Study of a physiotherapy evaluation that applies the motor retraction phenomenon to auditory stimuli

Takumi Yamanaka (20s1229@g.iuhw.ac.jp)
Narita Hospital, International University of Health and Welfare

Shinta Takeuchi
Faculty of Health and Medical Sciences, International University of Health and Welfare

Akino Aoki
Faculty of Health and Medical Sciences, International University of Health and Welfare

Yusuke Nishida
Faculty of Health and Medical Sciences, International University of Health and Welfare

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Abstract

The accuracy and precision of synchronization and phase coherence values have been used as evaluation measures of retraction. However, it has been pointed out that accuracy and precision of synchronization may show a discrepancy between neural entrainment and performance accuracy. Therefore, this study determined whether the phenomenon of motor retraction to auditory stimuli can be evaluated by using phase synchronization with tapping. For this purpose, we examined phase coherence values, surrogate data methods, and effect sizes from a mathematical perspective. The auditory stimulus interval at which retraction is most likely to occur was also identified. Specifically, tapping tasks at six tempi (400, 500, 600, 750, 1,000, and 2,000 ms) were performed on 20 young adults. A comparison of the data for each auditory stimulus condition revealed significant differences at 400, 500, 600, 750, and 1,000 ms. Moreover, the effect size was greatest at 400 ms. The results suggest that, among the five conditions in which retraction occurred, the 400 ms auditory stimulus interval had the lowest probability of being an error in retraction determination and was therefore deemed suitable for evaluation.

Introduction

Auditory stimuli are closely related to daily life, and the perception of temporal regularity in such stimuli is central to many human activities. For example, when catching a thrown object, one must time his/her actions. In a musical performance, one must keep the timing of his/her activities in tune with the external stimuli. In this regard, we live our daily lives by timing our own activities based on external auditory stimuli.[1]

In general, interventions using auditory stimuli in clinical settings are a cost effective, accessible, and comprehensive treatment option.[2] The retraction phenomenon that uses auditory stimuli is characterized by being quick, accurate, and easy, especially when detecting time patterns.[3] In addition, the auditory system is closely and diffusely linked to the motor system.[4] Thus, it is considered superior to retraction phenomena that use visual and tactile senses.

One of the typical clinical situations for adapting periodic auditory stimuli is the induction of walking. The use of rhythmic auditory stimuli to assist exercise therapy has been shown to improve walking among Parkinson’s disease, cerebral palsy, and stroke hemiplegic patients. It has also been reported that walking speed, overlapping walking distance, and cadence improve, especially for patients with Parkinson’s disease.[5] An interesting feature of a person whose walking improves by auditory stimulation is that the pace at the time of walking can be matched to an auditory stimulus. Conversely, previous studies have reported that walking deteriorates among such patients.[6] It has also been shown that the sense of rhythm, rhythm generation, and musicality are not related to an improvement in walking.[6] Thus, it is necessary to evaluate the ability to draw in auditory stimuli and synchronize movements, especially since the method has not been clarified. In addition, a method for evaluating the presence (or absence) of retraction phenomena has yet to be established.

Synchronous phenomena are generally understood as temporal coupling between body movement and rhythmic stimuli such as hearing, vision, and tactile sensation.[7,8] In short, it refers to the input of an external stimulus and that the timing of the output of one's action is matched.[9] As for these evaluation methods, a setting for synchronizing periodic auditory stimuli and finger tapping is used. Moreover, accuracy and precision of synchronization and phase coherence are used as evaluation indices for the retraction phenomenon.[10–13] However, a discrepancy between neural entrainment and performance accuracy has been observed in the accuracy and precision of synchronization.[10] In this regard, it is necessary to not only consider frequency synchronization, but also phase synchronization.

Therefore, the purpose of this study is to determine whether the phenomenon of motor retraction to auditory stimuli can be evaluated by using phase synchronization with tapping on a sample of healthy participants. It should be noted that we do not consider tapping behavior as a change in performance, but as a temporal oscillator. Moreover, by using phase coherence values and surrogate data methods, we determine whether the retraction phenomenon occurs from a mathematical point of view.

