do not affect recovery performance at all.

Table 4.13: Overall influence of the data characteristics on the synchrony methods when using MSE_{br} as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall without MI	Overall with MI
κ	0.5	0.19	0.22	0.10	0.28	0.19	0.12	0.25	0.13	0.13	0.13	101.77	0.17	9.41
κ	1	0.19	0.21	0.10	0.28	0.19	0.12	0.25	0.13	0.14	0.14	101.77	0.17	9.41
κ	2	0.19	0.18	0.10	0.28	0.19	0.12	0.25	0.13	0.14	0.14	101.83	0.17	9.41
true synchrony	low	0.01	0.02	0.25	0.59	0.42	0.28	0.54	0.32	0.32	0.32	107.81	0.31	10.08
true synchrony	average	0.13	0.15	0.04	0.22	0.13	0.06	0.19	0.07	0.08	0.08	101.75	0.12	9.36
true synchrony	high	0.43	0.43	0.01	0.03	0.01	0.01	0.02	0.00	0.01	0.01	95.81	0.10	8.80
time length	1006	0.19	0.20	0.10	0.28	0.19	0.12	0.25	0.13	0.14	0.15	80.50	0.18	7.48
time length	10054	0.19	0.20	0.10	0.28	0.18	0.11	0.25	0.13	0.13	0.13	123.09	0.17	11.34
noise level	0.2	0.19	0.16	0.10	0.28	0.19	0.12	0.25	0.13	0.14	0.15	101.74	0.17	9.40
noise level	0.5	0.19	0.24	0.10	0.28	0.19	0.12	0.25	0.13	0.13	0.13	101.84	0.18	9.42
noise type	ar	0.19	0.20	0.10	0.28	0.19	0.12	0.25	0.13	0.13	0.13	101.83	0.17	9.41
noise type	white	0.19	0.20	0.10	0.28	0.19	0.12	0.25	0.13	0.14	0.15	101.76	0.17	9.41
time lag	0	0.19	0.13	0.10	0.28	0.19	0.12	0.25	0.13	0.14	0.14	101.81	0.17	9.41
time lag	2	0.19	0.28	0.10	0.28	0.19	0.12	0.25	0.13	0.13	0.14	101.77	0.18	9.42
Overall		0.19	0.20	0.10	0.28	0.19	0.11	0.25	0.13	0.14	0.14	101.79	0.17	9.41

In Table 4.14, the results for MSE_{bc} are displayed. For true synchrony, the results are in the same direction as for MSE_{br} (Table 4.13), without, however, the true synchrony exerting a larger influence for MSE_{br} than for MSE_{bc}. Contrary to the MSE_{br} results, for MSE_{bc} there is some effect of κ, with larger κ leading to worse recovery for coherence and phase synchrony. Noise level and time lag only influence the phase synchrony method. The effect of time length is negligible for all the synchrony methods apart from MI.

Table 4.14: Overall influence of the data characteristics to the synchrony methods when using MSE_{bc} as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall without MI	Overall with MI
κ	0.5	0.23	0.27	0.07	0.22	0.13	0.08	0.19	0.09	0.09	0.09	100.38	0.15	9.26
κ	1	0.27	0.29	0.04	0.16	0.09	0.05	0.13	0.06	0.06	0.06	99.34	0.12	9.14
κ	2	0.36	0.32	0.01	0.07	0.03	0.01	0.05	0.01	0.02	0.02	97.21	0.09	8.92
true synchrony	low	0.13	0.14	0.09	0.30	0.19	0.10	0.26	0.13	0.13	0.13	102.76	0.16	9.49
true synchrony	average	0.27	0.28	0.02	0.12	0.06	0.02	0.09	0.03	0.03	0.03	98.85	0.09	9.07
true synchrony	high	0.46	0.46	0.02	0.03	0.00	0.01	0.02	0.01	0.01	0.01	95.32	0.10	8.76
time length	1006	0.29	0.29	0.05	0.16	0.09	0.05	0.13	0.06	0.07	0.07	78.08	0.13	7.21
time length	10054	0.28	0.30	0.04	0.14	0.07	0.04	0.12	0.05	0.05	0.05	119.88	0.11	11.00
noise level	0.2	0.28	0.23	0.04	0.15	0.08	0.05	0.12	0.05	0.06	0.07	98.93	0.11	9.10
noise level	0.5	0.29	0.36	0.04	0.15	0.08	0.05	0.12	0.05	0.05	0.05	99.03	0.13	9.12
noise type	ar	0.29	0.29	0.04	0.15	0.08	0.05	0.12	0.05	0.06	0.05	99.01	0.12	9.11
noise type	white	0.28	0.29	0.04	0.15	0.29	0.05	0.12	0.05	0.06	0.06	98.95	0.12	9.10
time lag	0	0.28	0.20	0.04	0.15	0.08	0.05	0.12	0.05	0.06	0.06	99.01	0.11	9.10
time lag	2	0.29	0.39	0.04	0.15	0.29	0.05	0.12	0.05	0.06	0.05	98.95	0.13	9.11
Overall		0.29	0.29	0.04	0.15	0.08	0.05	0.12	0.05	0.06	0.06	98.98	0.12	9.11

The results in terms of Cor_{br}, as displayed in Table 4.15, are very bad for all synchrony methods except for coherence and phase synchrony. Both coherence and phase synchrony are influenced by κ, although only slightly, with smaller κ yielding better recovery. The amount of true synchrony also has a small influence on performance, with the correlation (and the performance) increasing when the true synchrony becomes larger for coherence. Time length has the largest effect with longer time length increasing performance for phase synchrony and coherence. Noise level has a minor impact on the performance of phase synchrony and coherence. Noise type slightly influences coherence but has no effect on phase synchrony. Time lag has a substantial impact on phase synchrony and a minor impact on coherence.

Table 4.15: Overall influence of the data characteristics to the synchrony methods when using Cor_{br} as the performance measure

	level	coherence	phase synchrony	KL	R01	R05	R09	JS	JR2	JR6	JR10	MI	Overall
κ	0.5	0.20	0.23	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.05
κ	1	0.17	0.18	-0.01	-0.01	-0.01	-0.00	-0.01	-0.00	0.01	0.02	-0.01	0.03
κ	2	0.18	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.03
true synchrony	low	0.07	0.15	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04
true synchrony	average	0.19	0.13	0.01	0.00	0.01	0.01	0.01	0.01	0.03	0.03	0.00	0.04
true synchrony	high	0.29	0.18	-0.01	-0.01	-0.01	-0.01	-0.01	-0.00	0.00	0.00	-0.01	0.04
time length	1006	0.05	0.09	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.02
time length	10054	0.31	0.21	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.00	0.05
noise level	0.2	0.20	0.16	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.01	0.05
noise level	0.5	0.17	0.14	0.00	-0.00	-0.00	0.00	-0.00	-0.00	0.00	0.01	-0.00	0.03
noise type	ar	0.17	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	-0.00	0.03
noise type	white	0.20	0.15	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.01	0.04
time lag	0	0.22	0.46	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.01	0.07
time lag	2	0.14	-0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	-0.00	0.00
Overall		0.18	0.15	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.00	0.04

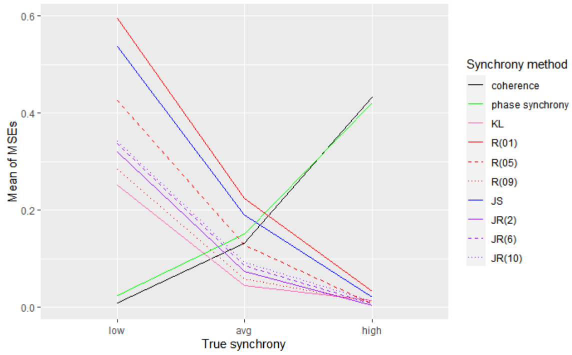
From Table 4.16, which displays the results for Cor_{bc}, it can be seen that only for coherence and phase synchrony the recovery performance is affected by (some of) the manipulated factors. For the other synchrony methods, performance is bad in general (i.e., correlations close to zero). The recovery of coherence increases when the true synchrony increases, time length increases and there is no time lag (compared to a time lag of 2). For phase synchrony, performance is only considerably affected by the time lag, with recovery performance being the best when there is no time lag. The recovery slightly increases when the amount of true synchrony decreases for phase synchrony.

Table 4.16: Overall influence of the data characteristics to the synchrony methods when using Cor_{bc} as the performance measure

	level	coherence	phase synchrony	KL	R(01)	R(05)	R(09)	JS	JR(2)	JR(6)	JR(10)	MI	Overall
κ	0.5	0.30	0.47	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.10
κ	1	0.27	0.46	0.01	0.01	0.02	0.02	0.02	0.02	0.04	0.05	0.02	0.09
κ	2	0.27	0.47	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.08
true synchrony	low	0.19	0.54	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.09
true synchrony	average	0.29	0.46	0.03	0.02	0.03	0.03	0.03	0.04	0.05	0.05	0.02	0.10
true synchrony	high	0.36	0.40	0.01	0.02	0.01	0.01	0.01	0.02	0.03	0.03	0.01	0.08
time length	1006	0.17	0.49	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.08
time length	10054	0.39	0.45	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.03	0.10
noise level	0.2	0.30	0.49	0.03	0.03	0.03	0.03	0.03	0.04	0.06	0.06	0.03	0.11
noise level	0.5	0.26	0.44	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.07
noisetype	ar	0.26	0.46	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.08
noisetype	white	0.30	0.48	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.05	0.03	0.10
time lag	0	0.36	0.90	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.06	0.03	0.14
time lag	2	0.20	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Overall		0.28	0.47	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.04	0.02	0.09

4.2.3 Mixed ANOVA

Table 4.17 presents the main and interaction significant effects with ges larger than 0.75 when the dependent variable is MSE_{br}. This results in one important three-way



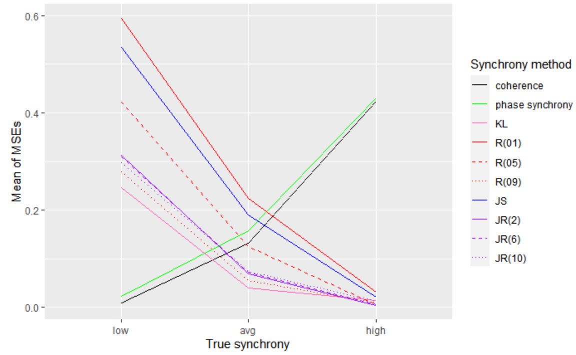


Figure 4.7: Significant three-way interaction effect between true synchrony, synchrony method and time length with ges larger than 0.75 when the performance measure is MSE_{br}. Because mutual information (MI) is not on the same scale as other synchrony methods, to see the interaction effects more clearly, MI is not displayed in the figures. The Interaction between true synchrony and synchrony method is displayed when time length is 1006 (left panel) and 10054 (right panel).

interaction, which is the interaction between synchrony method, time length and true synchrony.

Table 4.17: ANOVA table for MSE_{br} presenting significant effects with ges greater than 0.75.

Effect	DF	F-value	p-value	ges
synchrony method	10	3.85×10^{8}	<0.0001	1
time length×synchrony method	10	1.69×10^{7}	<0.0001	1
time length	1	1.18×10^{7}	<0.0001	1
true synchrony×synchrony method	20	4.36×10^{5}	<0.0001	1
true synchrony	2	4.36×10^{5}	<0.0001	0.98
true synchrony×time length×synchrony method	20	4.92×10^{3}	<0.0001	0.76

The three-way interaction between true synchrony, synchrony method and time length is visualized in Figure 4.7 (not showing MI). From this figure, one can see that for coherence and phase synchrony larger amounts of synchrony lead to worse recovery, whereas the reverse is true for the other methods. The difference between the two conditions with time length as 1006 and as 10054 is negligible, which seems strange at first glance. The patterns are expected to be considerably different since the ges is a large value of 0.76. However, this makes sense when we consider that the interaction effect has a substantial impact on MI (not shown in Figure 4.7), which is remarkably affected by the change in time length as shown in Table 4.13.

Table 4.18 presents the main and interaction significant effects with ges larger than 0.75 when the dependent variable is MSE_{bc}. There is a large three-way interaction between true synchrony, κ and synchrony method, and a two-way interaction between time length

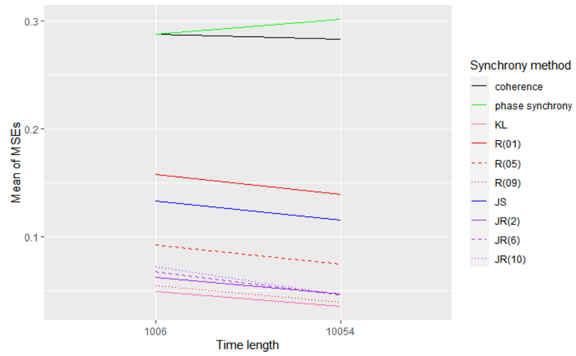


Figure 4.8: Significant two-way interaction effect between time length and synchrony method with ges larger than 0.75 when the performance measure is MSE_{bc}. Because mutual information is not on the same scale as other synchrony methods, to see the interaction effects more clearly, MI results are discarded from the figures.

and synchrony method.

