A mechanism of timing variability underlying the association between the mean and SD of asynchrony

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ABSTRACT

Sensorimotor timing behaviors typically exhibit an elusive phenomenon known as the negative asynchrony. When synchronizing movements (e.g. finger taps) with an external sequence (e.g. a metronome), people's taps precede event onsets by a few tens of milliseconds. We recently reported that asynchrony is less negative in participants with lower asynchrony variability. This indicates an association between negative asynchrony and variability of timing. Here, in 24 metronome-synchronization data sets, we modeled asynchrony series using a sensorimotor synchronization model that accounts for serial dependence of asynchronies. The results showed that the modeling well captured the negative correlation between the mean and SD of asynchrony. The finding suggests that serial dependence in asynchronies is an essential mechanism of timing variability underlying the association between the mean and SD of asynchrony.

1. Introduction

Timing is essential for cognitive functions (Ivry, 1996; Mauk & Buonomano, 2004), and coordination of motor output with sensory input requires precise temporal processing in the range of tens to hundreds of milliseconds (Iversen & Balasubramaniam, 2016; Repp & Su, 2013). Sensorimotor timing research typically requires participants to tap in synchrony with a temporally regular sequence (i.e. a metronome) (Iversen & Balasubramaniam, 2016; Patel, 2014). One of the best-known phenomena in sensorimotor timing is that people tend to tap ahead of the timed events by a few tens of milliseconds (Repp & Su, 2013; Repp, 2005). This phenomenon of negative asynchrony is also termed synchronization error or anticipation tendency. Because the mean of asynchronies, i.e. the differences between the times of the taps and the times of the corresponding event onsets, is typically negative, negative asynchrony is often described as negative mean asynchrony (Aschersleben, 2002; Repp, 2005). Negative asynchrony is generally considered to reflect anticipatory behaviors (Aschersleben, 2002; Patel, 2014). However, it has already been pointed out

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that anticipatory responses do not need to precede the stimulus as long as the response time is shorter than approximately 150 ms, the minimum reaction time (Mates, Radil, & Pöppel, 1992). Despite extensive research on the possible mechanisms underlying negative asynchrony, little progress has been made in finding an explanation for the negative asynchrony (for reviews, see Repp, 2005; Repp & Su, 2013).

Recently, a study reported a correlation between the mean ($MEAN_{asy}$) and standard deviation (SD_{asy}) of asynchrony: asynchrony is less negative in participants with lower asynchrony variability (Yang et al., 2018). In this study, we systematically investigated 24 metronome-synchronization data sets involving different experimental settings. The negative $MEAN_{asy}$-SD_{asy} correlation was demonstrated by meta analyses across the data sets. The analyses also revealed that the negative $MEAN_{asy}$-SD_{asy} correlation is related to the lag 1 autocorrelation (AC-1) of inter-response intervals (IRI). The AC-1 of IRIs is a measure of serial dependence in time series often adopted in sensorimotor studies (Gan, Huang, Zhou, Qian, & Wu, 2015; Hove, Spivey, & Krumhansl, 2010; Iversen, Patel, Nicodemus, & Emmorey, 2015; Mu, Huang, Ji, Gu, & Wu, 2018; Vorberg & Wing, 1996). Statistically negative AC-1 of IRIs suggests the involvement of error correction and is an indicator that subjects are capable of synchronizing to a sequence (Hove & Keller, 2010; Hove et al., 2010; Iversen et al., 2015; Vorberg & Wing, 1996). In Yang et al. (2018), reliably negative $MEAN_{asy}$-SD_{asy} correlation was likely to be observed in 21 of the 24 data sets in which the AC-1 of IRIs was statistically negative. In the other 3 data sets that were difficult to tap with and had a statistically non-negative AC-1 of IRIs, reliably negative $MEAN_{asy}$-SD_{asy} correlation was unlikely to be observed. An important implication of the observed negative $MEAN_{asy}$-SD_{asy} correlation to the understanding of negative asynchrony is that it suggests an association between negative asynchrony and timing variability. Variability of timing has been suggested to play an essential role in understanding cognitive functions such as perception, attention, motor control, and music (Vorberg & Wing, 1996; Wagenmakers, Farrell, & Ratcliff, 2004). For sensorimotor timing, the SD of asynchrony represents the global measure of timing variability of synchronization, and the AC-1 of IRIs is often studied indicating serial dependence in time series (for review, see Repp, 2005; Repp & Su, 2013). However, the significance of timing variability for the phenomenon of negative asynchrony has not been under consideration. The finding of the negative $MEAN_{asy}$-SD_{asy} correlation suggests a direct link between negative asynchrony and the global measure of timing variability. This link is also suggested to be related to serial dependence in time series.