Results

Mean and standard deviation of the phase coherence values for each condition

The calculated means and standard deviations are shown in Table 1 and Fig. 1. The original data was greater than the average of the surrogate data at auditory stimulus intervals of 400, 500, 600, 750, and 1,000 ms. Conversely, the surrogate data was only larger at 2,000 ms. The mean value also increased as the stimulus interval increased. In addition, the original data had smaller standard deviations than the surrogate data at 400, 500, 600, and 750 ms of auditory stimulation. At 1,000 ms, they were comparable, while at 2,000 ms, the surrogate data was smaller.

Table 1
Analysis results

		Auditory Stimulus Interval					
		400 ms	**500 ms**	**600 ms**	**750 ms**	**1,000 ms**	**2,000 ms**
Mean	Original data	0.84	0.88	0.90	0.91	0.94	0.94
	Surrogate data	0.78	0.84	0.87	0.90	0.93	0.94
SD	Original data	0.05	0.05	0.04	0.03	0.03	0.02
	Surrogate data	0.08	0.07	0.05	0.05	0.03	0.02
		0.00007	0.0004	0.00001	0.00023	0.00006	0.68824
Effect size		0.83	0.45	0.7	0.45	0.22	0.04

Results Of The T-tests, With Corresponding Means Of The Phase Coherence Values For Each Condition

The results of the corresponding t-tests are shown in Table 1. Since the significance level was set at 5%, differences were found in all five conditions, except at 2,000 ms ($p < 0.05$). Additionally, the 2,000 ms auditory stimulus interval was not significantly different ($p = 0.688$).

Effect Size Of The Phase Coherence Values For Each Condition

The calculated effect sizes are shown in Table 1. The effect size was 0.89 for an auditory stimulus interval of 400 ms, 0.59 for 500 ms, 0.72 for 600 ms, 0.49 for 750 ms, 0.22 for 1,000 ms, and 0.04 for 2,000 ms. Moreover, the stimulus interval with the largest effect size was 400 ms, the stimulus intervals with medium effect sizes were 500 and 600 ms, the stimulus intervals with small effect sizes were 750 and 1,000 ms, and the stimulus interval with almost no effect size was 2,000 ms.

Discussion

In this study, the phenomenon of motor retraction to auditory stimuli was verified by tapping. This phenomenon was evaluated by using phase coherence values. As shown in Table 1, there were considerable differences in the auditory stimulus intervals of 400, 500, 600, 750, and 1,000 ms. In other words, since the null hypothesis that the original data was linear was rejected, a retraction phenomenon occurred. Conversely, no significant difference was found for the condition with an auditory stimulus interval of 2,000 ms, indicating that the retraction phenomenon did not occur.

The phenomenon of motor retraction in response to auditory stimuli was also limited to 5–7 times per second at fast tempo, while noting that the limit at which rhythmic movements can be sustained is 200 ms.[6,14] At stimulus rates faster than 200 ms, tapping and auditory stimulation diverge. Thus, the participant cannot recognize whether they are synchronized, which is considered a biomechanical limitation.[9] Meanwhile, the critical threshold for slow tempo is considered to be approximately 1,800 ms.[15] If the auditory stimulus interval is longer than this, then attention to the stimulus presentation cannot be sustained. Hence, based on previous studies, the stimulus interval at which auditory stimuli and tapping are synchronized is considered to be between 200 ms and 1,800 ms. The results of the present study were within the range of the stimulus intervals at which retraction occurs, while the phase coherence value and surrogate data method were used to evaluate the retraction phenomenon.

Interestingly, since there was no significant difference between the original data and surrogate data at the auditory stimulus interval of 2,000 ms, no retraction occurred. This neuronal mechanism allowed us to integrate information over time and bind successive temporally separated events into a single unit.[16] Again, when the auditory stimulus interval exceeds 1,800 ms, attention is not sustained and it becomes difficult to judge a series of temporally separated consecutive stimuli as a series of events. Since it becomes impossible to accurately time the next stimulus, some responses were replaced by simple

reactions to the stimulus, which is believed to cause reactive tapping. Previous studies have shown that if the response to an auditory stimulus is delayed for more than 100 ms, then it is considered to be responsive to the stimulus.[15] This is due to the fact that there is a latency of roughly 80–200 ms from the time the auditory stimulus is heard to the time the evoked response occurs in the auditory cortex.[17]

Reactive tapping was also observed in many of the measurements at the 2,000 ms auditory stimulus interval. In this regard, attention was not sustained, making it difficult to judge the two sounds as rhythmic. In addition, there was a mixture of anticipatory and reactive tapping in response to the auditory stimuli. As a result, the discrepancy between the auditory stimulus onset time and the tapping onset time became larger, and synchronization did not occur.