Table 4.18: ANOVA table for MSE_{bc} presenting significant effects with ges greater than 0.75.

Effect	DF	F-value	p-value	ges
synchrony method	10	1.71×10^8	<0.0001	1
time length×synchrony method	10	7.66×10^6	<0.0001	1
time length	1	5.21×10^6	<0.0001	1
true synchrony×synchrony method	20	8.03×10^4	<0.0001	0.98
κ × synchrony method	20	1.49×10^4	<0.0001	0.90
true synchrony	2	6.48×10^4	<0.0001	0.86
true synchrony×κ×synchrony method	40	3.87×10^3	<0.0001	0.83

For the two-way interaction, which is presented in Figure 4.8, it can be seen that for phase synchrony the increasing time length lead to worse recovery, whereas the reverse is true for the other methods.

The three-way interaction between the true synchrony, κ and synchrony method is displayed in Figure 4.9, with the different panels pertaining to different values of κ. It appears that when the amount of the true synchrony increases, the recovery decreases for coherence and phase synchrony, and increases for the other methods. The two-way interaction effect between true synchrony and synchrony method is more pronounced for data with κ equal to 0.5 and 1 than for data with κ equal to 2.

Table 4.19, which presents the significant effect with the largest ges as 0.14 when the dependent variable is Cor_{br}. Thus, no effects will be discussed when the performance measure is Cor_{br}.

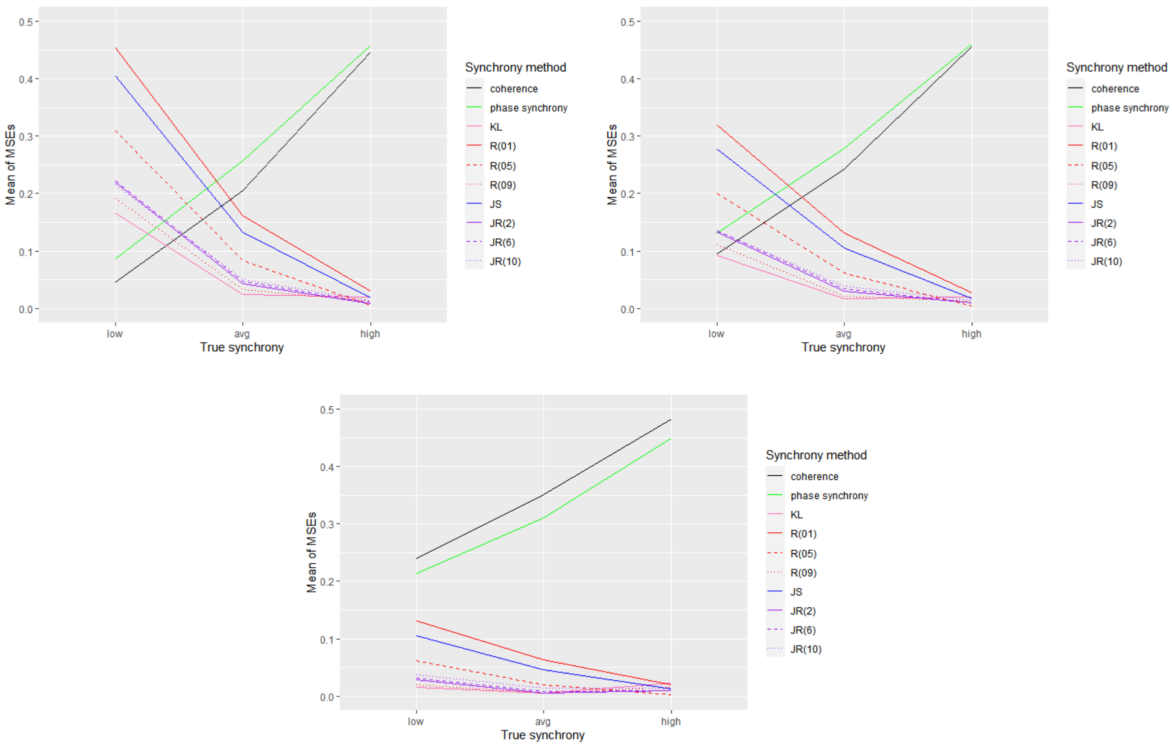


Figure 4.9: Significant three-way interaction effect between true synchrony, synchrony method and κ with ges larger than 0.75 when the performance measure is MSE_{bc}. Because mutual information is not on the same scale as other synchrony methods, to see the interaction effects more clearly, MI results are discarded from the figures. The Interaction between true synchrony and synchrony method is displayed when κ is 0.5 (top left), 1 (top right) and 2 (bottom panel).

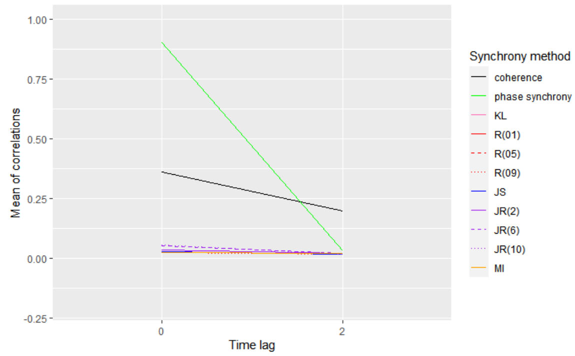


Figure 4.10: Significant two-way interaction effect between time lag and synchrony method with ges larger than 0.2 when the performance measure is Cor_{bc}.

Table 4.19: ANOVA table for Cor_{br} presenting significant effect with the largest ges

Effect	DF	F-value	p-value	ges
time lag×synchrony method	10	9.58×10^2	<0.0001	0.14

Table 4.20 presents the main and interaction significant effects with ges larger than 0.2 when the dependent variable is Cor_{bc}. It appears that there only is a main effect of the synchrony method and a two-way interaction effect between time lag and synchrony method. From Table 4.12 one can see that coherence and phase synchrony perform better than the other synchrony methods.

Table 4.20: ANOVA table for Cor_{bc} presenting significant effects with ges greater than 0.2.

Effect	DF	F-value	p-value	ges
synchrony method	10	2.62×10^3	<0.0001	0.28
time lag×synchrony method	20	2.03×10^3	<0.0001	0.23

Figure 4.10 presents the two-way interaction effect between time lag and synchrony method. The figure reveals that for phase synchrony the recovery performance is considerably better for no time lag than for time lag as 2, and for coherence the recovery is also larger when time lag is 0 compared with when time lag is 2, but the difference is much smaller. For the information-theoretic measures, the difference is negligible.

4.3 Summary of results and comparison between both simulation studies

The goal of this study was to evaluate the performance of several synchrony methods in terms of their capacity for capturing the (changes in the) amount of synchrony between two time series. For data generated from Hénon maps, coherence is without a doubt the best synchrony method, with phase synchrony as second best. Phase synchrony and coherence are considerably better than the information-theoretic methods. With the exception of JR(10), the general results of the information-theoretic methods are very similar. JR(10) is the lowest rated synchrony method among all the synchrony methods, and its performance is substantially worse than other information-theoretic methods in terms of $\mathrm{Cor}_{h\mu}$ and Cor_{hc}. All the synchrony methods, except phase synchrony, perform significantly worse for data generated from the bivariate von Mises distribution than for data generated from Hénon maps. Phase synchrony is considered as the best performing method among the methods. The second most effective synchrony method is coherence. However, although phase synchrony and coherence reflect to a large extent the change in the amount of the true synchrony, the performance in capturing the true amount of true synchrony is rather poor. Information-theoretic methods perform so poorly that they are no real competitors for coherence and phase synchrony.

As to the influence of the data characteristics, the true synchrony always has a substantial impact on the performance of the synchrony methods. For data generated from both data generating mechanisms, when using MSEs as the performance measure, for coherence and phase synchrony larger amounts of true synchrony lead to worse recovery, whereas the reverse is true for the other methods. When using the correlations as the performance measure, for data generated from Hénon maps, recovery performance becomes better when the amount of true synchrony changes from other levels to the average level in most cases. For data generated from the bivariate von Mises distribution, recovery increases for coherence when the amount of true synchrony increases. The amount of true synchrony has a more negligible impact on phase synchrony, and the effect varies depending on the performance measure. For data generated from Hénon maps, the values of the metaparameters b and d influence the performance of all the synchrony methods, where the performance of all the synchrony methods is better when $b = d = 0.3$. The change in time lag has a large impact on phase synchrony, but other synchrony methods are less impacted by the time lag. Coherence and phase synchrony are definitely affected by noise levels, with more noise decreasing the performance. As time length increases, all the synchrony methods perform better. Noise type has no effect on phase synchrony and slightly affects all synchrony methods, and time lag has no effect on coherence. For data generated from the bivariate von Mises distribution, the results for phase synchrony are remarkably different when using Cor_{br} compared to when using Cor_{bc} as the performance measure. Phase synchrony is substantially influenced by time length and κ when using Cor_{br}, and is not influenced by the change of κ when using Cor_{bc}. Coherence is not stable, and is remarkably influenced by the change of time length and true synchrony, whereas it is slightly affected by the data characteristics in most other cases. No matter which performance measure is used, phase synchrony is sensitive to the change of time lag, and is stable when the noise type changes.

As to the interaction effects, for data generated from Hénon maps, two-way and three-way interaction effects are shown that (almost) always involve the synchrony methods and the amount of true synchrony. For all of the conditions tested for data generated from Hénon maps, the information-theoretic measures perform quite similarly. Only JR(10) and MI differ from the other information-theoretic measures in terms of performance. Two-way and three-way interactions are encountered for data generated from the bivariate von Mises distribution. In general, all synchrony methods are not stable under most changing situations. In the interaction plots, although the MSEs of some information-theoretic measures are lower than the MSEs of coherence and phase synchrony, we do not consider the information-theoretic measures to be good synchrony methods under the conditions since the correlations of the information-theoretic measures are too low. The patterns of information-theoretic measures are similar. Among the information-theoretic measures, for almost all the conditions, mean of MSEs of KL is lowest, and mean of MSEs of R(01) is the highest. There are no sizeable interaction effects when the performance measure is Cor_{br}.

Chapter 5

Discussion

5.1 Summary and discussion of results

In this study, the performance of various synchrony methods for capturing the (changes in the) amount of synchrony between two time series is evaluated. To this end, two extensive simulation study are performed in which data are generated from Hénon maps and the bivariate von Mises distribution. The MSE, which quantifies the extent to which the synchrony methods capture (in terms of absolute differences) the true amount of synchrony, is used as a first performance measure. As a second performance measure, the correlation between the true and estimated synchrony is studied, which focuses on the extent to which the synchrony methods capture changes in the true synchrony score. Moreover, the performance of the synchrony methods is studied and compared across several varied data characteristics. The results show that, in general, the best method is coherence for data generated from Hénon maps and phase synchrony for data generated from the bivariate von Mises distribution. Comparing both data generating mechanisms (i.e., Hénon maps and bivariate von Mises distribution), it appears that all the synchrony methods except phase synchrony perform substantially worse for the bivariate von Mises distribution than for Hénon maps. Regarding the varied data characteristics, especially the amount of true synchrony has a large effect on recovery performance. The influence of the amount of true synchrony is different for different cases, with performance becoming better when the amount of true synchrony changes from other levels to the average level in most cases with the correlations as the performance measures for data generated from Hénon maps. For data generated from the bivariate von Mises distribution, recovery performance becomes better for coherence when the amount of true synchrony increases. For phase synchrony, the influence of the amount of true synchrony is smaller, and is different when the performance measure changes. These main effects are qualified by several two-way and three-way interactions that almost always include the synchrony methods and the amount of true synchrony.

In sum, for data generated from Hénon maps, coherence is recommended, and phase synchrony is considered as the second best method. For different conditions, the best synchrony method is different. However, in most cases, coherence is the best performing method. For data generated from the bivariate von Mises distribution, we recommend to use phase synchrony when there is no time lag, otherwise coherence is recommended.

5.2 Limitations and future research

One limitation of this study is that the dependent variable in the mixed ANOVA violates some of the assumptions of mixed ANOVA. When the dependent variable is the MSEs, the assumption of homogeneity of variance, normality and sphericity are somewhat violated. When Cor_{br} and Cor_{bc} are employed as the performance measure, the assumptions above are only slightly violated. After experimenting with some classic transformations (e.g., the Johnson transformation, Box-Cox transform, log transformation, inverse transformation), the situation is not significantly improved. Only when $\text{Cor}_{h\mu}$ and Cor_{hc} are used as the performance measure, the transformation (i.e., Johnson transformation) improves the situation considerably. The violation of the assumptions can influence the p-values in the significant testing and also the values of ges. Given that the data we have is from a design with a large sample size with equal groups, we consider it is acceptable to neglect the possible violation(s) of these assumptions. However, it can still be that the interaction effects that we pick to interpret could be different compared to when the assumptions are met. In future research, therefore, designing a study such that the obtained data (better) match the assumptions is one option. An alternative is investigating what kind of transformation can make the data meet the assumption(s) or at least less violate the assumption(s) so that the results are more reliable.

