Asymmetric Error Correction in the Synchronization Tapping Task

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Received 30 September 2021; accepted 8 September 2023

Abstract
In synchronization tapping tasks, tapping onset often precedes metronome one by a few tens of milliseconds, which is known as negative mean asynchrony. However, the mechanism by which negative mean asynchrony occurs remains incompletely understood. This study hypothesized that one of the mechanisms was the asymmetric error correction process for asynchrony. We examined this hypothesis using a generalized linear mixed model. The results suggested that the error correction rate for the positive asynchrony was larger than that for the negative asynchrony. This finding may contribute to improving mathematical models of the synchronization tapping task.

Keywords
rhythm, synchronization tapping, negative mean asynchrony, Paillard–Fraisse hypothesis, sensory accumulation hypotheses

1. Introduction
Humans sometimes dance to the beat of music, which has been studied as sensorimotor synchronization (SMS). The principal method for examining humans’ SMS ability is the synchronization tapping task, in which subjects are required to tap along with metronome sounds (see Repp, 2005; Repp & Su, 2013 for a review). One of the best-known phenomena in the synchronization tapping task is that tapping onset tends to precede metronome onset by a few tens of milliseconds (negative mean asynchrony (NMA); e.g., Aschersleben, 2002).
Recent studies have contributed to revealing the characteristics of NMA. For instance, less NMA is associated with low tapping variability (Yang et al., 2019, 2020). In addition, Lagarde (2021) suggested the possibility of the culture dependence of NMA, showing that Indians did not necessarily exhibit it.

Meanwhile, the mechanism by which NMA occurs remains an open question. The Paillard–Fraisse hypothesis is one of the major hypotheses regarding why NMA occurs (Fraisse, 1980; Paillard, 1946). This hypothesis proposes that NMA is caused by the difference in the speeds at which auditory (metronome sounds) and tactile (tapping) stimuli are transmitted to the central nervous system. Therefore, the subjects need to tap a few tens of milliseconds ahead of the metronome to subjectively tap at the same time as the metronome. Similarly, Aschersleben (2002) also proposed the sensory accumulation hypothesis, which hypothesized subjective synchrony is achieved with accumulation at different rates from different sensory channels (auditory and tactile). Corresponding to these hypotheses, a mathematical model that includes parameters of perceptual and motor delays has been proposed, which is known as the linear phase correction model (e.g., Jacoby et al., 2015; Vorberg & Schulze, 2002).

However, these hypotheses do not explain all the mechanisms by which NMA occurs. From the viewpoint of the Paillard–Fraisse and sensory accumulation hypotheses (Aschersleben, 2002; Fraisse, 1980; Paillard, 1946), we could anticipate that NMA would not occur when both the onsets of the stimulus and the finger tap were presented to the subject as auditory stimuli. Nevertheless, previous studies showed that NMA did not disappear under these experimental conditions. For instance, when auditory feedback from tapping was presented to the subject, NMA did not disappear, although it did decrease (Aschersleben & Prinz, 1995). Similarly, NMA did not disappear when subjects were required to synchronize to the metronome through vocalizing, which was accompanied by auditory feedback by its nature, and not by tapping (Castro-Meneses & Sowman, 2018).

In this study, we focused on the asymmetric error correction process, another potential mechanism of NMA. Müller et al. (1999) proposed an asymmetric error correction process. They assumed that the correction rate for asynchrony \((n + 1)\) was larger in the negative direction when asynchrony \(n\) was positive than when it was negative. If asymmetric error correction occurs, the average tapping timing should have negative values (negative mean asynchrony; NMA). However, Müller et al. (1999) suggested the existence of this asymmetric error correction process with qualitative examination of a scatter plot of asynchrony in tap \(n\) and tap \((n + 1)\) without conducting a statistical analysis (Müller et al., 1999). To the best of our knowledge, further research based on this finding has not been conducted. Additionally, the linear phase correction model does not have a parameter accounting for this asymmetric error correction.

Here, this study investigated the existence of the asymmetric error correction process in the synchronization tapping task using a generalized linear mixed model.
model (GLMM). GLMM enabled us to incorporate the effect of the sign of asynchrony. Thus, the correction rates for positive and negative asynchrony could be estimated separately. We hypothesized that the correction rate would be larger for positive asynchrony than for negative asynchrony.