Table 1 shows that the auditory stimulus interval of 400 ms produced the largest effect size, while 500 ms and 600 ms produced a moderate effect size. In other conditions, the effect size was small to almost none. Moreover, the effect size in the surrogate data was presented as a reference for the difficulty of rejecting the new null-hypotheses generated by each of the surrogate data generation methods and not for determining significance.[18] In other words, the probability that the judgment that the null hypothesis has been rejected (i.e., that there was a retraction) is incorrect is lower the larger the effect size. Thus, among the five conditions in which a retraction phenomenon occurred in the analysis using the phase coherence value and surrogate data method, the effect size was found to be the largest at 400 ms and the probability that the judgment was incorrect was the lowest.

According to the study by Loen et al.,[19] in which tapping was measured 40 times to various styles of music (e.g., dance music, jazz, etc.), spontaneous movements occurred at a period of 2 Hz, after which they proposed the “2-Hz resonance theory.” The normal walking rate of humans is 1.87–1.91 steps/min, which translates into 523–535 ms per step. As a result, a relationship with resonance frequency has been suggested in walking. Conversely, Madison,[14] who examined movement tempo using a free tapping task, reported that the tapping interval showed bimodal data, with a peak at 300 or 600 ms. There was also a slight difference regarding the optimal speed of human movement. As for the present study, the effect size was large at 400 ms and medium at 500 ms and 600 ms, which are relatively close to Madison’s viewpoint.

As stated earlier, in Loen et al.’s study,[19] music was used as the auditory stimulus, and the number of tapping measurements was only 40 times, which was a relatively short synchronization task. Although the conditions in the present study were different because the auditory stimulus was a metronome, it was clear that a shorter auditory stimulus interval of 400 ms was preferable to 2 Hz (500 ms stimulus interval) for the longer tapping task.

In this study, several limitations should be noted. First, it was impossible to standardize the time period measured for each participant. Hence, the participants’ arousal levels may have differed, which may have affected their attention. Second, the number of tapping times in each task was inconsistent. In addition, the measurement time was standardized, but the auditory stimulus interval differed. In the case of the shortest interval of 400 ms, the number of time points was 750, whereas in the case of the longest

interval of 2,000 ms, the number of time points was 150. In general, as the number of time points increases and the magnitude of the effect size increases, the probability of determining that there is a difference when there is no initial difference (Type I error) and the probability of determining that there is no difference when there is actually a difference (Type II error) decreases.[20] Therefore, the number of tapping times per condition differed, which may have affected the results. Finally, the participants were only young healthy adults in their 20s. Although previous studies on auditory stimulation and tapping reported no differences between young and older adults,[21] different results may be obtained for different target ages.

Methods

Participants

The participants in this study consisted of 20 healthy young adults (ages: 23.4 ± 1.32). One of them was excluded because the data measurement was not properly performed, due to inadequate equipment. The sample size was calculated by means of G*Power software (parameters: alfa = 0.05; power = 0.80; effect size = 0.8), resulting in 15 participants. The exclusion criteria included those with hearing impairments or upper limb motor impairments. In addition, in order to unify the conditions, all of the participants were right-handed. This study was also conducted with the approval (Certification no. 20-Io-148) of the Ethics Committee at the International University of Health and Welfare. This study was performed in accordance with the Declaration of Helsinki. Besides, the research subjects were verbally informed of the purpose of the study, the research methods, and the risks and ethical considerations involved, and their informed consent was obtained after explanations.