Another limitation is about the definition of the true synchrony. The degree of true synchrony, for one of the two definitions, is determined by the parameters for the two data generation mechanisms that control the amount of true synchrony. The values of these parameters, however, cannot be guaranteed to adequately reflect the level of true synchrony. When evaluating the performance of synchrony methods, the correlation coefficient between the obtained synchrony and the true synchrony was used as a complement in order to provide a different perspective. However, as shown by the results, the synchrony methods that work in a similar way to the correlation coefficient (i.e., linear methods) benefit from this. Moreover, the performance of the correlation coefficient is satisfactory when there is no time lag and noise in the data. However, under those circumstances, the correlation coefficient is not always ideal. We can therefore not clearly conclude which definition of true synchrony is the more biased one when there is a substantial gap between the two ways of defining true synchrony. Future work could focus on how to define true synchrony in a more objective and fair way.

The current study only includes phase synchrony, coherence and several information-theoretic measures. The number of synchrony methods evaluated in this study is limited due to the computational demands involved in performing an extensive simulation study. For future research, synchrony methods with other features can be involved. For example, some methods for measuring non-linear relationship between time series (e.g., corr-entropy coefficient, coh-entropy coefficient) are interesting to consider in this regard.

More research is also needed on the effect of the metaparameters in some of the studied synchrony methods (e.g., the value of α in Rényi and Jensen-Rényi divergence). Besides, this study mainly focuses on the performance of the synchrony methods on a pair of time series. Research on detecting the synchrony between three or more time series is also an interesting topic to explore.

5.3 Concluding remarks

Many methods for measuring synchrony between time series have been presented in the literature. A clear view on which method to prefer in which situation is lacking. Our simulation study revealed that for our generated data coherence and phase synchrony are the two best performing methods. Except for phase synchrony, all the synchrony methods perform worse when the data is generated from the bivariate von Mises distribution compared to when the data is generated from Hénon maps. No synchrony method is perfect under all the varied data characteristics and all the synchrony methods in this study are not always stable. Therefore, to detect synchrony, using a combination of different synchrony methods is recommended.

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Appendix

To reproduce the results, the R code can be seen from: https://github.com/MiaTan517/Comparison-of-statistical-methods-to-quantify-synchrony-between-subjects.

Table A1-A8 display the ANOVA table when the performance measures are used as the dependent variables.

Table A1: ANOVA Table when $\text{MSE}_{h\mu}$ is the dependent variable

Effects	DF	F-value	p-value	ges
synchrony method	10.00	301924138.60	<0.01	1.00
time length×synchrony method	10.00	13248981.50	<0.01	1.00
time length	1.00	8207875.14	<0.01	1.00
true synchrony×synchrony method	20.00	222769.10	<0.01	0.99
true synchrony	2.00	226088.43	<0.01	0.97
noise level×synchrony method	10.00	15288.18	<0.01	0.88
true synchrony×noise level×synchrony method	20.00	3783.45	<0.01	0.78
true synchrony×bd×synchrony method	20.00	1793.77	<0.01	0.63
true synchrony×time length×synchrony method	20.00	1594.04	<0.01	0.60
bd×synchrony method	10.00	3020.32	<0.01	0.59
noise level	1.00	8158.63	<0.01	0.38
time length×noise level×synchrony method	10.00	785.61	<0.01	0.27
true synchrony×bd×noise level×synchrony method	20.00	391.08	<0.01	0.27
noise type×synchrony method	10.00	629.27	<0.01	0.23
bd×noise level×synchrony method	10.00	589.96	<0.01	0.22
true synchrony×noise level	2.00	1560.67	<0.01	0.19
true synchrony×noise type×synchrony method	20.00	233.15	<0.01	0.18
true synchrony×time length×noise level×synchrony method	20.00	200.77	<0.01	0.16
true synchrony×time length	2.00	1000.20	<0.01	0.13
bd	1.00	1848.65	<0.01	0.12
true synchrony×bd	2.00	873.51	<0.01	0.12
true synchrony×bd×time length×synchrony method	20.00	123.09	<0.01	0.10
bd×time length×synchrony method	10.00	150.30	<0.01	0.07
true synchrony×time lag×synchrony method	20.00	64.43	<0.01	0.06
true synchrony×bd×noise type×synchrony method	20.00	54.82	<0.01	0.05
noise level×noise type×synchrony method	10.00	104.43	<0.01	0.05
time lag×synchrony method	10.00	83.11	<0.01	0.04
true synchrony×noise level×noise type×synchrony method	20.00	41.48	<0.01	0.04
time length×noise level	1.00	493.78	<0.01	0.04
noise type	1.00	480.23	<0.01	0.04
true synchrony×bd×noise level	2.00	225.61	<0.01	0.03
bd×noise level	1.00	397.87	<0.01	0.03
true synchrony×noise type	2.00	170.01	<0.01	0.02
bd×noise type×synchrony method	10.00	48.92	<0.01	0.02
true synchrony×bd×time length×noise level×synchrony method	20.00	25.29	<0.01	0.02
true synchrony×time length×noise level	2.00	124.74	<0.01	0.02
time length×noise type×synchrony method	10.00	38.93	<0.01	0.02
bd×time length×noise level×synchrony method	10.00	29.86	<0.01	0.01
true synchrony×time length×noise type×synchrony method	20.00	15.02	<0.01	0.01

true synchrony×bd×time length	2.00	75.97	<0.01	0.01
true synchrony×time lag×time length×synchrony method	20.00	10.85	<0.01	0.01
true synchrony×time lag×noise level×synchrony method	20.00	10.22	<0.01	0.01
time lag×noise level×synchrony method	10.00	19.64	<0.01	0.01
true synchrony×bd×noise level×noise type×synchrony method	20.00	8.71	<0.01	0.01
bd×time length	1.00	92.27	<0.01	0.01
noise level×noise type	1.00	62.70	<0.01	0.00
true synchrony×bd×noise type	2.00	36.11	<0.01	0.00
time lag	1.00	55.93	<0.01	0.00
true synchrony×bd×time length×noise type×synchrony method	20.00	3.79	0.02	0.00
true synchrony×time lag	2.00	16.72	<0.01	0.00
true synchrony×noise level×noise type	2.00	21.77	<0.01	0.00
true synchrony×bd×time lag×synchrony method	20.00	2.72	0.07	0.00
time length×noise level×noise type×synchrony method	10.00	5.96	0.01	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	2.92	0.05	0.00
bd×noise type	1.00	30.42	<0.01	0.00
time length×noise type	1.00	24.72	<0.01	0.00
true synchrony×bd×time length×noise level	2.00	15.65	<0.01	0.00
true synchrony×time lag×time length	2.00	8.31	<0.01	0.00
bd×time length×noise level	1.00	18.93	<0.01	0.00
true synchrony×time length×noise type	2.00	8.94	<0.01	0.00
bd×time length×noise type×synchrony method	10.00	3.11	0.08	0.00
bd×noise level×noise type×synchrony method	10.00	3.12	0.08	0.00
true synchrony×bd×noise level×noise type	2.00	5.61	<0.01	0.00
bd×time lag×synchrony method	10.00	1.19	0.28	0.00
true synchrony×bd×time length×noise level×noise type×synchrony method	20.00	0.49	0.61	0.00
time lag×time length×synchrony method	10.00	0.87	0.35	0.00
true synchrony×time lag×noise level	2.00	2.66	0.07	0.00
true synchrony×bd×time length×noise type	2.00	2.38	0.09	0.00
true synchrony×bd×time lag×time length×synchrony method	20.00	0.38	0.68	0.00
true synchrony×bd×time lag×noise level×synchrony method	20.00	0.35	0.70	0.00
time length×noise level×noise type	1.00	3.66	0.06	0.00
true synchrony×time length×noise level×noise type	2.00	1.81	0.16	0.00
true synchrony×bd×time lag	2.00	1.18	0.31	0.00
time lag×noise level	1.00	2.14	0.14	0.00
bd×time length×noise type	1.00	1.88	0.17	0.00
bd×noise level×noise type	1.00	1.80	0.18	0.00
bd×time lag	1.00	1.61	0.20	0.00
bd×time lag×time length×synchrony method	10.00	0.25	0.62	0.00
bd×time length×noise level×noise type×synchrony method	10.00	0.19	0.67	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	0.06	0.94	0.00
time lag×time length	1.00	0.69	0.41	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.06	0.95	0.00
time lag×noise type×synchrony method	10.00	0.10	0.75	0.00
true synchrony×bd×time length×noise level×noise type	2.00	0.32	0.73	0.00
time lag×time length×noise level×synchrony method	10.00	0.09	0.76	0.00
true synchrony×bd×time lag×noise type×synchrony method	20.00	0.04	0.96	0.00
true synchrony×bd×time lag×time length	2.00	0.20	0.82	0.00
bd×time lag×noise type×synchrony method	10.00	0.06	0.81	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.03	0.97	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.03	0.97	0.00
bd×time lag×time length×noise level×synchrony method	10.00	0.06	0.81	0.00
true synchrony×bd×time lag×time length×noise type×synchrony method	20.00	0.03	0.97	0.00
bd×time lag×noise level×synchrony method	10.00	0.05	0.82	0.00
true synchrony×bd×time lag×noise level×noise type×synchrony method	20.00	0.02	0.98	0.00
true synchrony×bd×time lag×noise level	2.00	0.11	0.89	0.00
bd×time lag×time length	1.00	0.20	0.65	0.00
true synchrony×bd×time lag×time length×noise level×noise type×synchrony method	20.00	0.02	0.98	0.00
time lag×time length×noise type×synchrony method	10.00	0.03	0.86	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.01	0.99	0.00
bd×time length×noise level×noise type	1.00	0.12	0.73	0.00
true synchrony×time lag×time length×noise level	2.00	0.06	0.95	0.00
time lag×time length×noise level	1.00	0.10	0.76	0.00
bd×time lag×time length×noise type×synchrony method	10.00	0.01	0.92	0.00
true synchrony×bd×time lag×noise type	2.00	0.03	0.97	0.00

true synchrony×time lag×noise type	2.00	0.03	0.97	0.00
time lag×noise type	1.00	0.06	0.81	0.00
true synchrony×time lag×time length×noise type	2.00	0.02	0.98	0.00
true synchrony×bd×time lag×time length×noise type	2.00	0.02	0.98	0.00
bd×time lag×time length×noise level×noise type×synchrony method	10.00	0.01	0.94	0.00
bd×time lag×noise type	1.00	0.04	0.85	0.00
true synchrony×time lag×noise level×noise type	2.00	0.02	0.98	0.00
true synchrony×bd×time lag×time length×noise level×synchrony method	20.00	0.00	1.00	0.00
bd×time lag×time length×noise level	1.00	0.03	0.86	0.00
true synchrony×bd×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.00	0.95	0.00
bd×time lag×noise level×noise type×synchrony method	10.00	0.00	0.96	0.00
time lag×noise level×noise type×synchrony method	10.00	0.00	0.96	0.00
true synchrony×bd×time lag×noise level×noise type	2.00	0.01	0.99	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
bd×time lag×time length×noise type	1.00	0.01	0.92	0.00
true synchrony×bd×time lag×time length×noise level	2.00	0.00	1.00	0.00
time lag×time length×noise type	1.00	0.00	0.95	0.00
time lag×time length×noise level×noise type	1.00	0.00	0.96	0.00
bd×time lag×noise level×noise type	1.00	0.00	0.96	0.00
bd×time lag×noise level	1.00	0.00	0.97	0.00
bd×time lag×time length×noise level×noise type	1.00	0.00	0.97	0.00
time lag×noise level×noise type	1.00	0.00	1.00	0.00