2. Methods

2.1. Data

This study used an open dataset (dataset16) from Yang et al. (2020). The subjects were required to synchronize their tap with metronome sounds 200 times in a row in a session (Yang et al., 2020). The interonset interval (IOI) of the metronome was 600 ms. The experiment was conducted over three sessions; a total of 600 taps were required. Auditory feedback from one’s tapping was not presented in the task. The dataset consisted of the metronome and the tapping onsets in the synchronization tapping task. The study enrolled 17 subjects who had normal hearing. All subjects were right-handed.

2.2. Analysis

2.2.1. Data Processing

Ideally, 600 taps should have been obtained for each subject in Yang et al. (2020). However, subjects occasionally fail to tap with the metronome. Therefore, a time window of 300 ms (1/2 of the IOI) was set before and after metronome onset. The nearest tap onset to each metronome in the time window was regarded as a tapping response related to the stimulus (e.g., Tomyta & Seki, 2020). When tapping onset was outside the window, the tap was excluded from further analysis. After analyzing the tap timing (to two decimal places), we divided the taps into time windows. This data processing is later referred to as ‘Data Exclusion’. Although data processing has been previously applied in the synchronization tapping task, the exclusions might have been arbitrary. To increase the reliability of the analysis, we also performed another data-processing step, which we refer to as ‘Data Inclusion’. During this data-processing step, we established a time window of 300 ms (1/2 of the IOI) before and after metronome onset, similar to Data Exclusion. However, this process included and analyzed all tapping in all time windows. This study mainly reports the results of Data Exclusion. The results of Data Inclusion are described in the Supplementary Materials (See ‘Additional Analyses 1. GLMM with Data Inclusion’).

Then, we calculated the asynchrony or the timing difference between tap and metronome onset (equation 1):

\[
\text{asynchrony (n)} = \text{tapping onset (n)} - \text{metronome onset (n)}
\]  

(1)
From this equation, the asynchrony had a negative or positive value when the subject’s tap preceded or followed the metronome respectively.

2.3. Statistical Analysis

2.3.1. Test of Normality
The Kolmogorov–Smirnov test (K–S test) was performed to examine whether subjects’ asynchrony followed a normal distribution.

2.3.2. GLMM
This study examined the existence of the asymmetric error correction process using GLMM with subject and session as random effects. First, regression equation (2) was considered the simplest equation, which explained the asynchrony \((n + 1)\) based on the asynchrony \((n)\) without an asymmetry error correction process. This was an autoregressive model similar to that performed in many previous studies (e.g., Timmers et al., 2014; Wing et al., 2014):

\[
asynchrony (n + 1) = \beta_0 + \beta_1 \times \text{asynchrony} (n)
\]

where \(\beta_0\) is the intercept, and \(\beta_1\) represents the error correction rate (the degree to which the subject adjusts asynchrony \([n + 1]\) from asynchrony \([n]\)). The dependent variable was asynchrony \((n + 1)\) in this model. We named this model the symmetric error correction model. Moreover, the asymmetry error correction process is expressed in equation 3.

\[
asynchrony (n + 1) = \beta_0 + \beta_1 \times \text{asynchrony} (n) + \beta_2 \times \text{asynchrony} (n) \times \text{Sign} \times \text{Error} (n)
\]

where not only \(\beta_1\) but also \(\beta_2\) represents the error correction rate, and the sign of error is a dummy variable. In this model, the dependent variable was also asynchrony \((n + 1)\). We named this model the asymmetric error correction model. When the asynchrony \((n)\) was positive or negative, ‘1’ or ’0’ was assigned to the sign of error so that the error correction rate would be \(\beta_1\) when the asynchrony \((n)\) was negative, while it would be \(\beta_1 + \beta_2\) when the error was positive. Based on our hypothesis, the error correction rate would be larger when the value of asynchrony \((n)\) was positive than when it was negative. Moreover, \(\beta_2\) should be a significant and negative value. In addition, the variance inflation factor (VIF) was calculated to examine the possibility of multicollinearity in equation (3). We also conducted a model comparison between the symmetric and asymmetric error correction models with the Akaike information criterion (AIC).
3. Results