Although the negative mean-SD correlation of asynchrony suggests an association between negative asynchrony and variability of timing, detailed mechanisms of timing variability remain unclear. Cognitive research usually focuses on measuring the mean of performance, whereas performance fluctuations in time are typically treated as residual errors or noises. In this regard, studies have emphasized the role of timing variability in cognitive functions, particularly in terms of short-range trial-to-trial serial dependence in time series (Vorberg & Wing, 1996; Wagenmakers et al., 2004). Serial dependence are typically evaluated by lags 0–2 of the auto-covariance function or the autocorrelation function, which is the autocovariance function normalized by the lag 0 autocovariance. Positive AC-1 of IRIs is characterized by successive short or successive long tap intervals and suggests that tap intervals drift away from the inter stimulus onset interval (ISI). In contrast, negative AC-1 of IRIs is characterized by alternating shorter and longer tap intervals and may suggest error correction preventing the drift (Hove & Keller, 2010; Hove et al., 2010; Iversen et al., 2015; Vorberg & Wing, 1996).

The negative mean-SD correlation of asynchrony, as introduced above, is related to the AC-1 of IRIs. A general relation between the negative $MEAN_{asy}$-SD_{asy} correlation and serial dependence was indicated in our previous study, with respect to the statistically negative or non-negative AC-1 of IRIs that roughly differentiated between Data sets 1–21 and Data sets 22–24. This general relation, however, was incapable of interpreting the differences among individual data sets (see Fig. 2 in Yang et al. (2018)). Therefore, whether the negative $MEAN_{asy}$-SD_{asy} correlation could be accounted for by mechanisms of serial dependence remains unanswered. In order to reveal variability and dependence in timing, sensorimotor research has a long history of modeling time series (for reviews, see Vorberg & Wing, 1996; Vorberg & Schulze, 2002; Repp, 2005). Specifically, modeling work of sensorimotor synchronization has developed a linear model in which asynchrony in metronome tapping is described by an internal interval, a motor delay, and an error correction factor (Vorberg & Wing, 1996). This sensorimotor synchronization model has provided satisfied accounts for the auto-covariance or autocorrelation function of asynchronies (Jacoby, Tishby, Repp, Ahissar, & Keller, 2015; Repp, Keller, & Jacoby, 2012; Vorberg & Schulze, 2002; Vorberg & Wing, 1996). Therefore, a question is whether the mean-SD correlation of asynchrony could be captured by the modeling that accounts for the autocovariance function of asynchronies. This is addressed in the present study.

Together, the finding of the negative mean-SD correlation of asynchrony indicates an association between negative asynchrony and variability of timing (Yang et al., 2018). The purpose of the present study is to investigate the underlying mechanism of timing variability, using a linear sensorimotor synchronization model accounting for serial dependence of asynchronies (Jacoby et al., 2015; Vorberg & Wing, 1996). Specifically, the current modeling study aims to extend the experimental study of Yang et al. (2018) by examining whether the model could capture the mean-SD correlation of asynchrony.