Experimental tasks and procedures

The auditory stimulus intervals were 400, 500, 600, 750, 1,000, and 2,000 ms, with the order of tasks randomized. The measurements were taken in a quiet room, and the tasks were performed with the participant sitting comfortably in a chair with a backrest. Tapping was performed as an opposing motion of the right thumb and index finger, after which the participant was instructed to pinch the pressure-sensitive gage with the thumb and index finger during the tapping. The participants practiced tapping to match the auditory stimuli and were asked to signal when they believed they had matched the tapping and started the measurement. If the tapping was not responsive during the task, then the measurer raised the upper-right extremity and informed the participant that it was not responsive. Based on previous research, the participants were asked to avoid making rhythmic movements other than the opposing movements of the right thumb and index finger (e.g., nodding the head or tapping the foot).[1] Additionally, the digital waveforms of the auditory stimuli and tapping displayed on the computer were not presented to the participants, and bio-feedback was not performed. Each task was measured for 5 minutes, with a 2-minute break between tasks to allow for rest.

Equipment used in the experiments

In this study, we used a device to input auditory stimuli, a device to input the participant's tapping, and a system to analyze these signals. An electronic metronome (Seiko Holdings Corporation, DM-71) was used to input the auditory stimuli. Analog signals of auditory stimuli were input from an electret condenser microphone (Sony Group Corporation, ECM-PCV80) via an amplifier to an AD converter (ADInstruments, PL3516). The digitized signal was further displayed on a personal computer (PC) (Lenovo Japan G.K., TP00086A) via USB. As for the tapping, an analog signal was input from the pressure-sensitive meter via an amplifier to an AD converter. The digitized signal was then displayed on a PC via USB.

Data analysis methods

In this study, phase synchronization was used to determine whether auditory stimuli and tapping were synchronized. The time difference between the auditory stimulus and the corresponding tapping in each condition was recorded as a negative value if the tapping was earlier than the stimulus sound, with a positive value if it was later. If the tapping was slower than 100 ms relative to the auditory stimulus, then it was considered to be reactive tapping and excluded.[15] The following procedures were used to analyze the phase synchronization:

1) Extraction of auditory stimuli and tapping rhythm

As for the analysis software, we used LabChart 8 Japanese to extract the measured auditory stimulus and tapping rhythms. All onset times of the auditory stimuli (hereafter referred to as "onset times") and tapping onset times were recorded (in time units of msecs) and stored on a data pad (chronologically sorted on Excel). If the tapping onset time was reacted more than once in a short period of time, e.g., due to a malfunction of the measurement device, then the first tapping onset time was adopted and the one immediately after was excluded.

2) Calculation of normalized relative phase

Normalized relative phase was calculated to examine the timing of the auditory stimuli and tapping. The auditory stimulus onset time and tapping onset time were arranged side-by-side on Excel so that they could be easily compared and evaluated. In this case, the nth auditory stimulus onset time was An and the tapping onset time was Tn (n is an integer). The calculation of the nth normalized relative phase (φn) is shown in the following equation:

$$\varphi n = \frac{(Tn - An)}{\text{Auditory Stimulus Intervals}} \quad (1)$$

3) Creation of a phase-locking diagram

The phase-locking diagram shows the normalized relative phase (φn) on the vertical axis and time (sec) on the horizontal axis, allowing us to visually determine whether phase-locking is occurring. When this

diagram shows a horizontal direction, it indicates that tapping continues to occur at a constant phase relative to the auditory stimulus. It also indicates that phase synchronization occurs between the auditory stimulus rhythm and tapping rhythm. Comparing the phase-locking diagram of the original and surrogate data, we analyze whether there is any difference in the delta variation of the normalized relative phase. A scatter plot (phase-locking diagram) was created by selecting the columns of the auditory stimulus time axis and the columns for which the normalized relative phase (φn) was calculated on Excel (see Figs. 2a, 2b).

4) Calculation of phase coherence value (λ)

The phase coherence value assesses the deviation of each value of the normalized relative phase (φn) and represents the coupling degree of phase synchronization. In this case, the phase coherence value is between 0 and 1. If it is close to 0, then the correlation between the auditory stimulus rhythm and the tapping rhythm is low in this cycle. Conversely, if it is close to 1, then the correlation is very high.