3.1. Scatter Plot Showing the Relationship between Asynchrony (n) and Asynchrony (n + 1)

The scatter plot for asynchrony (n) and asynchrony (n + 1) is shown in Fig. 1 and Supplementary Fig. S2. From this, we can observe that when asynchrony (n) was negative, asynchrony (n + 1) also tended to be negative. Additionally, when asynchrony (n) was approximately 0.15 s (positive value), asynchrony (n + 1) was approximately 0.00 s (see Supplementary Fig. S1). In other words, the subjects tended to correct tap timing to a greater extent when asynchrony (n) had a positive rather than a negative value, which implied the existence of the asymmetric error correction process. Although these results were consistent with the scatter plot in Müller et al. (1999), their analysis was qualitative, not quantitative. Therefore, in the following section, we investigate asymmetric error correction with a statistical analysis.

![Scatter plot with asynchrony (n) plotted on the horizontal axis and asynchrony (n + 1) plotted on the vertical axis. The red circle shows trials of correcting in a negative direction for the asynchrony (n + 1) when the asynchrony (n) is a positive value.](image-url)
The scatter plot showed clusters of outliers in the upper and lower right-hand quadrants (Supplementary Fig. S2). We mainly analyzed the dataset excluding outliers (Fig. 1). In addition, we also conducted other analyses (See ‘Additional Analyses 2. GLMM including outliers’ in the Supplemental Material).

3.2. Test of Normality for Tap Timing

The K–S test showed that the distribution of the subject’s tap timing significantly deviated from the normal distribution ($D = 0.042, p < -0.001$) (Supplementary Fig. S2).

3.3. Model Comparison Using AIC

The AIC scores of the asymmetric and symmetric error correction models were $-31,284$ and $-31,064$ respectively. The AIC of the baseline model including only the intercept was $-23,086$. Therefore, the model comparison suggested that the asymmetric error correction model was better than the symmetric and baseline models.

3.4. GLMM

The scatter plot (Fig. 1) had clusters in the upper right and lower right quadrants. Generally, clusters can be handled with circular statistics. However, this study aimed to investigate the existence of asymmetric error correction (i.e., does the correction rate of positive asynchrony differ from that of negative asynchrony?). Thus, we needed to determine whether asynchrony was negative or positive. Even if we applied circular statistics, we would need to define whether the tap timing follows (from 0 to $\pi$) or precedes (from $\pi$ to 0) that of the metronome. In other words, both the GLMM and circular statistics would generate clusters, thus eliminating the advantage of applying circular statistics. However, linear regression analysis (e.g., GLM, GLMMs and linear phase correction model) has been utilized in this field; thus, applying a GLMM in this study enables comparison with previous studies. Therefore, this study removed the clusters and analyzed the data with a GLMM. Specifically, we removed the two clusters in the bottom right quadrant [asynchrony ($t > 0.15$) and asynchrony ($t + 1 < -0.15$)] and the upper right quadrant [asynchrony ($t > 0.15$) and asynchrony ($t + 1 > 0.15$)] (Fig. 1).

In the asymmetric model, the estimate of the correction rate for both negative and positive asynchrony ($\hat{\beta}_1$) was 0.71 ($t = 17.59, p < -0.001$, standardized coefficient = 0.73) (Table 1). The asymmetric effect for positive synchronization ($\hat{\beta}_2$) was $-0.45$ ($t = -5.94, p < -0.001$, standardized coefficient = $-0.11$), and the intercept was $-0.02$ ($t = -3.80, p < -0.01$, standardized coefficient = 0.00). The estimates of $\beta_2$ for individual subjects were all negative except for three subjects (Supplementary Table S1). The estimated parameter values throughout the three sessions are shown in Supplementary Table S2. The adjusted $R^2$ value in the asymmetric error correction model was 0.66. The VIF of this model was 1.51.
for both independent variables (\(\beta_1\) and \(\beta_2\); because the model has only two independent variables, the VIF scores were identical), which suggested lack of multicollinearity.

In the symmetric model, the estimate of the correction rate for both negative and positive asynchrony (\(\beta_1\)) was 0.64 (\(t = 20.11, p < -0.001\), standardized coefficient = 0.66). The intercept was −0.03 (\(t = -5.73 p < -0.001\), standardized coefficient = 0.00). The adjusted \(R^2\) in the asymmetric error correction model was 0.65.