2. Material and methods

The data have been described in detail in Yang et al. (2018); here we concisely introduce the experimental data and analysis, and then focus on describing the modeling analysis.

2.1. Participants

There were 24 metronome-synchronization data sets. The data sets were from eight experiments. Data set 1 in Experiment 1 had 31 participants. Data set 2 in Experiment 2 had 13 participants. Data set 3 in Experiment 3 had 19 participants. Data sets 4–7 and 22–23 in Experiment 4 had 15 participants. Data sets 8–14 and 24 in Experiment 5 had 14 participants. Data sets 15–17 in

Experiment 6 had 17 participants. Data sets 18–19 in Experiment 7 had 15 participants. Data sets 20–21 in Experiment 8 had 15 participants. The research protocols in this study were approved by the Institutional Review Board of Psychology Department of Sun Yat-Sen University. All participants gave written informed consent.

2.2. Stimuli and procedure

Each of the 24 data sets had three stimulus sequences. All the experiments used the same task of synchronizing finger taps to a temporally regular sequence. The data sets involved different experimental settings, including stimulus duration (10–100 ms), ISI (300–900 ms), number of sequence events (55–200 events), modality of stimulus presentation (audition or vision, including auditory sounds, visual flashes, or visual bouncing balls), whether auditory feedback was provided, and whether a sequence type was appropriate for synchronization. Synchronization appropriateness generally describes whether synchronization to a sequence is performed without much difficulty.

2.3. Data analyses

The raw experimental tapping data consisted of sequences of tap times. Asynchrony was defined as the difference between the time of a tap and the time of the corresponding event onset. The $MEAN_{asy}$ and SD_{asy} were computed. For each participant, the $MEAN_{asy}$ and SD_{asy} were calculated for individual sequences and averaged across sequences. Pearson correlation coefficient was used to measure the correlation between the $MEAN_{asy}$ and SD_{asy}. For all data sets, both the $MEAN_{asy}$ and SD_{asy} satisfied the normality assumption (Kolmogorov-Smirnov test, $p > 0.05$). The taps to the first five events in each sequence were omitted from analyses. Invalid taps included the missing taps, multiple taps, or taps with excessive asynchrony variation. The asynchrony to an event with invalid taps was interpolated with the average of the asynchronies of its neighboring events (three preceding and three following events). The interpolation approach was used because the linear model adopted in the present study and the computation of the AC-1 of IRIs required successive taps (Jacoby et al., 2015; Mu et al., 2018). The sequence in which the events with invalid taps exceeded 10% was excluded (see details in Yang et al. 2018).

Several notes about the analyses would be mentioned. (1) The $MEAN_{asy}$ and the SD_{asy} can be calculated by the standard linear analysis method and the circular analysis method (Fisher, 1993). The present study used the linear method because the linear sensorimotor synchronization model is based on linear calculation (Jacoby et al., 2015; Vorberg & Wing, 1996). The current data sets involved different ISIs. It is well-known that the linear $MEAN_{asy}$ and SD_{asy} increase as the ISI increases (Repp & Su, 2013), thus a potential concern could be whether the present $MEAN_{asy}$-SD_{asy} correlation is affected by the influence of tempi. First, the influence of tempi can be treated by a normalization procedure. Take the commonly adopted coefficient of variation as an example. The coefficient of variation represents SD_{asy} /t (t refers to the ISI) and is a solution for SD_{asy} when different tempi are involved. Note that it was the mean-SD correlation of asynchrony that was investigated in the present study. When both the mean and SD of asynchrony are divided by t, it is easy to prove that corr(mean, SD) = corr(mean/t, SD/t). Second, the concern can also be clarified by using the circular analysis method. In the circular method asynchrony is not affected by tempi because asynchronies for different tempi are all transformed to the relative phase on a unit circle. As has been proved in Yang et al. (2018), the linear and circular results were consistent. (2) The Rayleigh test of uniform distribution of responses is often considered to assess whether a sequence was successfully synchronized (Hove et al., 2010). For the current data sets, the Rayleigh test yielded consistent results (Yang et al., 2018). Moreover, the present data sets had different levels of synchronization performance and Data sets with lower SD_{asy} values would also be informative in evaluating the $MEAN_{asy}$-SD_{asy} correlation. Therefore, the present analyses were carried out without performing the Rayleigh test.