Table A2: ANOVA Table when MSE_{hc} is the dependent variable

Effects	DF	F-value	p-value	ges
synchrony method	10.00	231259456.01	<0.01	1.00
time length×synchrony method	10.00	9965329.05	<0.01	1.00
time length	1.00	4897211.10	<0.01	1.00
true synchrony×synchrony method	20.00	416203.75	<0.01	1.00
true synchrony	2.00	339932.17	<0.01	0.98
true synchrony×bd×synchrony method	20.00	20878.53	<0.01	0.95
noise level×synchrony method	10.00	11308.26	<0.01	0.84
true synchrony×time length×synchrony method	20.00	3359.83	<0.01	0.75
true synchrony×bd	2.00	14514.69	<0.01	0.73
true synchrony×noise level×synchrony method	20.00	2747.80	<0.01	0.71
bd×synchrony method	10.00	4148.61	<0.01	0.65
bd	1.00	9243.90	<0.01	0.46
noise level	1.00	4630.58	<0.01	0.30
true synchrony×time length	2.00	1543.52	<0.01	0.22
time length×noise level×synchrony method	10.00	579.80	<0.01	0.21
true synchrony×bd×noise level×synchrony method	20.00	273.02	<0.01	0.20
noise type×synchrony method	10.00	461.33	<0.01	0.17
bd×noise level×synchrony method	10.00	429.79	<0.01	0.16
true synchrony×bd×time length×synchrony method	20.00	201.99	<0.01	0.15
true synchrony×noise type×synchrony method	20.00	168.05	<0.01	0.13
true synchrony×time length×noise level×synchrony method	20.00	145.37	<0.01	0.12
true synchrony×noise level	2.00	683.42	<0.01	0.11
true synchrony×time lag×synchrony method	20.00	69.19	<0.01	0.06
bd×time length×synchrony method	10.00	124.66	<0.01	0.05
time lag×synchrony method	10.00	95.69	<0.01	0.04
noise level×noise type×synchrony method	10.00	76.65	<0.01	0.03
true synchrony×bd×noise type×synchrony method	20.00	37.93	<0.01	0.03
true synchrony×noise level×noise type×synchrony method	20.00	30.04	<0.01	0.03
time length×noise level	1.00	286.23	<0.01	0.03
noise type	1.00	279.99	<0.01	0.02
true synchrony×time lag×time length×synchrony method	20.00	22.14	<0.01	0.02
true synchrony×bd×time length	2.00	97.31	<0.01	0.02
true synchrony×noise type	2.00	93.10	<0.01	0.02
true synchrony×bd×time length×noise level×synchrony method	20.00	17.57	<0.01	0.02
bd×noise type×synchrony method	10.00	34.36	<0.01	0.01
bd×noise level	1.00	148.14	<0.01	0.01
true synchrony×time length×noise level	2.00	69.26	<0.01	0.01
time length×noise type×synchrony method	10.00	28.47	<0.01	0.01
true synchrony×bd×noise level	2.00	57.89	<0.01	0.01
true synchrony×time lag×noise level×synchrony method	20.00	11.91	<0.01	0.01
bd×time length×noise level×synchrony method	10.00	21.44	<0.01	0.01
true synchrony×time length×noise type×synchrony method	20.00	10.86	<0.01	0.01
bd×time lag×synchrony method	10.00	19.85	<0.01	0.01
time lag×noise level×synchrony method	10.00	18.45	<0.01	0.01
true synchrony×bd×time lag×synchrony method	20.00	8.59	<0.01	0.01
true synchrony×bd×noise level×noise type×synchrony method	20.00	6.16	<0.01	0.01
bd×time length	1.00	52.52	<0.01	0.00
true synchrony×time lag	2.00	21.44	<0.01	0.00
true synchrony×time lag×time length	2.00	20.82	<0.01	0.00
noise level×noise type	1.00	35.15	<0.01	0.00
true synchrony×bd×noise type	2.00	17.89	<0.01	0.00
time lag×time length×synchrony method	10.00	5.77	0.02	0.00
time lag	1.00	21.75	<0.01	0.00
true synchrony×noise level×noise type	2.00	11.43	<0.01	0.00
true synchrony×bd×time length×noise level	2.00	8.17	<0.01	0.00
bd×time lag×time length×synchrony method	10.00	4.75	0.03	0.00
time length×noise level×noise type×synchrony method	10.00	4.28	0.04	0.00
true synchrony×bd×time length×noise type×synchrony method	20.00	2.67	0.07	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	2.10	0.12	0.00
bd×noise type	1.00	16.07	<0.01	0.00
time length×noise type	1.00	14.42	<0.01	0.00

true synchrony×bd×time lag	2.00	7.10	<0.01	0.00
bd×time length×noise type×synchrony method	10.00	2.21	0.14	0.00
true synchrony×bd×time lag×noise level×synchrony method	20.00	1.36	0.26	0.00
bd×noise level×noise type×synchrony method	10.00	2.17	0.14	0.00
true synchrony×time length×noise type	2.00	5.35	<0.01	0.00
true synchrony×bd×time lag×time length×synchrony method	20.00	1.04	0.35	0.00
bd×time length×noise level	1.00	10.05	<0.01	0.00
bd×time lag×time length	1.00	6.92	0.01	0.00
true synchrony×time lag×noise level	2.00	2.90	0.06	0.00
true synchrony×bd×noise level×noise type	2.00	2.37	0.09	0.00
time lag×time length	1.00	4.35	0.04	0.00
bd×time lag×noise level×synchrony method	10.00	0.79	0.38	0.00
true synchrony×bd×time length×noise level×noise type×synchrony method	20.00	0.35	0.71	0.00
true synchrony×bd×time lag×time length	2.00	1.67	0.19	0.00
bd×time lag	1.00	3.11	0.08	0.00
true synchrony×bd×time length×noise type	2.00	1.37	0.25	0.00
time length×noise level×noise type	1.00	2.20	0.14	0.00
true synchrony×time length×noise level×noise type	2.00	1.10	0.33	0.00
time lag×noise level	1.00	2.03	0.15	0.00
bd×time length×noise type	1.00	1.07	0.30	0.00
true synchrony×bd×time lag×noise level	2.00	0.37	0.69	0.00
bd×time length×noise level×noise type×synchrony method	10.00	0.13	0.72	0.00
bd×noise level×noise type	1.00	0.62	0.43	0.00
time lag×noise type×synchrony method	10.00	0.09	0.76	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	0.04	0.96	0.00
time lag×time length×noise level×synchrony method	10.00	0.08	0.78	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.04	0.96	0.00
true synchrony×bd×time lag×noise type×synchrony method	20.00	0.03	0.97	0.00
true synchrony×bd×time length×noise level×noise type	2.00	0.16	0.85	0.00
bd×time lag×noise level	1.00	0.28	0.59	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.03	0.97	0.00
true synchrony×bd×time lag×time length×noise type×synchrony method	20.00	0.02	0.98	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.02	0.98	0.00
bd×time lag×noise type×synchrony method	10.00	0.04	0.83	0.00
bd×time lag×time length×noise level×synchrony method	10.00	0.04	0.85	0.00
true synchrony×bd×time lag×noise level×noise type×synchrony method	20.00	0.01	0.99	0.00
true synchrony×bd×time lag×time length×noise level×noise type×synchrony method	20.00	0.01	0.99	0.00
time lag×time length×noise type×synchrony method	10.00	0.02	0.88	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.01	0.99	0.00
bd×time lag×time length×noise type×synchrony method	10.00	0.01	0.91	0.00
true synchrony×time lag×time length×noise level	2.00	0.03	0.97	0.00
time lag×time length×noise level	1.00	0.06	0.81	0.00
bd×time length×noise level×noise type	1.00	0.06	0.81	0.00
true synchrony×time lag×noise type	2.00	0.02	0.98	0.00
true synchrony×time lag×time length×noise type	2.00	0.02	0.98	0.00
true synchrony×bd×time lag×time length×noise level×synchrony method	20.00	0.00	1.00	0.00
true synchrony×bd×time lag×time length×noise type	2.00	0.02	0.98	0.00
bd×time lag×noise type	1.00	0.03	0.86	0.00
true synchrony×bd×time lag×noise type	2.00	0.01	0.99	0.00
time lag×noise type	1.00	0.02	0.88	0.00
true synchrony×bd×time lag×noise level×noise type	2.00	0.01	0.99	0.00
true synchrony×time lag×noise level×noise type	2.00	0.01	0.99	0.00
bd×time lag×time length×noise level×noise type×synchrony method	10.00	0.00	0.95	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.00	0.95	0.00
true synchrony×bd×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
bd×time lag×time length×noise level	1.00	0.01	0.92	0.00
bd×time lag×noise level×noise type×synchrony method	10.00	0.00	0.96	0.00
time lag×noise level×noise type×synchrony method	10.00	0.00	0.96	0.00
true synchrony×bd×time lag×time length×noise level	2.00	0.00	1.00	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.00	1.00	0.00
time lag×time length×noise type	1.00	0.00	0.95	0.00
bd×time lag×time length×noise type	1.00	0.00	0.95	0.00
bd×time lag×time length×noise level×noise type	1.00	0.00	0.97	0.00
time lag×noise level×noise type	1.00	0.00	0.99	0.00
bd×time lag×noise level×noise type	1.00	0.00	0.99	0.00

time lag×time length×noise level×noise type	1.00	0.00	1.00	0.00

Table A3: ANOVA Table when transformed $\mathrm{Cor}_{h\mu}$ is the dependent variable

Effects	DF	F-value	p-value	ges
true synchrony×bd	2.00	1060.18	<0.01	0.41
synchrony method	10.00	2486.98	<0.01	0.35
true synchrony	2.00	501.33	<0.01	0.25
noise level	1.00	862.03	<0.01	0.22
time length	1.00	861.53	<0.01	0.22
true synchrony×synchrony method	20.00	545.01	<0.01	0.19
bd	1.00	674.42	<0.01	0.18
true synchrony×bd×synchrony method	20.00	433.93	<0.01	0.16
true synchrony×time lag×synchrony method	20.00	281.81	<0.01	0.11
true synchrony×bd×time length	2.00	181.09	<0.01	0.11
true synchrony×bd×noise level	2.00	176.96	<0.01	0.10
bd×synchrony method	10.00	403.81	<0.01	0.08
time lag×synchrony method	10.00	396.14	<0.01	0.08
bd×time lag×synchrony method	10.00	391.52	<0.01	0.08
true synchrony×bd×time lag×synchrony method	20.00	150.25	<0.01	0.06
true synchrony×time length	2.00	61.82	<0.01	0.04
time length×noise level	1.00	123.11	<0.01	0.04
true synchrony×bd×time length×synchrony method	20.00	93.41	<0.01	0.04
true synchrony×bd×noise level×synchrony method	20.00	93.00	<0.01	0.04
time length×synchrony method	10.00	184.61	<0.01	0.04
bd×noise level	1.00	94.66	<0.01	0.03
true synchrony×time length×synchrony method	20.00	62.52	<0.01	0.03
bd×time length	1.00	77.56	<0.01	0.02
true synchrony×time lag×time length×synchrony method	20.00	45.97	<0.01	0.02
true synchrony×noise level	2.00	23.92	<0.01	0.02
noise level×synchrony method	10.00	67.88	<0.01	0.01
true synchrony×noise level×synchrony method	20.00	31.79	<0.01	0.01
true synchrony×bd×time length×noise level	2.00	21.47	<0.01	0.01
noise type×synchrony method	10.00	56.33	<0.01	0.01
bd×time lag×time length×synchrony method	10.00	47.69	<0.01	0.01
noise type	1.00	25.89	<0.01	0.01
true synchrony×time lag	2.00	13.02	<0.01	0.01
time lag×time length	1.00	28.34	<0.01	0.01
true synchrony×bd×time lag	2.00	12.10	<0.01	0.01
time length×noise level×synchrony method	10.00	37.61	<0.01	0.01
true synchrony×bd×time lag×time length×synchrony method	20.00	17.97	<0.01	0.01
true synchrony×bd×noise type	2.00	11.18	<0.01	0.01
true synchrony×time lag×time length	2.00	9.66	<0.01	0.01
true synchrony×bd×time length×noise level×synchrony method	20.00	11.74	<0.01	0.00
true synchrony×time length×noise level	2.00	6.42	<0.01	0.00
bd×time length×synchrony method	10.00	20.48	<0.01	0.00
true synchrony×time lag×noise level×synchrony method	20.00	10.30	<0.01	0.00
time lag	1.00	7.80	<0.01	0.00
bd×time lag	1.00	10.45	<0.01	0.00
true synchrony×time length×noise level×synchrony method	20.00	6.06	<0.01	0.00
true synchrony×bd×noise type×synchrony method	20.00	7.61	<0.01	0.00
bd×noise type	1.00	5.34	0.02	0.00
noise level×noise type	1.00	6.58	0.01	0.00
bd×time length×noise level	1.00	4.74	0.03	0.00
time lag×time length×synchrony method	10.00	7.04	<0.01	0.00
bd×time lag×noise level×synchrony method	10.00	10.02	<0.01	0.00
bd×time length×noise level×synchrony method	10.00	8.95	<0.01	0.00
true synchrony×bd×time lag×noise level×synchrony method	20.00	4.29	<0.01	0.00
time length×noise type	1.00	3.62	0.06	0.00
bd×noise level×synchrony method	10.00	5.55	<0.01	0.00
bd×noise type×synchrony method	10.00	3.83	0.01	0.00
noise level×noise type×synchrony method	10.00	3.74	0.01	0.00
time lag×time length×noise level×synchrony method	10.00	3.53	0.02	0.00
bd×noise level×noise type	1.00	1.91	0.17	0.00
bd×time lag×time length	1.00	1.86	0.17	0.00
true synchrony×bd×time lag×noise level	2.00	0.89	0.41	0.00