The phase coherence value can be calculated by using the normalized relative phase(φn). Since the range of 2–30 seconds is recommended for the data,[18] we chose the normalized relative phase of 30 seconds. The phase coherence values were then calculated by shifting the normalized relative phase(φn) of 30 seconds by 15 seconds. The phase coherence value (λ) was calculated by using the following equation:

$$\lambda = \langle \sin(\varphi n \times 2\pi) \rangle^2 + \langle \cos(\varphi n \times 2\pi) \rangle^2 \quad (2)$$

In this case, represents the average. Moreover, the changes in the time series were examined by shifting the data by 15 seconds from the beginning of the recorded data.

In order to convert the normalized relative phase (φn), which ranged from 0 to 1 on Excel, into an angle from 0º to 360º, the value of the normalized relative phase (φn) cell was multiplied by 2π. In addition, values using the sin and cos functions were calculated for these values. This was performed for the normalized relative phase (φn) of 30 seconds from the beginning of the recorded data, after which the average of each was calculated. Each average value was then squared and totaled to obtain the phase coherence value (λ). Finally, this process was checked for changes in the time series by shifting the values by 15 seconds from the beginning of the recorded data. Overall, the phase coherence values (λ) were calculated for all six conditions of the 19 participants.

5) Data calculation for the surrogate data method

The surrogate data method determines whether the null hypothesis in which a time series signal is “linear” is rejected in order to test for nonlinearity.[22] In the present study, statistically homogeneous surrogate data (surrogate data) was generated and examined for significant differences from the original data. If significant differences were found, then the null hypothesis was rejected and it was concluded

that nonlinearity (i.e., the retraction phenomenon) occurred.[23] In order to create surrogate data in this study, a data shuffling method was used.[18] Time series were also randomized using a RAND function on the original data, while the phase coherence values were calculated from the randomized normalized relative phase (φn).

Statistical analysis

First, the mean and standard deviation (SD) of the 19 phase coherence values were calculated for each condition. Next, the Shapiro–Wilk test was conducted to examine the normality of the data. In this case, normality was confirmed for all of the data. Additionally, significant differences between the original and surrogate data in each condition were examined using the corresponding t-tests, with a significance level of 5%. Under the condition of an auditory stimulus interval of 2,000 ms, the number of excluded data greatly varied from one participant to another. Therefore, the data from immediately after the start of the measurement to 240 seconds later was used. Finally, the effect size (d) of the phase coherence value between the data in each condition was calculated by using the following equation:

$$d = \frac{(\text{Average of original data} - \text{Average of surrogate data})}{\sqrt{\frac{\text{SD of original data}^2 + \text{SD of surrogate data}^2}{2}}} \quad (3)$$

Declarations

Data availability statement

Datasets created and analyzed in this study are publicly available at https://doi.org/10.6084/m9.figshare.21220010.

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Author contributions

All of the authors were involved in designing the experiments, analyzing the data, and writing the manuscript, while T Y. oversaw the data acquisition.