For modeling, Vorberg and Wing (1996) modeled asynchrony (A) of metronome synchronization with an internal interval T, a motor delay M, and an error correction factor α:

$$A_{n+1} = (1 - \alpha)A_n + (T_n + M_{n+1} - M_n) - \pi$$

where π refers to the ISI. This linear sensorimotor synchronization model was used in modeling the current asynchrony sequences by the bounded generalized least squares (bGLS) method (https://doi.org/10.6084/m9.figshare.1391910) (Jacoby et al., 2015). First, model parameters were estimated for each sequence of each participant. The error correction factor (α), the standard deviation of the internal interval (T_{SD}), and standard deviation of the motor delay (M_{SD}) were computed using the bGLS function "*bGLS_phase_model_single_and_multiperson*". To estimate the mean of the internal interval (T_{mean}), 400 asynchrony sequences were simulated with the three parameters estimated above and the T_{mean} ranging from $(1 - 1/3)$ ISI to $(1 + 1/3)$ ISI in the step of 1/600 ISI, using a modified version of the bGLS function *Simulate_phase_correction_non_isochronous*. The goodness-of-fit between the mean asynchrony of the experimental asynchrony sequence and that of a simulated asynchrony sequence was determined by computing the root mean square error. The value of T_{mean} that yielded the smallest root mean square error was taken as the best-fitting estimate of T_{mean}. Second, a simulated asynchrony sequence was generated with the four estimated parameters for each sequence of each participant, using the modified version of the bGLS function *Simulate_phase_correction_non_isochronous*. This simulation procedure was repeated 1000 times.

3. Results

The experimental results of the correlation between the $MEAN_{asy}$ and SD_{asy}, as well as the $MEAN_{asy}$, the SD_{asy}, and the AC-1 of IRIs, have been presented in detail in Yang et al. (2018). Here we first concisely describe the experimental results of the $MEAN_{asy}$-
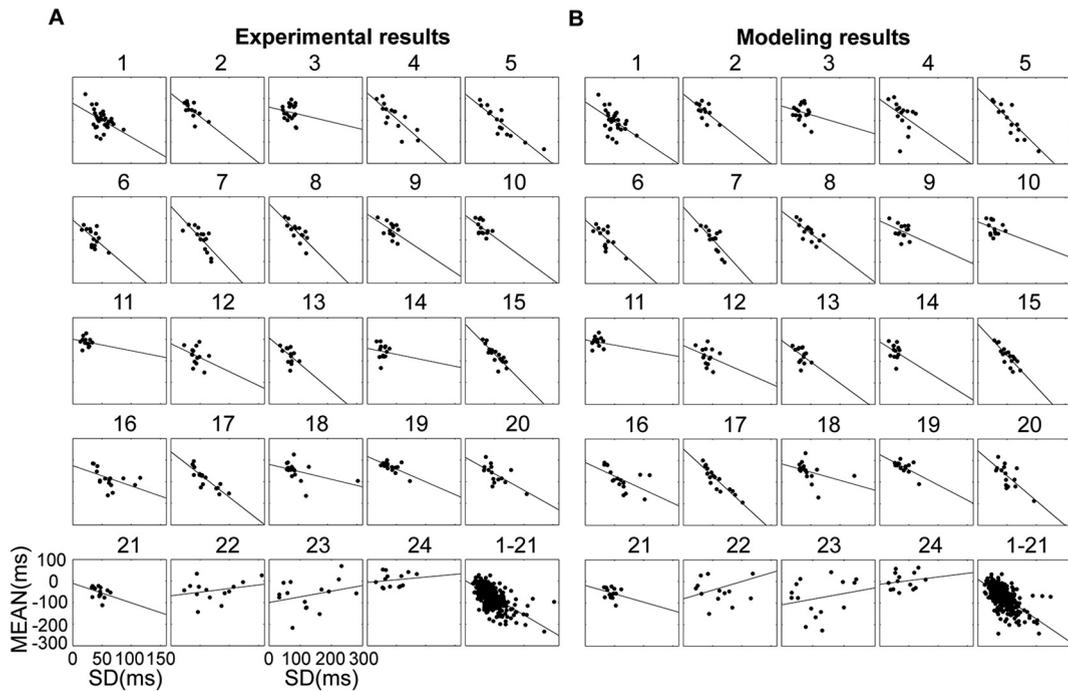
Fig. 1. Correlation between the $MEAN_{asy}$ and SD_{asy} for twenty-four metronome-synchronization data sets. **A** depicts experimental results, showing a negative $MEAN_{asy}$-SD_{asy} correlation in 21 (1–21) out of the 24 data sets. Data points represent the data from individual participants. The bottom-right image shows the pooled data of Data sets1-21. All images were plotted on the same axes as displayed in the bottom-left image (except for Data set 23 in which the x axis is 0–300 ms). **B** shows modeling results, in which experimental asynchrony sequences were modeled using a linear sensorimotor synchronization model. After estimation of model parameters, simulated asynchrony sequences were generated and the simulation procedure was repeated 1000 times. The simulated data of one representative simulation run are plotted, showing that the negative $MEAN_{asy}$-SD_{asy} correlation was well captured by the model.