true synchrony×noise type×synchrony method	20.00	1.35	0.24	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	1.18	0.31	0.00
time lag×noise level×synchrony method	10.00	2.02	0.12	0.00
true synchrony×time lag×time length×noise level	2.00	0.54	0.58	0.00
time lag×noise type	1.00	0.99	0.32	0.00
true synchrony×bd×time length×noise type	2.00	0.49	0.61	0.00
time lag×time length×noise level	1.00	0.97	0.32	0.00
true synchrony×noise type	2.00	0.48	0.62	0.00
time length×noise type×synchrony method	10.00	1.47	0.22	0.00
bd×noise level×noise type×synchrony method	10.00	1.35	0.26	0.00
time length×noise level×noise type	1.00	0.87	0.35	0.00
true synchrony×time lag×noise level	2.00	0.43	0.65	0.00
true synchrony×time length×noise type×synchrony method	20.00	0.63	0.68	0.00
true synchrony×noise level×noise type×synchrony method	20.00	0.59	0.72	0.00
true synchrony×bd×noise level×noise type	2.00	0.36	0.70	0.00
true synchrony×time length×noise type	2.00	0.35	0.71	0.00
time lag×noise level	1.00	0.59	0.44	0.00
bd×time lag×noise level	1.00	0.56	0.46	0.00
true synchrony×bd×time length×noise type×synchrony method	20.00	0.41	0.84	0.00
true synchrony×bd×time lag×time length×noise level×synchrony method	20.00	0.34	0.89	0.00
bd×time length×noise type	1.00	0.42	0.52	0.00
time length×noise level×noise type×synchrony method	10.00	0.64	0.57	0.00
true synchrony×time length×noise level×noise type	2.00	0.18	0.83	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.28	0.93	0.00
true synchrony×bd×time lag×time length	2.00	0.18	0.84	0.00
true synchrony×bd×time length×noise level×noise type	2.00	0.18	0.84	0.00
true synchrony×time lag×noise type	2.00	0.15	0.86	0.00
true synchrony×bd×time lag×time length×noise type×synchrony method	20.00	0.20	0.96	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.20	0.97	0.00
time lag×time length×noise type×synchrony method	10.00	0.35	0.76	0.00
true synchrony×bd×time length×noise level×noise type×synchrony method	20.00	0.17	0.97	0.00
bd×time length×noise level×noise type	1.00	0.20	0.65	0.00
bd×time length×noise type×synchrony method	10.00	0.30	0.80	0.00
true synchrony×bd×noise level×noise type×synchrony method	20.00	0.15	0.98	0.00
true synchrony×bd×time lag×noise type×synchrony method	20.00	0.14	0.98	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.09	0.91	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.13	0.99	0.00
time lag×noise type×synchrony method	10.00	0.22	0.86	0.00
bd×time lag×time length×noise level×synchrony method	10.00	0.21	0.86	0.00
true synchrony×bd×time lag×noise level×noise type	2.00	0.06	0.94	0.00
true synchrony×bd×time lag×noise level×noise type×synchrony method	20.00	0.08	0.99	0.00
time lag×time length×noise type	1.00	0.11	0.74	0.00
bd×time lag×noise type×synchrony method	10.00	0.16	0.90	0.00
true synchrony×bd×time lag×time length×noise type	2.00	0.05	0.95	0.00
true synchrony×noise level×noise type	2.00	0.05	0.95	0.00
bd×time lag×time length×noise type	1.00	0.09	0.76	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	0.07	1.00	0.00
true synchrony×bd×time lag×time length×noise level×noise type×synchrony method	20.00	0.06	1.00	0.00
bd×time lag×time length×noise type×synchrony method	10.00	0.12	0.93	0.00
bd×time length×noise level×noise type×synchrony method	10.00	0.12	0.93	0.00
bd×time lag×time length×noise level	1.00	0.07	0.79	0.00
bd×time lag×noise level×noise type×synchrony method	10.00	0.10	0.94	0.00
true synchrony×time lag×noise level×noise type	2.00	0.03	0.97	0.00
true synchrony×bd×time lag×time length×noise level	2.00	0.03	0.97	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.03	1.00	0.00
true synchrony×bd×time lag×time length×noise level×noise type	2.00	0.02	0.98	0.00
bd×time lag×time length×noise level×noise type×synchrony method	10.00	0.06	0.97	0.00
time lag×noise level×noise type	1.00	0.04	0.85	0.00
time lag×noise level×noise type×synchrony method	10.00	0.05	0.98	0.00
bd×time lag×time length×noise level×noise type	1.00	0.03	0.86	0.00
time lag×time length×noise level×noise type	1.00	0.03	0.87	0.00
true synchrony×bd×time lag×noise type	2.00	0.01	0.99	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.03	0.98	0.00
bd×time lag×noise level×noise type	1.00	0.02	0.90	0.00
true synchrony×time lag×time length×noise type	2.00	0.00	1.00	0.00

bd×time lag×noise type	1.00	0.00	0.97	0.00

Table A4: ANOVA Table when transformed Cor_{hc} is the dependent variable

Effects	DF	F-value	p-value	ges
true synchrony×bd	2.00	1242.30	<0.01	0.45
synchrony method	10.00	3176.45	<0.01	0.41
true synchrony×synchrony method	20.00	1046.19	<0.01	0.32
true synchrony	2.00	570.45	<0.01	0.27
time lag×synchrony method	10.00	1504.87	<0.01	0.25
time length	1.00	874.93	<0.01	0.22
noise level	1.00	746.71	<0.01	0.20
bd	1.00	408.03	<0.01	0.12
bd×synchrony method	10.00	479.93	<0.01	0.10
true synchrony×bd×time length	2.00	163.67	<0.01	0.10
true synchrony×bd×noise level	2.00	145.69	<0.01	0.09
true synchrony×bd×time lag×synchrony method	20.00	209.63	<0.01	0.08
true synchrony×bd×synchrony method	20.00	132.23	<0.01	0.06
true synchrony×time length	2.00	74.15	<0.01	0.05
bd×time lag×synchrony method	10.00	216.88	<0.01	0.05
true synchrony×noise level	2.00	52.72	<0.01	0.03
time length×noise level	1.00	100.80	<0.01	0.03
true synchrony×time length×synchrony method	20.00	71.08	<0.01	0.03
true synchrony×bd×time length×synchrony method	20.00	63.86	<0.01	0.03
true synchrony×bd×time lag	2.00	37.97	<0.01	0.02
true synchrony×bd×noise level×synchrony method	20.00	45.14	<0.01	0.02
time lag	1.00	58.06	<0.01	0.02
true synchrony×bd×time lag×time length×synchrony method	20.00	44.24	<0.01	0.02
true synchrony×time lag×time length×synchrony method	20.00	42.13	<0.01	0.02
bd×time length	1.00	52.47	<0.01	0.02
bd×noise level	1.00	50.48	<0.01	0.02
time length×synchrony method	10.00	64.99	<0.01	0.01
true synchrony×bd×time length×noise level	2.00	21.22	<0.01	0.01
noise type×synchrony method	10.00	48.03	<0.01	0.01
true synchrony×time lag×synchrony method	20.00	24.95	<0.01	0.01
true synchrony×noise level×synchrony method	20.00	22.75	<0.01	0.01
time length×noise level×synchrony method	10.00	45.41	<0.01	0.01
noise type	1.00	21.15	<0.01	0.01
time lag×time length	1.00	23.13	<0.01	0.01
noise level×synchrony method	10.00	31.54	<0.01	0.01
true synchrony×bd×time length×noise level×synchrony method	20.00	14.69	<0.01	0.01
time lag×noise level×synchrony method	10.00	22.36	<0.01	0.00
true synchrony×time length×noise level	2.00	6.64	<0.01	0.00
true synchrony×bd×noise type	2.00	6.74	<0.01	0.00
bd×time length×synchrony method	10.00	11.51	<0.01	0.00
true synchrony×noise type×synchrony method	20.00	6.27	<0.01	0.00
true synchrony×time lag×noise level×synchrony method	20.00	6.55	<0.01	0.00
true synchrony×time lag	2.00	2.68	0.07	0.00
true synchrony×time lag×time length	2.00	3.11	0.04	0.00
bd×time lag×time length	1.00	5.44	0.02	0.00
time lag×time length×synchrony method	10.00	7.42	<0.01	0.00
bd×time lag×time length×synchrony method	10.00	8.46	<0.01	0.00
bd×time lag×noise level×synchrony method	10.00	11.15	<0.01	0.00
true synchrony×time length×noise level×synchrony method	20.00	4.28	<0.01	0.00
time lag×time length×noise level×synchrony method	10.00	8.87	<0.01	0.00
true synchrony×bd×noise type×synchrony method	20.00	4.26	<0.01	0.00
true synchrony×bd×time lag×noise level×synchrony method	20.00	4.29	<0.01	0.00
time lag×noise level	1.00	4.20	0.04	0.00
true synchrony×noise type	2.00	1.82	0.16	0.00
noise level×noise type	1.00	4.27	0.04	0.00
bd×time length×noise level	1.00	3.48	0.06	0.00
bd×time length×noise level×synchrony method	10.00	6.31	<0.01	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	2.28	0.04	0.00
noise level×noise type×synchrony method	10.00	4.39	0.01	0.00
time length×noise type	1.00	2.73	0.10	0.00
true synchrony×bd×time lag×time length	2.00	1.36	0.26	0.00

bd×noise type×synchrony method	10.00	3.32	0.02	0.00
bd×noise type	1.00	2.25	0.13	0.00
bd×noise level×synchrony method	10.00	2.89	0.04	0.00
true synchrony×time lag×noise level	2.00	0.75	0.47	0.00
true synchrony×noise level×noise type×synchrony method	20.00	1.07	0.37	0.00
true synchrony×bd×time lag×noise level	2.00	0.72	0.49	0.00
true synchrony×bd×time length×noise type	2.00	0.70	0.50	0.00
bd×time lag	1.00	1.25	0.26	0.00
bd×time length×noise type	1.00	0.96	0.33	0.00
true synchrony×time length×noise type	2.00	0.46	0.63	0.00
bd×noise level×noise type	1.00	0.88	0.35	0.00
bd×time lag×time length×noise level	1.00	0.87	0.35	0.00
true synchrony×time lag×noise type	2.00	0.33	0.72	0.00
bd×noise level×noise type×synchrony method	10.00	0.87	0.44	0.00
true synchrony×bd×time lag×time length×noise level×synchrony method	20.00	0.43	0.84	0.00
bd×time lag×time length×noise type	1.00	0.57	0.45	0.00
true synchrony×time lag×time length×noise level	2.00	0.28	0.76	0.00
time length×noise type×synchrony method	10.00	0.74	0.51	0.00
true synchrony×time length×noise type×synchrony method	20.00	0.36	0.88	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.36	0.88	0.00
bd×time length×noise type×synchrony method	10.00	0.71	0.53	0.00
time lag×time length×noise type×synchrony method	10.00	0.66	0.56	0.00
bd×time lag×noise level	1.00	0.40	0.53	0.00
true synchrony×bd×time length×noise level×noise type	2.00	0.20	0.82	0.00
time length×noise level×noise type×synchrony method	10.00	0.57	0.61	0.00
true synchrony×bd×noise level×noise type	2.00	0.18	0.83	0.00
time length×noise level×noise type	1.00	0.36	0.55	0.00
true synchrony×bd×time length×noise type×synchrony method	20.00	0.25	0.94	0.00
bd×time length×noise level×noise type	1.00	0.33	0.56	0.00
true synchrony×bd×time lag×noise type	2.00	0.15	0.86	0.00
true synchrony×bd×time lag×noise type×synchrony method	20.00	0.22	0.96	0.00
true synchrony×bd×time lag×time length×noise type×synchrony method	20.00	0.22	0.96	0.00
bd×time lag×time length×noise level×synchrony method	10.00	0.42	0.71	0.00
true synchrony×bd×noise level×noise type×synchrony method	20.00	0.21	0.96	0.00
true synchrony×noise level×noise type	2.00	0.13	0.88	0.00
true synchrony×bd×time lag×noise level×noise type	2.00	0.12	0.89	0.00
true synchrony×bd×time lag×time length×noise level	2.00	0.12	0.89	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.10	0.90	0.00
true synchrony×time lag×time length×noise type	2.00	0.10	0.91	0.00
bd×time length×noise level×noise type×synchrony method	10.00	0.24	0.84	0.00
bd×time lag×time length×noise type×synchrony method	10.00	0.24	0.85	0.00
true synchrony×bd×time length×noise level×noise type×synchrony method	20.00	0.12	0.99	0.00
time lag×noise type	1.00	0.16	0.69	0.00
time lag×time length×noise type	1.00	0.15	0.70	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.10	0.99	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.09	0.99	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	0.09	0.99	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.09	1.00	0.00
bd×time lag×noise level×noise type×synchrony method	10.00	0.17	0.90	0.00
true synchrony×time length×noise level×noise type	2.00	0.06	0.95	0.00
true synchrony×bd×time lag×time length×noise level×noise type	2.00	0.05	0.95	0.00
true synchrony×bd×time lag×noise level×noise type×synchrony method	20.00	0.07	1.00	0.00
bd×time lag×time length×noise level×noise type×synchrony method	10.00	0.12	0.93	0.00
time lag×noise type×synchrony method	10.00	0.10	0.95	0.00
bd×time lag×noise type×synchrony method	10.00	0.10	0.95	0.00
time lag×noise level×noise type×synchrony method	10.00	0.08	0.96	0.00
true synchrony×bd×time lag×time length×noise type	2.00	0.03	0.97	0.00
true synchrony×bd×time lag×time length×noise level×noise type×synchrony method	20.00	0.03	1.00	0.00
bd×time lag×noise type	1.00	0.04	0.84	0.00
time lag×time length×noise level×noise type	1.00	0.02	0.89	0.00
time lag×noise level×noise type	1.00	0.02	0.90	0.00
bd×time lag×noise level×noise type	1.00	0.02	0.90	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.01	0.99	0.00
true synchrony×time lag×noise level×noise type	2.00	0.00	1.00	0.00
bd×time lag×time length×noise level×noise type	1.00	0.00	0.96	0.00