We also conducted simulations with those estimated parameters (Supplementary Fig. S3). For the simulations, we generated 100,000 random numbers from a normal distribution within −0.3 to 0.3 s as asynchrony (\(n\)). Then, using the estimated parameters, each asynchrony (\(n + 1\)) was generated from these random numbers based on the symmetric and asymmetric models. Both the simulated data generated by the symmetric and asymmetric models agree well with the actual data in negative asynchrony. In contrast, for positive asynchrony, simulated data from neither model perfectly aligned with the actual data, although the data from the asymmetric model appeared more consistent with the distribution (Supplementary Fig. S3).

### 4. Discussion

This study investigated whether the error correction process in the synchronization tapping task was asymmetric or symmetric. Statistical analysis with GLMM suggested that the error correction rate was larger when the asynchrony was positive than when it was negative. This result was consistent with the hypothesis in Müller et al. (1999), which proposed that NMA came about because of an asymmetric error correction process.

The asymmetry correction rate hypothesis does not deny the Paillard–Fraisse (Fraisse, 1980; Paillard, 1946) or sensory accumulation hypotheses (Aschersleben, 2002). These hypotheses are not mutually exclusive. For example, the intercept (\(\beta_0\)) estimated by GLMM was a negative value in this study. This suggested that asynchrony (\(n + 1\)) was negative when the asynchrony (\(n\)) was 0. In other words, the asynchrony was biased in the negative direction to some extent because of factors other than the asymmetric error correction process. The bias might be

| Table 1. Results of the GLMM for the asymmetric error correction model. |
|---------------------|-----|-----|-----|
| **Estimate**       | **SE** | **t** | **p**   |
| Intercept          | -0.023 | 0.006 | -3.804 | < 0.01 |
| \(\beta_1\)        | 0.713 | 0.041 | 17.592 | < -0.001 |
| \(\beta_2\)        | -0.451 | 0.067 | -6.769 | < -0.001 |
accounted for by the Paillard–Fraisse hypothesis (Fraisse, 1980; Paillard, 1946) and/or the sensory accumulation hypothesis (Aschersleben, 2002).

This study examined the existence of the asymmetric error correction process in the synchronization tapping task. Meanwhile, previous studies investigated the error correction process in the synchronization tapping task with perturbation (Repp, 2002; Bavassi et al., 2013). In the task involving perturbation, the timing of the presented metronome suddenly switches. In contrast to our results, these studies have shown that the correction rate was larger when the metronome sounded slower than expected. In other words, when the asynchrony was a negative value, subjects strongly corrected for the error in the positive direction with the next tapping. If this error correction process could be applied to the synchronization tapping task with no perturbation, humans should show not NMA but a positive mean asynchrony. However, their tapping timing is biased in a negative direction (Aschersleben, 2002). Therefore, the error correction process could differ between the synchronization tapping task and that with perturbation. For instance, Repp et al. (2012) reported that the error correction rate in a synchronization tapping task with perturbation was larger than in that with no perturbation. Our study is the first to report that the asymmetric error correction rate could be in opposite directions in these two tasks.

A limitation of this study is that the simulations generated from the symmetric and asymmetric error correction model did not adequately fit the real data especially in positive asynchrony (Supplementary Fig. S3). We considered two possible reasons for these results. Firstly, in the synchronization tapping task, the actual data overwhelmingly showed negative asynchrony. In contrast, for this simulation, 100,000 random numbers were generated from a normal distribution within a range of $-0.3 \, \text{s}$ to $0.3 \, \text{s}$ as asynchrony ($n$). As a result, the simulated data exhibited a higher proportion of positive asynchrony compared to the actual data. Secondly, relying solely on the asymmetry correction rate hypothesis may not comprehensively account for the error correction process observed in synchronization tapping data. Integrating the Paillard–Fraisse hypothesis and the sensory accumulation hypothesis with the asymmetry correction rate hypothesis would produce a better model. This integration could be an avenue for future research.

In conclusion, this study showed that the error correction rate was larger when the asynchrony was positive than when the asynchrony was negative. This result supports the hypothesis in Müller et al. (1999), which suggests that NMA comes about because of the asymmetric error correction process. This finding could contribute to improving the model of the synchronization tapping task. The question of why the error correction rate was asymmetric in the synchronization tapping task remains unresolved.
Supplementary material

Supplementary material is available online at:
https://doi.org/10.6084/m9.figshare.24131199

References