SD_{asy} correlation, for a convenient comparison with the modeling results. After that, we focus on the modeling results of the $MEAN_{asy}$-SD_{asy} correlation. Visual inspection of the experimental results (Fig. 1A) indicated that the direction of the negative $MEAN_{asy}$-SD_{asy} correlation was present in 21 (Data sets 1–21) out of the 24 data sets. A meta-analysis across 24 data sets confirmed the reliability of the negative $MEAN_{asy}$-SD_{asy} correlation. Further analyses relying on confidence intervals (CI) revealed that reliably negative $MEAN_{asy}$-SD_{asy} correlation was likely to be observed in Data sets 1–21 that had a statistically negative AC-1 of IRIs. The $MEAN_{asy}$-SD_{asy} correlation was statistically negative for 13 out of the 21 data sets with a statistical criterion of $p < 0.05$. In Data sets 22–24, which displayed a statistically non-negative AC-1 of IRIs, reliably negative $MEAN_{asy}$-SD_{asy} correlation was unlikely to be observed. Note that, despite of the difference between Data sets 1–21 and Data sets 22–24 in terms of the statistically negative or non-negative AC-1 of IRIs, the AC-1 of IRIs did not provide more information to interpret the differences in the negative $MEAN_{asy}$-SD_{asy} correlation among individual data sets.

We examined whether the negative $MEAN_{asy}$-SD_{asy} correlation observed in the experimental results could be captured in the modeling accounting for serial dependence of asynchronies. A linear sensorimotor synchronization model (Vorberg & Wing, 1996) was adopted. We used the bounded generalized least squares method (Jacoby et al., 2015) to determine the parameters corresponding to the correction factor, the mean and standard deviation of the internal interval, and the standard deviation of the motor delay. These parameter estimates were used to simulate the data for 1000 times. The simulated data of one representative simulation run is presented in Fig. 1B. Visual inspection suggests that the modeled data well captured the $MEAN_{asy}$- SD_{asy} correlation.