time lag×time length×noise level	1.00	0.00	0.97	0.00

Table A5: ANOVA Table when MSE_{br} is the dependent variable

Effects	DF	F-value	p-value	ges
synchrony method	10.00	385495327.18	<0.01	1.00
time length×synchrony method	10.00	16930303.39	<0.01	1.00
time length	1.00	11823455.73	<0.01	1.00
true synchrony×synchrony method	20.00	435595.35	<0.01	1.00
true synchrony	2.00	436235.11	<0.01	0.98
true synchrony×time length×synchrony method	20.00	4923.72	<0.01	0.76
true synchrony×time length	2.00	3160.44	<0.01	0.22
time lag×synchrony method	10.00	238.08	<0.01	0.07
true synchrony×time lag×synchrony method	20.00	87.12	<0.01	0.05
noise level×synchrony method	10.00	156.16	<0.01	0.05
true synchrony×κ×synchrony method	40.00	13.21	<0.01	0.02
noise type×synchrony method	10.00	50.79	<0.01	0.02
true synchrony×noise level×synchrony method	20.00	24.62	<0.01	0.02
κ×synchrony method	20.00	23.21	<0.01	0.01
time lag×noise level×synchrony method	10.00	38.98	<0.01	0.01
true synchrony×time lag×noise level×synchrony method	20.00	16.23	<0.01	0.01
true synchrony×time lag	2.00	91.17	<0.01	0.01
true synchrony×κ×time lag×synchrony method	40.00	6.07	<0.01	0.01
noise level	1.00	157.88	<0.01	0.01
noise level×noise type×synchrony method	10.00	22.59	<0.01	0.01
κ×time lag×synchrony method	20.00	8.54	<0.01	0.00
κ×noise level×synchrony method	20.00	8.56	<0.01	0.00
true synchrony×κ	4.00	23.66	<0.01	0.00
time lag×time length×synchrony method	10.00	11.75	<0.01	0.00
time lag	1.00	73.36	<0.01	0.00
κ×noise type×synchrony method	20.00	4.26	0.01	0.00
true synchrony×κ×time length×synchrony method	40.00	2.66	0.03	0.00
true synchrony×κ×time lag×time length×synchrony method	40.00	2.54	0.04	0.00
κ×time lag×time length×synchrony method	20.00	3.59	0.03	0.00
true synchrony×noise level	2.00	12.64	<0.01	0.00
true synchrony×κ×noise level×synchrony method	40.00	0.84	0.50	0.00
κ×time length×synchrony method	20.00	1.52	0.22	0.00
true synchrony×noise type×synchrony method	20.00	1.50	0.22	0.00
true synchrony×κ×time lag	4.00	5.14	<0.01	0.00
time lag×noise type×synchrony method	10.00	2.88	0.09	0.00
κ×noise level×noise type×synchrony method	20.00	1.32	0.27	0.00
noise type	1.00	15.24	<0.01	0.00
κ	2.00	7.13	<0.01	0.00
κ×noise level	2.00	6.92	<0.01	0.00
time length×noise level×synchrony method	10.00	1.94	0.16	0.00
true synchrony×time lag×time length×synchrony method	20.00	0.92	0.40	0.00
true synchrony×time lag×noise level	2.00	5.80	<0.01	0.00
time lag×time length	1.00	11.55	<0.01	0.00
κ×noise type	2.00	5.58	<0.01	0.00
true synchrony×κ×noise type×synchrony method	40.00	0.38	0.83	0.00
true synchrony×κ×time lag×time length	4.00	2.52	0.04	0.00
κ×time lag×noise level×synchrony method	20.00	0.69	0.50	0.00
true synchrony×κ×noise level	4.00	2.29	0.06	0.00
κ×time lag	2.00	4.25	0.01	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.60	0.55	0.00
true synchrony×κ×time length	4.00	2.07	0.08	0.00
time lag×noise level×noise type×synchrony method	10.00	1.05	0.31	0.00
noise level×noise type	1.00	6.91	0.01	0.00
true synchrony×time length×noise level×synchrony method	20.00	0.46	0.63	0.00
time lag×time length×noise level×synchrony method	10.00	0.91	0.34	0.00
κ×time lag×time length	2.00	2.75	0.06	0.00
true synchrony×noise level×noise type×synchrony method	20.00	0.37	0.69	0.00
κ×time length	2.00	2.54	0.08	0.00
true synchrony×time length×noise type×synchrony method	20.00	0.32	0.73	0.00
κ×noise level×noise type	2.00	2.13	0.12	0.00
time length×noise type×synchrony method	10.00	0.58	0.45	0.00

true synchrony×κ×noise level×noise type×synchrony method	40.00	0.13	0.97	0.00
time lag×noise level	1.00	3.36	0.07	0.00
κ×time length×noise level×synchrony method	20.00	0.23	0.79	0.00
true synchrony×κ×noise type	4.00	0.81	0.52	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.22	0.81	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	0.21	0.81	0.00
true synchrony×time length×noise level	2.00	1.35	0.26	0.00
time lag×noise type	1.00	2.50	0.11	0.00
κ×time lag×noise type×synchrony method	20.00	0.16	0.85	0.00
κ×time length×noise type×synchrony method	20.00	0.16	0.85	0.00
true synchrony×time lag×time length	2.00	1.06	0.35	0.00
true synchrony×κ×time length×noise level×synchrony method	40.00	0.08	0.99	0.00
true synchrony×κ×time lag×noise level×synchrony method	40.00	0.06	0.99	0.00
true synchrony×time length×noise type	2.00	0.78	0.46	0.00
κ×time length×noise level×noise type×synchrony method	20.00	0.11	0.90	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	0.11	0.90	0.00
true synchrony×κ×noise level×noise type	4.00	0.33	0.86	0.00
true synchrony×κ×time length×noise type×synchrony method	40.00	0.05	1.00	0.00
time length×noise type	1.00	1.14	0.28	0.00
time length×noise level×noise type×synchrony method	10.00	0.14	0.71	0.00
time lag×noise level×noise type	1.00	0.95	0.33	0.00
time lag×time length×noise type×synchrony method	10.00	0.13	0.72	0.00
time lag×time length×noise level	1.00	0.88	0.35	0.00
κ×time lag×noise level×noise type×synchrony method	20.00	0.06	0.94	0.00
true synchrony×κ×time lag×noise type×synchrony method	40.00	0.02	1.00	0.00
true synchrony×time length×noise level×noise type	2.00	0.32	0.73	0.00
time length×noise level	1.00	0.61	0.43	0.00
true synchrony×κ×time length×noise level×noise type×synchrony method	40.00	0.02	1.00	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.04	0.96	0.00
κ×time length×noise type	2.00	0.27	0.76	0.00
true synchrony×κ×time lag×noise level×noise type×synchrony method	40.00	0.02	1.00	0.00
true synchrony×time lag×noise type	2.00	0.23	0.80	0.00
κ×time length×noise level	2.00	0.22	0.80	0.00
true synchrony×κ×time length×noise level	4.00	0.10	0.98	0.00
true synchrony×κ×time lag×time length×noise level×synchrony method	40.00	0.01	1.00	0.00
true synchrony×time lag×time length×noise level	2.00	0.20	0.82	0.00
true synchrony×κ×time length×noise type	4.00	0.09	0.98	0.00
κ×time lag×noise type	2.00	0.16	0.85	0.00
κ×time length×noise level×noise type	2.00	0.15	0.86	0.00
true synchrony×κ×time lag×time length×noise type×synchrony method	40.00	0.01	1.00	0.00
κ×time lag×time length×noise level×synchrony method	20.00	0.02	0.98	0.00
true synchrony×time lag×noise level×noise type	2.00	0.11	0.90	0.00
time length×noise level×noise type	1.00	0.18	0.67	0.00
true synchrony×noise type	2.00	0.09	0.92	0.00
true synchrony×κ×time length×noise level×noise type	4.00	0.04	1.00	0.00
κ×time lag×time length×noise type×synchrony method	20.00	0.01	0.99	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.02	0.90	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.01	0.99	0.00
true synchrony×κ×time lag×noise level	4.00	0.02	1.00	0.00
κ×time lag×noise level×noise type	2.00	0.04	0.96	0.00
κ×time lag×time length×noise level	2.00	0.04	0.96	0.00
κ×time lag×time length×noise level×noise type×synchrony method	20.00	0.00	0.99	0.00
true synchrony×κ×time lag×time length×noise level×noise type×synchrony method	40.00	0.00	1.00	0.00
true synchrony×time lag×time length×noise type	2.00	0.03	0.97	0.00
true synchrony×κ×time lag×time length×noise level	4.00	0.01	1.00	0.00
κ×time lag×noise level	2.00	0.03	0.97	0.00
κ×time lag×time length×noise type	2.00	0.02	0.98	0.00
true synchrony×κ×time lag×time length×noise type	4.00	0.01	1.00	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.02	0.98	0.00
true synchrony×κ×time lag×noise type	4.00	0.01	1.00	0.00
time lag×time length×noise type	1.00	0.03	0.87	0.00
true synchrony×noise level×noise type	2.00	0.01	0.99	0.00
true synchrony×κ×time lag×noise level×noise type	4.00	0.00	1.00	0.00
κ×time lag×time length×noise level×noise type	2.00	0.00	0.99	0.00
true synchrony×κ×time lag×time length×noise level×noise type	4.00	0.00	1.00	0.00

time lag×time length×noise level×noise type	1.00	0.00	0.97	0.00

Table A6: ANOVA Table when MSE_{bc} is the dependent variable

Effects	DF	F-value	p-value	ges
synchrony method	10.00	171352331.99	<0.01	1.00
time length×synchrony method	10.00	7660826.37	<0.01	1.00
time length	1.00	5212319.78	<0.01	1.00
true synchrony×synchrony method	20.00	80298.00	<0.01	0.98
κ×synchrony method	20.00	14868.38	<0.01	0.90
true synchrony	2.00	64774.49	<0.01	0.86
true synchrony×κ×synchrony method	40.00	3866.55	<0.01	0.83
κ	2.00	14239.62	<0.01	0.57
true synchrony×κ	4.00	4390.51	<0.01	0.45
true synchrony×time length×synchrony method	20.00	999.93	<0.01	0.39
κ×time length×synchrony method	20.00	140.68	<0.01	0.08
true synchrony×κ×time length×synchrony method	40.00	64.99	<0.01	0.08
time lag×synchrony method	10.00	172.71	<0.01	0.05
true synchrony×time length	2.00	492.92	<0.01	0.04
noise level×synchrony method	10.00	104.34	<0.01	0.03
true synchrony×time lag×synchrony method	20.00	37.76	<0.01	0.02
true synchrony×κ×time lag×time length×synchrony method	40.00	10.32	<0.01	0.01
true synchrony×κ×time lag×synchrony method	40.00	9.57	<0.01	0.01
time lag×noise level×synchrony method	10.00	27.74	<0.01	0.01
noise type×synchrony method	10.00	21.73	<0.01	0.01
noise level	1.00	132.28	<0.01	0.01
κ×time length	2.00	59.46	<0.01	0.01
true synchrony×κ×time length	4.00	33.88	<0.01	0.01
κ×noise level×synchrony method	20.00	8.06	<0.01	0.00
true synchrony×noise level×synchrony method	20.00	5.66	<0.01	0.00
true synchrony×time lag×noise level×synchrony method	20.00	6.69	<0.01	0.00
true synchrony×time lag	2.00	29.83	<0.01	0.00
noise level×noise type×synchrony method	10.00	9.74	<0.01	0.00
time lag	1.00	47.85	<0.01	0.00
true synchrony×κ×time lag×time length	4.00	8.38	<0.01	0.00
true synchrony×κ×time lag	4.00	6.88	<0.01	0.00
time lag×time length×synchrony method	10.00	4.56	0.03	0.00
κ×noise type×synchrony method	20.00	2.00	0.14	0.00
κ×time lag×time length×synchrony method	20.00	1.62	0.20	0.00
true synchrony×time lag×time length×synchrony method	20.00	1.45	0.23	0.00
true synchrony×κ×noise level×synchrony method	40.00	0.64	0.63	0.00
noise type	1.00	10.19	0.00	0.00
time lag×noise type×synchrony method	10.00	1.36	0.24	0.00
κ×noise level×noise type×synchrony method	20.00	0.62	0.54	0.00
true synchrony×noise type×synchrony method	20.00	0.48	0.62	0.00
κ×time lag×synchrony method	20.00	0.46	0.63	0.00
time lag×noise level	1.00	5.51	0.02	0.00
true synchrony×κ×noise type×synchrony method	40.00	0.16	0.96	0.00
noise level×noise type	1.00	4.33	0.04	0.00
time length×noise level×synchrony method	10.00	0.58	0.45	0.00
true synchrony×time lag×noise level	2.00	1.97	0.14	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.28	0.75	0.00
κ×time lag×time length	2.00	1.86	0.15	0.00
time lag×noise level×noise type×synchrony method	10.00	0.49	0.48	0.00
κ×noise type	2.00	1.59	0.20	0.00
true synchrony×noise level	2.00	1.55	0.21	0.00
time lag×time length	1.00	2.72	0.10	0.00
time lag×time length×noise level×synchrony method	10.00	0.39	0.54	0.00
κ×time lag×noise level×synchrony method	20.00	0.19	0.83	0.00
κ×time length×noise level×synchrony method	20.00	0.10	0.90	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	0.10	0.90	0.00
true synchrony×time lag×time length	2.00	0.70	0.50	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.10	0.91	0.00
true synchrony×time length×noise level×synchrony method	20.00	0.10	0.91	0.00
true synchrony×noise level×noise type×synchrony method	20.00	0.10	0.91	0.00
κ×time length×noise type×synchrony method	20.00	0.08	0.92	0.00