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References

1. Niida, M. & Tayama, T. Time information processing in synchronized tapping. *Jpn. J. Psychon. Sci.* **38**, 203-213 (2020). 10.14947/psychono.38.30
2. McPherson, T., Berger, D., Alagapan, S. & Fröhlich, F. Intrinsic rhythmicity predicts synchronization-continuation entrainment performance. *Sci. Rep.* **8**, 11782 (2018). 10.1038/s41598-018-29267-z
3. Shelton, J. & Kumar, G. P. Comparison between auditory and visual simple reaction times. *Neurosci. Med.* **01**, 30-32 (2010). 10.4236/nm.2010.11004
4. Koshimori, Y. & Thaut, M. H. Future perspectives on neural mechanisms underlying rhythm and music based neurorehabilitation in Parkinson's disease. *Ageing Res. Rev.* **47**, 133-139 (2018). 10.1016/j.arr.2018.07.001
5. McIntosh, G. C., Brown, S. H., Rice, R. R. & Thaut, M. H. Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. *J. Neurol. Neurosurg. Psychiatry* **62**, 22-26 (1997). 10.1136/jnnp.62.1.22
6. Cochen De Cock, V. *et al.* Rhythmic abilities and musical training in Parkinson's disease: do they help? *NPJ Parkinsons Dis.* **4**, 8 (2018). 10.1038/s41531-018-0043-7
7. Phillips-Silver, J., Aktipis, C. A. & Bryant, G. A. The ecology of entrainment: foundations of coordinated rhythmic movement. *Music Percept.* **28**, 3-14 (2010). 10.1525/mp.2010.28.1.3
8. Ross, J. M. & Balasubramaniam, R. Physical and neural entrainment to rhythm: human sensorimotor coordination across tasks and effector systems. *Front. Hum. Neurosci.* **8**, 576 (2014). 10.3389/fnhum.2014.00576
9. Repp, B. H. Sensorimotor synchronization: a review of the tapping literature. *Psychon. Bull. Rev.* **12**, 969-992 (2005). 10.3758/BF03206433
10. Nozaradan, S., Peretz, I. & Keller, P. E. Individual differences in rhythmic cortical entrainment correlate with predictive behavior in sensorimotor synchronization. *Sci. Rep.* **6**, 20612 (2016). 10.1038/srep20612
11. Pollok, B., Gross, J., Müller, K., Aschersleben, G. & Schnitzler, A. The cerebral oscillatory network associated with auditorily paced finger movements. *Neuroimage* **24**, 646-655 (2005). 10.1016/j.neuroimage.2004.10.009
12. Damm, L., Varoqui, D., De Cock, V. C., Dalla Bella, S. & Bardy, B. Why do we move to the beat? A multi-scale approach, from physical principles to brain dynamics. *Neurosci. Biobehav. Rev.* **112**, 553-584 (2020). 10.1016/j.neubiorev.2019.12.024
13. Te Woerd, E. S., Oostenveld, R., De Lange, F. P. & Praamstra, P. Impaired auditory-to-motor entrainment in Parkinson's disease. *J. Neurophysiol.* **117**, 1853-1864 (2017). 10.1152/jn.00547.2016
14. Madison, G. An auditory illusion of infinite tempo change based on multiple temporal levels. *PLOS ONE* **4**, e8151 (2009). 10.1371/journal.pone.0008151
15. Miyake, Y., Onishi, Y. & Popnel, E. Two types of anticipation in sensory-motor coupling. *Acta Neurobiol. Exp.* **64**, 415-426 (2004). 10.11499/sicep.2003.0.27.1

16. Szelgg, E., von Steinbiichl, N. & ME. Temporal constraints in processing of nonverbal rhythmic patterns. *Acta neurobiol. exp.* **56**, 215-225 (1996)
17. Fujioka, T., Zendel, B. R. & Ross, B. Endogenous neuromagnetic activity for mental hierarchy of timing. *J. Neurosci.* **30**, 3458-3466 (2010). 10.1523/JNEUROSCI.3086-09.2010
18. Moulder, R. G., Boker, S. M., Ramseyer, F. & Tschacher, W. Determining synchrony between behavioral time series: an application of surrogate data generation for establishing falsifiable null-hypotheses Determining Synchrony Between Behavioural Time Series. *Psychol. Methods* **23**, 757-773 (2018). 10.1037/met0000172
19. van Noorden, L. & Moelants, D. Resonance in the perception of musical pulse. *J. New Music Res.* **28**, 43-66 (1999). 10.1076/jnmr.28.1.43.3122
20. Liu, S. & Molenaar, P. Testing for Granger causality in the frequency domain: a phase resampling method. *Multivariate Behav. Res.* **51**, 53-66 (2016). 10.1080/00273171.2015.1100528
21. Rose, D., Delevoye-Turrell, Y., Ott, L., Annett, L. E. & Lovatt, P. J. Music and metronomes differentially impact motor timing in people with and without Parkinson's disease: effects of slow, medium, and fast tempi on entrainment and synchronization performances in finger tapping, toe tapping, and stepping on the spot tasks. *Parkinsons Dis.* **2019**, 6530838 (2019). 10.1155/2019/6530838
22. Theiler, J., Eubank, S., Longtin, A., Galdrikian, B. & Doyne Farmer, J. Testing for nonlinearity in time series: the method of surrogate data testing for nonlinearity in time series. *Phys. D Nonlinear Phenom.* **58**, 77-94 (1992). 10.1016/0167-2789(92)90102-S
23. Päeske, L. *et al.* Surrogate data method requires end-matched segmentation of electroencephalographic signals to estimate non-linearity. *Front. Physiol.* **9**, 1350 (2018). 10.3389/fphys.2018.01350