The mean and SD of the four estimated model parameters are listed in Table S1. For the 1000 simulation runs, the distributions of the $MEAN_{asy}$-SD_{asy} correlation *r* values are presented in Fig. S1, and the mean and 95% CI of the $MEAN_{asy}$-SD_{asy} correlation *r* values are listed in Table 1. As shown in Table 1, in all the 24 data sets with the only exception of Data set 4, the mean and the 95% CI of the $MEAN_{asy}$-SD_{asy} correlation *r* values in the simulate data fell within the 95% CI of the $MEAN_{asy}$-SD_{asy} correlation r value in the experimental data. This confirmed that the modeling provided good accounts for the negative $MEAN_{asy}$-SD_{asy} correlations observed in experimental data.

4. Discussion

The present study modeled asynchrony series in 24 metronome-tapping data sets using a sensorimotor synchronization model that accounts for serial dependence of asynchronies. The results showed that the modeling well captured the empirical finding of a negative correlation between the mean and SD of asynchrony.

Table 1

The mean, 95% CI, and range of the $MEAN_{asy}$-SD_{asy} correlation r values in the modeling results. For each data set, the $MEAN_{asy}$-SD_{asy} correlation was calculated for each of the 1000 simulation runs. The mean, 95% CI, and range were computed for the correlation r values of the 1000 simulation runs. The 95% CIs of the $MEAN_{asy}$-SD_{asy} correlation r values in the experimental results were also listed. Data set 4 is marked in Bold because its 95% CI of the simulate data fell out of its 95% CI of the experimental data. This may be may be related to the sampling bias due to the small sample size (Yang et al., 2018). Other conventions are as in Fig. 1.

Data set	Modeling results			Experimental results
	Mean	95% CI	Range	95% CI
1	−0.40	[−0.41–0.40]	[−0.55–0.25]	[−0.70, −0.13]
2	−0.60	[−0.60–0.59]	[−0.77–0.42]	[−0.90, −0.22]
3	−0.09	[−0.10–0.09]	[−0.48 0.30]	[−0.56, 0.34]
4	**−0.47**	**[−0.48–0.47]**	**[−0.76–0.21]**	**[−0.93, −0.49]**
5	−0.85	[−0.86–0.85]	[−0.97–0.59]	[−0.96, −0.69]
6	−0.66	[−0.67–0.66]	[−0.82–0.48]	[−0.86, −0.16]
7	−0.65	[−0.65–0.64]	[−0.83–0.35]	[−0.91, −0.37]
8	−0.70	[−0.70–0.69]	[−0.89–0.41]	[−0.92, −0.40]
9	−0.50	[−0.50–0.49]	[−0.74–0.20]	[−0.81, 0.06]
10	−0.41	[−0.42–0.41]	[−0.73–0.05]	[−0.81, 0.04]
11	−0.06	[−0.07–0.05]	[−0.42 0.33]	[−0.63, 0.41]
12	−0.26	[−0.26–0.25]	[−0.56 0.09]	[−0.73, 0.25]
13	−0.58	[−0.58–0.57]	[−0.82–0.38]	[−0.82, 0.01]
14	−0.06	[−0.07–0.05]	[−0.47 0.28]	[−0.60, 0.46]
15	−0.74	[−0.74–0.74]	[−0.93–0.49]	[−0.94, −0.61]
16	−0.53	[−0.53–0.52]	[−0.75–0.16]	[−0.79, −0.03]
17	−0.80	[−0.81–0.80]	[−0.92–0.61]	[−0.95, −0.65]
18	−0.38	[−0.39–0.37]	[−0.67–0.05]	[−0.76, 0.04]
19	−0.66	[−0.66–0.66]	[−0.83–0.48]	[−0.87, −0.29]
20	−0.71	[−0.71–0.70]	[−0.86–0.51]	[−0.87, −0.22]
21	−0.27	[−0.27–0.26]	[−0.51 0.04]	[−0.73, 0.21]
22	0.20	[0.19 0.21]	[−0.48 0.70]	[−0.22, 0.72]
23	0.17	[0.16 0.18]	[−0.45 0.69]	[−0.26, 0.70]
24	0.21	[0.20 0.21]	[−0.27 0.58]	[−0.41, 0.63]