κ×noise level×noise type	2.00	0.55	0.58	0.00
true synchrony×κ×noise level×noise type×synchrony method	40.00	0.04	1.00	0.00
κ×time lag×noise type×synchrony method	20.00	0.07	0.93	0.00
true synchrony×κ×time length×noise level×synchrony method	40.00	0.03	1.00	0.00
time lag×noise type	1.00	0.92	0.34	0.00
true synchrony×time length×noise type×synchrony method	20.00	0.06	0.94	0.00
true synchrony×κ×time lag×noise level×synchrony method	40.00	0.03	1.00	0.00
true synchrony×κ×noise type	4.00	0.19	0.94	0.00
time length×noise type×synchrony method	10.00	0.09	0.76	0.00
κ×time length×noise level×noise type×synchrony method	20.00	0.04	0.96	0.00
true synchrony×κ×time length×noise type×synchrony method	40.00	0.02	1.00	0.00
κ×noise level	2.00	0.24	0.78	0.00
true synchrony×κ×noise level	4.00	0.11	0.98	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	0.03	0.97	0.00
true synchrony×time length×noise level	2.00	0.20	0.82	0.00
time lag×time length×noise type×synchrony method	10.00	0.06	0.81	0.00
κ×time lag×noise level×noise type×synchrony method	20.00	0.03	0.97	0.00
time lag×noise level×noise type	1.00	0.36	0.55	0.00
time lag×time length×noise level	1.00	0.32	0.57	0.00
true synchrony×time length×noise type	2.00	0.15	0.86	0.00
κ×time length×noise level	2.00	0.15	0.86	0.00
true synchrony×κ×time lag×noise type×synchrony method	40.00	0.01	1.00	0.00
κ×time length×noise type	2.00	0.13	0.87	0.00
true synchrony×time lag×time length×noise level	2.00	0.13	0.88	0.00
true synchrony×time lag×noise type	2.00	0.13	0.88	0.00
true synchrony×κ×noise level×noise type	4.00	0.06	0.99	0.00
true synchrony×κ×time length×noise level×noise type×synchrony method	40.00	0.01	1.00	0.00
κ×time lag	2.00	0.12	0.89	0.00
true synchrony×κ×time length×noise level	4.00	0.06	0.99	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.02	0.98	0.00
true synchrony×κ×time lag×time length×noise level×synchrony method	40.00	0.01	1.00	0.00
true synchrony×noise type	2.00	0.11	0.90	0.00
time length×noise level×noise type×synchrony method	10.00	0.03	0.86	0.00
true synchrony×κ×time lag×noise level×noise type×synchrony method	40.00	0.01	1.00	0.00
κ×time lag×noise level	2.00	0.09	0.91	0.00
time length×noise type	1.00	0.16	0.69	0.00
true synchrony×κ×time length×noise type	4.00	0.04	1.00	0.00
κ×time lag×noise type	2.00	0.07	0.93	0.00
true synchrony×time length×noise level×noise type	2.00	0.07	0.93	0.00
κ×time length×noise level×noise type	2.00	0.06	0.94	0.00
true synchrony×κ×time lag×time length×noise type×synchrony method	40.00	<0.01	1.00	0.00
true synchrony×time lag×noise level×noise type	2.00	0.04	0.96	0.00
κ×time lag×time length×noise level×synchrony method	20.00	0.01	0.99	0.00
true synchrony×κ×time length×noise level×noise type	4.00	0.02	1.00	0.00
κ×time lag×time length×noise type×synchrony method	20.00	0.00	0.99	0.00
true synchrony×noise level×noise type	2.00	0.03	0.97	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.01	0.93	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.00	1.00	0.00
κ×time lag×noise level×noise type	2.00	0.02	0.98	0.00
true synchrony×κ×time lag×time length×noise level×noise type×synchrony method	40.00	0.00	1.00	0.00
true synchrony×κ×time lag×time length×noise level	4.00	0.01	1.00	0.00
true synchrony×time lag×time length×noise type	2.00	0.01	0.99	0.00
κ×time lag×time length×noise level	2.00	0.01	0.99	0.00
true synchrony×κ×time lag×noise type	4.00	0.01	1.00	0.00
κ×time lag×time length×noise type	2.00	0.01	0.99	0.00
true synchrony×κ×time lag×noise level×noise type	4.00	0.00	1.00	0.00
κ×time lag×time length×noise level×noise type×synchrony method	20.00	0.00	1.00	0.00
time lag×time length×noise type	1.00	0.02	0.89	0.00
time length×noise level×noise type	1.00	0.01	0.90	0.00
true synchrony×κ×time lag×time length×noise type	4.00	0.00	1.00	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
true synchrony×κ×time lag×time length×noise level×noise type	4.00	0.00	1.00	0.00
κ×time lag×time length×noise level×noise type	2.00	0.00	1.00	0.00
time length×noise level	1.00	0.01	0.94	0.00
true synchrony×κ×time lag×noise level	4.00	0.00	1.00	0.00

time lag×time length×noise level×noise type	1.00	0.00	0.95	0.00

Table A7: ANOVA Table when Cor_{br} is the dependent variable

Effects	DF	F-value	p-value	ges
time lag×synchrony method	10.00	958.48	<0.01	0.14
synchrony method	10.00	499.74	<0.01	0.08
time length×synchrony method	10.00	214.42	<0.01	0.03
time lag×time length×synchrony method	10.00	216.03	<0.01	0.03
time lag	1.00	142.28	<0.01	0.03
true synchrony×synchrony method	20.00	56.25	<0.01	0.02
κ×synchrony method	20.00	34.16	<0.01	0.01
true synchrony×time lag×synchrony method	20.00	22.57	<0.01	0.01
time length	1.00	30.76	<0.01	0.01
true synchrony×κ×synchrony method	40.00	7.47	<0.01	0.00
true synchrony×time length×synchrony method	20.00	15.84	<0.01	0.00
true synchrony×κ	4.00	5.55	<0.01	0.00
κ	2.00	6.81	<0.01	0.00
true synchrony×time length	2.00	7.86	<0.01	0.00
time lag×time length	1.00	13.61	<0.01	0.00
κ×time lag×time length	2.00	6.66	<0.01	0.00
true synchrony×κ×time lag×synchrony method	40.00	4.27	<0.01	0.00
true synchrony×κ×time length×synchrony method	40.00	4.11	<0.01	0.00
true synchrony×κ×time lag×time length×synchrony method	40.00	3.88	<0.01	0.00
noise level	1.00	7.82	<0.01	0.00
κ×time length	2.00	3.80	0.02	0.00
true synchrony×κ×time lag	4.00	2.29	0.06	0.00
true synchrony×κ×time length	4.00	2.13	0.07	0.00
κ×time lag×time length×synchrony method	20.00	7.14	<0.01	0.00
true synchrony×time lag×time length	2.00	2.65	0.07	0.00
κ×time length×synchrony method	20.00	4.28	<0.01	0.00
true synchrony×time lag×time length×synchrony method	20.00	3.26	<0.01	0.00
noise type	1.00	3.75	0.05	0.00
time lag×noise level	1.00	3.48	0.06	0.00
κ×time lag	2.00	1.49	0.23	0.00
κ×time lag×synchrony method	20.00	1.59	0.15	0.00
true synchrony×time lag	2.00	1.25	0.29	0.00
true synchrony×κ×time lag×time length	4.00	0.62	0.64	0.00
κ×noise level	2.00	1.21	0.30	0.00
κ×noise level×synchrony method	20.00	1.04	0.39	0.00
time lag×noise type	1.00	1.61	0.20	0.00
noise level×synchrony method	10.00	1.92	0.13	0.00
κ×noise type	2.00	0.65	0.52	0.00
true synchrony×κ×noise level×synchrony method	40.00	0.34	0.97	0.00
time length×noise level	1.00	0.94	0.33	0.00
true synchrony×κ×noise level	4.00	0.23	0.92	0.00
true synchrony×κ×time length×noise level×synchrony method	40.00	0.25	0.99	0.00
κ×noise type×synchrony method	20.00	0.49	0.79	0.00
true synchrony×time lag×noise level	2.00	0.39	0.68	0.00
true synchrony×κ×noise level×noise type×synchrony method	40.00	0.23	0.99	0.00
κ×time length×noise level×synchrony method	20.00	0.46	0.82	0.00
time lag×noise level×synchrony method	10.00	0.91	0.43	0.00
noise type×synchrony method	10.00	0.88	0.44	0.00
true synchrony×noise level×synchrony method	20.00	0.44	0.83	0.00
time length×noise level×synchrony method	10.00	0.78	0.49	0.00
true synchrony×time length×noise level×synchrony method	20.00	0.32	0.91	0.00
noise level×noise type×synchrony method	10.00	0.64	0.57	0.00
true synchrony×κ×time lag×noise level×noise type×synchrony method	40.00	0.14	1.00	0.00
time lag×noise level×noise type×synchrony method	10.00	0.56	0.62	0.00
true synchrony×κ×time lag×time length×noise level×synchrony method	40.00	0.13	1.00	0.00
true synchrony×κ×noise type	4.00	0.10	0.98	0.00
time lag×time length×noise level×synchrony method	10.00	0.50	0.66	0.00
time length×noise type×synchrony method	10.00	0.47	0.68	0.00
true synchrony×κ×time lag×time length×noise level	4.00	0.09	0.98	0.00
true synchrony×noise type×synchrony method	20.00	0.23	0.96	0.00
time length×noise type	1.00	0.36	0.55	0.00