The AC-1 of IRIs only differentiated between the mean-SD correlations of asynchrony in Data sets 22–24 and Data sets 1–21 (Yang et al., 2018). The present modeling of asynchronies was capable of identifying the differences in the mean-SD correlation of asynchrony among individual data sets. Therefore, although the AC-1 of IRIs and the present sensorimotor synchronization modeling both evaluated serial dependence of time series, the latter provided a much better account for the negative mean-SD correlation of asynchrony. This would be related to the differences between the two methods. First, when assessing the autocovariance or autocorrelation function, the AC-1 of IRIs is a measure examining the lag 1. The modeling does not have such restriction and the data would be interpreted more comprehensively (Vorberg & Wing, 1996; Vorberg & Schulze, 2002; see further details of the currently adopted implementation in Jacoby et al., 2015). Second, the AC-1 of IRIs measures inter-response interval series whereas the modeling measures asynchrony series. The IRI and asynchrony are not independent and can be mutually converted by the basic equation $I_n = \pi + A_{n+1} − A_n$, where I refers to the IRI (this is Equation 17 in Vorberg & Wing, 1996). Nevertheless, it has been suggested that asynchrony series could be more fundamental than IRI series with respect to "the role played by the error time series" (page 4503 in Chen, Ding, & Kelso, 1997). The present study primarily concerned asynchrony series, and future studies might clarify the relation between asynchrony series and IRI series further.

The present results suggest that less negative asynchrony is associated with lower variability. It is worth mentioning that the current finding appears to be conflicting with an assumption that negative asynchrony occurs when attempting to optimize tapping variability (Vorberg & Wing, 1996). The model of Vorberg and Wing is neutral with respect to the polarity of the mean of asynchrony, suggesting that a negative mean could occur when participants try to minimize the variance of their asynchronies (page 206 in Vorberg & Wing, 1996). This assumption aims to explain the sign of mean asynchrony but not to interpret how the extent of negative asynchrony changes with variability. It, however, indicates that as variability decreases, mean asynchrony changes from zero to negative. This assumption was proposed purely based on optimization of dynamic systems and is lacking empirical supports. The seeming conflict between the current finding and the prediction of the assumption would be further addressed.

In summary, the phenomenon of negative asynchrony in sensorimotor timing remains poorly understood (Repp & Su, 2013). Our recent finding of a negative mean-SD correlation of asynchrony indicates an association between negative asynchrony and variability of timing (Yang et al., 2018). The present study extends the study of Yang et al. (2018) by showing that the negative mean-SD correlation of asynchrony is well captured by a linear sensorimotor synchronization model accounting for serial dependence in asynchrony series. The results suggest that serial dependence in asynchronies is an essential mechanism for the association between negative asynchrony and timing variability, which has important implications for the understanding of the negative asynchrony. Instead of considering performance fluctuation over successive trials as random noise, serial dependence in time series emphasizes the influences of current behavior by past behavior and reflects the ability to adjust behavior (Iversen et al., 2015; Vorberg & Wing, 1996; Wagenmakers et al., 2004). The current findings indicate that people with stronger behavioral adjustments as indicated by

serial dependence in time series would have lower variability of timing, and that asynchronies of these people would be less negative. This would be further clarified in future research, particularly by employing more elaborate timing modeling (e.g. Wagenmakers et al., 2004).

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Author contributions

WX conceived the research; YJK, OYFY, LH, and WX designed the research; YJK, HYY, GLY, ZL, CHZ, WMY, and HMX collected experimental data; YJK analyzed experimental data; OYFY, YJK, and LH conducted model simulation, ZS, and YB were involved in the discussion of data; YJK, OYFY, LH, and WX wrote the manuscript. All authors commented on and edited the manuscript.

Data availability

The data generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.102500.

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