true synchrony×κ×time lag×time length×noise level×noise type×synchrony method	40.00	0.11	1.00	0.00
time length×noise level×noise type×synchrony method	10.00	0.39	0.73	0.00
true synchrony×κ×time length×noise type×synchrony method	40.00	0.10	1.00	0.00
κ×time length×noise type×synchrony method	20.00	0.19	0.97	0.00
κ×time lag×time length×noise level×synchrony method	20.00	0.19	0.97	0.00
true synchrony×κ×noise type×synchrony method	40.00	0.09	1.00	0.00
true synchrony×κ×noise level×noise type	4.00	0.07	0.99	0.00
true synchrony×time lag×noise level×synchrony method	20.00	0.18	0.97	0.00
κ×time lag×time length×noise level	2.00	0.12	0.88	0.00
κ×time lag×noise level×noise type×synchrony method	20.00	0.15	0.98	0.00
true synchrony×time length×noise type×synchrony method	20.00	0.13	0.99	0.00
true synchrony×κ×time length×noise level×noise type×synchrony method	40.00	0.06	1.00	0.00
true synchrony×κ×time length×noise level	4.00	0.05	1.00	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	0.10	0.99	0.00
true synchrony×κ×time lag×time length×noise type×synchrony method	40.00	0.05	1.00	0.00
true synchrony×κ×time lag×noise level×synchrony method	40.00	0.05	1.00	0.00
κ×time lag×time length×noise level×noise type×synchrony method	20.00	0.10	0.99	0.00
true synchrony×noise level	2.00	0.07	0.93	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.09	0.99	0.00
κ×time length×noise type	2.00	0.07	0.93	0.00
true synchrony×time length×noise type	2.00	0.06	0.94	0.00
κ×time lag×noise type×synchrony method	20.00	0.08	1.00	0.00
time lag×noise type×synchrony method	10.00	0.15	0.91	0.00
true synchrony×κ×time lag×noise level×noise type	4.00	0.03	1.00	0.00
true synchrony×κ×time lag×time length×noise level×noise type	4.00	0.03	1.00	0.00
true synchrony×noise level×noise type×synchrony method	20.00	0.07	1.00	0.00
true synchrony×κ×time length×noise type	4.00	0.03	1.00	0.00
true synchrony×time lag×noise type	2.00	0.06	0.94	0.00
true synchrony×κ×time lag×noise type×synchrony method	40.00	0.03	1.00	0.00
κ×noise level×noise type×synchrony method	20.00	0.07	1.00	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.07	1.00	0.00
true synchrony×noise type	2.00	0.06	0.95	0.00
κ×noise level×noise type	2.00	0.05	0.95	0.00
κ×time length×noise level	2.00	0.04	0.96	0.00
κ×time length×noise level×noise type×synchrony method	20.00	0.05	1.00	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	0.05	1.00	0.00
true synchrony×time length×noise level	2.00	0.04	0.96	0.00
true synchrony×κ×time length×noise level×noise type	4.00	0.02	1.00	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.09	0.95	0.00
κ×time lag×time length×noise type	2.00	0.04	0.96	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.04	1.00	0.00
κ×time lag×noise level×synchrony method	20.00	0.04	1.00	0.00
true synchrony×time lag×time length×noise type	2.00	0.03	0.97	0.00
time lag×time length×noise type×synchrony method	10.00	0.08	0.96	0.00
true synchrony×time lag×time length×noise level	2.00	0.03	0.97	0.00
κ×time lag×time length×noise type×synchrony method	20.00	0.04	1.00	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.04	1.00	0.00
κ×time lag×noise level×noise type	2.00	0.03	0.97	0.00
true synchrony×κ×time lag×time length×noise type	4.00	0.01	1.00	0.00
true synchrony	2.00	0.02	0.98	0.00
true synchrony×noise level×noise type	2.00	0.02	0.98	0.00
κ×time length×noise level×noise type	2.00	0.02	0.98	0.00
true synchrony×time lag×noise level×noise type	2.00	0.02	0.98	0.00
true synchrony×κ×time lag×noise level	4.00	0.01	1.00	0.00
true synchrony×time length×noise level×noise type	2.00	0.02	0.98	0.00
κ×time lag×time length×noise level×noise type	2.00	0.01	0.98	0.00
time lag×noise level×noise type	1.00	0.03	0.86	0.00
time lag×time length×noise type	1.00	0.03	0.87	0.00
time length×noise level×noise type	1.00	0.03	0.87	0.00
true synchrony×κ×time lag×noise type	4.00	0.01	1.00	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
noise level×noise type	1.00	0.01	0.91	0.00
κ×time lag×noise type	2.00	0.00	0.99	0.00
κ×time lag×noise level	2.00	0.00	1.00	0.00
time lag×time length×noise level	1.00	0.00	0.95	0.00

time lag×time length×noise level×noise type	1.00	0.00	0.98	0.00

Table A8: ANOVA Table when Cor_{bc} is the dependent variable

Effects	DF	F-value	p-value	ges
synchrony method	10.00	2621.32	<0.01	0.28
time lag×synchrony method	10.00	2029.22	<0.01	0.23
time lag	1.00	262.89	<0.01	0.05
time length×synchrony method	10.00	128.81	<0.01	0.02
time lag×time length×synchrony method	10.00	111.96	<0.01	0.02
true synchrony×synchrony method	20.00	51.38	<0.01	0.01
true synchrony×time length×synchrony method	20.00	40.26	<0.01	0.01
true synchrony×κ	4.00	6.60	<0.01	0.01
noise level	1.00	23.17	<0.01	0.00
true synchrony×κ×time length	4.00	5.63	<0.01	0.00
true synchrony×κ×time lag	4.00	4.35	<0.01	0.00
true synchrony×κ×synchrony method	40.00	7.01	<0.01	0.00
true synchrony×time lag×synchrony method	20.00	13.00	<0.01	0.00
true synchrony×κ×time lag×synchrony method	40.00	6.84	<0.01	0.00
time length	1.00	14.79	<0.01	0.00
noise type	1.00	11.73	<0.01	0.00
true synchrony×time lag	2.00	5.21	0.01	0.00
κ×time lag	2.00	3.66	0.03	0.00
true synchrony×time length	2.00	3.88	0.02	0.00
κ×time length×synchrony method	20.00	8.04	<0.01	0.00
true synchrony×κ×time length×synchrony method	40.00	3.33	<0.01	0.00
true synchrony×time lag×time length×synchrony method	20.00	6.48	<0.01	0.00
κ×time lag×time length×synchrony method	20.00	6.96	<0.01	0.00
true synchrony×κ×time lag×time length×synchrony method	40.00	3.16	<0.01	0.00
κ	2.00	2.45	0.09	0.00
time lag×noise level	1.00	5.84	0.02	0.00
true synchrony×time lag×time length	2.00	2.79	0.06	0.00
true synchrony×κ×time lag×time length	4.00	0.90	0.46	0.00
κ×synchrony method	20.00	2.49	0.03	0.00
noise level×synchrony method	10.00	3.95	0.01	0.00
time lag×noise type	1.00	2.27	0.13	0.00
true synchrony	2.00	1.09	0.34	0.00
true synchrony×noise level×synchrony method	20.00	1.57	0.16	0.00
time lag×noise level×synchrony method	10.00	2.78	0.05	0.00
noise level×noise type×synchrony method	10.00	2.52	0.07	0.00
κ×time lag×synchrony method	20.00	1.24	0.28	0.00
true synchrony×κ×time lag×time length×noise level	4.00	0.41	0.80	0.00
κ×noise level×synchrony method	20.00	1.15	0.33	0.00
true synchrony×κ×time lag×time length×noise level×synchrony method	40.00	0.52	0.88	0.00
κ×noise level	2.00	0.60	0.55	0.00
κ×noise type	2.00	0.52	0.59	0.00
noise type×synchrony method	10.00	1.42	0.24	0.00
κ×time length×noise level×synchrony method	20.00	0.68	0.64	0.00
time length×noise level×synchrony method	10.00	1.35	0.26	0.00
κ×time lag×noise level×synchrony method	20.00	0.67	0.65	0.00
true synchrony×noise type×synchrony method	20.00	0.63	0.68	0.00
time lag×time length×noise level×synchrony method	10.00	1.19	0.31	0.00
κ×time lag×time length	2.00	0.40	0.67	0.00
true synchrony×time lag×noise level×synchrony method	20.00	0.52	0.76	0.00
κ×noise type×synchrony method	20.00	0.48	0.79	0.00
time lag×noise level×noise type×synchrony method	10.00	0.94	0.41	0.00
κ×time lag×time length×noise level	2.00	0.31	0.73	0.00
κ×time lag×time length×noise level×synchrony method	20.00	0.44	0.82	0.00
true synchrony×time lag×noise level	2.00	0.30	0.74	0.00
true synchrony×time length×noise level×synchrony method	20.00	0.39	0.86	0.00
true synchrony×κ×time lag×time length×noise type	4.00	0.13	0.97	0.00
true synchrony×κ×time lag×time length×noise type×synchrony method	40.00	0.19	1.00	0.00
time lag×time length	1.00	0.47	0.49	0.00
κ×time lag×noise type×synchrony method	20.00	0.34	0.89	0.00
κ×time length×noise type×synchrony method	20.00	0.32	0.90	0.00
true synchrony×κ×time lag×noise level	4.00	0.11	0.98	0.00

true synchrony×κ×time length×noise level×synchrony method	40.00	0.15	1.00	0.00
true synchrony×κ×time length×noise type	4.00	0.10	0.98	0.00
time length×noise level×noise type×synchrony method	10.00	0.53	0.63	0.00
true synchrony×κ×time length×noise level	4.00	0.08	0.99	0.00
κ×time lag×time length×noise level×noise type×synchrony method	20.00	0.24	0.94	0.00
time length×noise type×synchrony method	10.00	0.48	0.66	0.00
time lag×time length×noise type×synchrony method	10.00	0.47	0.67	0.00
time lag×noise type×synchrony method	10.00	0.45	0.68	0.00
κ×time length×noise level	2.00	0.15	0.86	0.00
κ×noise level×noise type×synchrony method	20.00	0.21	0.96	0.00
true synchrony×κ×noise level×noise type×synchrony method	40.00	0.10	1.00	0.00
κ×time length	2.00	0.14	0.87	0.00
true synchrony×time length×noise level	2.00	0.14	0.87	0.00
κ×time lag×time length×noise type	2.00	0.14	0.87	0.00
true synchrony×κ×time lag×noise level×noise type×synchrony method	40.00	0.08	1.00	0.00
true synchrony×time length×noise type	2.00	0.12	0.89	0.00
κ×time length×noise type	2.00	0.11	0.89	0.00
true synchrony×κ×time lag×noise level×synchrony method	40.00	0.08	1.00	0.00
κ×time lag×noise level×noise type×synchrony method	20.00	0.15	0.98	0.00
true synchrony×κ×noise level×synchrony method	40.00	0.07	1.00	0.00
κ×time lag×time length×noise type×synchrony method	20.00	0.13	0.98	0.00
true synchrony×κ×time lag×noise type	4.00	0.04	1.00	0.00
κ×noise level×noise type	2.00	0.08	0.93	0.00
time lag×time length×noise level×noise type×synchrony method	10.00	0.21	0.86	0.00
true synchrony×time lag×time length×noise level	2.00	0.07	0.93	0.00
true synchrony×κ×time length×noise type×synchrony method	40.00	0.05	1.00	0.00
true synchrony×time lag×noise type	2.00	0.06	0.94	0.00
true synchrony×time length×noise type×synchrony method	20.00	0.09	0.99	0.00
κ×time lag×noise level	2.00	0.06	0.94	0.00
true synchrony×time length×noise level×noise type×synchrony method	20.00	0.09	0.99	0.00
true synchrony×κ×time lag×noise type×synchrony method	40.00	0.04	1.00	0.00
true synchrony×κ×time length×noise level×noise type×synchrony method	40.00	0.04	1.00	0.00
κ×time lag×noise level×noise type	2.00	0.06	0.95	0.00
true synchrony×time length×noise level×noise type	2.00	0.05	0.95	0.00
true synchrony×κ×time lag×time length×noise level×noise type	4.00	0.03	1.00	0.00
true synchrony×κ×noise level×noise type	4.00	0.02	1.00	0.00
true synchrony×κ×noise level	4.00	0.02	1.00	0.00
true synchrony×κ×time lag×time length×noise level×noise type×synchrony method	40.00	0.03	1.00	0.00
true synchrony×κ×noise type×synchrony method	40.00	0.03	1.00	0.00
true synchrony×noise level	2.00	0.04	0.96	0.00
true synchrony×time lag×time length×noise type×synchrony method	20.00	0.06	1.00	0.00
true synchrony×time lag×time length×noise level×synchrony method	20.00	0.05	1.00	0.00
true synchrony×noise level×noise type×synchrony method	20.00	0.05	1.00	0.00
time lag×noise level×noise type	1.00	0.07	0.79	0.00
κ×time length×noise level×noise type×synchrony method	20.00	0.05	1.00	0.00
noise level×noise type	1.00	0.06	0.81	0.00
true synchrony×time lag×noise type×synchrony method	20.00	0.04	1.00	0.00
true synchrony×time lag×noise level×noise type×synchrony method	20.00	0.04	1.00	0.00
true synchrony×κ×time lag×noise level×noise type	4.00	0.01	1.00	0.00
true synchrony×κ×noise type	4.00	0.01	1.00	0.00
time length×noise level	1.00	0.05	0.83	0.00
true synchrony×time lag×time length×noise type	2.00	0.02	0.98	0.00
κ×time lag×noise type	2.00	0.02	0.98	0.00
time length×noise type	1.00	0.04	0.84	0.00
time lag×time length×noise level	1.00	0.03	0.86	0.00
true synchrony×noise type	2.00	0.02	0.98	0.00
time lag×time length×noise type	1.00	0.03	0.86	0.00
κ×time length×noise level×noise type	2.00	0.02	0.98	0.00
true synchrony×time lag×time length×noise level×noise type×synchrony method	20.00	0.02	1.00	0.00
true synchrony×κ×time length×noise level×noise type	4.00	0.01	1.00	0.00
true synchrony×time lag×noise level×noise type	2.00	0.01	0.99	0.00
true synchrony×noise level×noise type	2.00	0.01	0.99	0.00
true synchrony×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
κ×time lag×time length×noise level×noise type	2.00	0.01	0.99	0.00
time length×noise level×noise type	1.00	0.01	0.92	0.00

time lag×time length×noise level×noise type	1.00	0.00	1.00	0.00