Figures

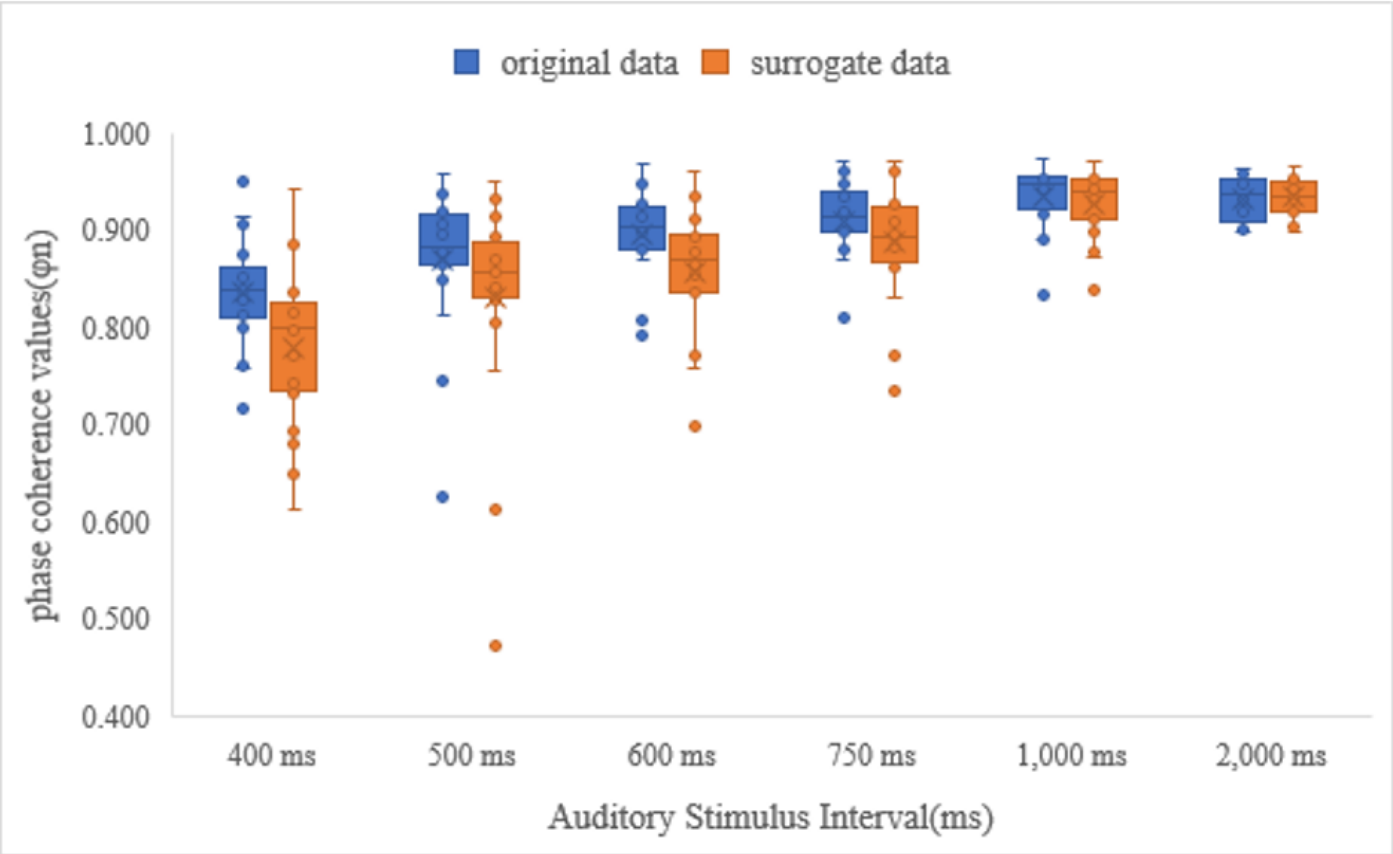

Figure 1

The phase coherence values of the original and surrogate data for each condition

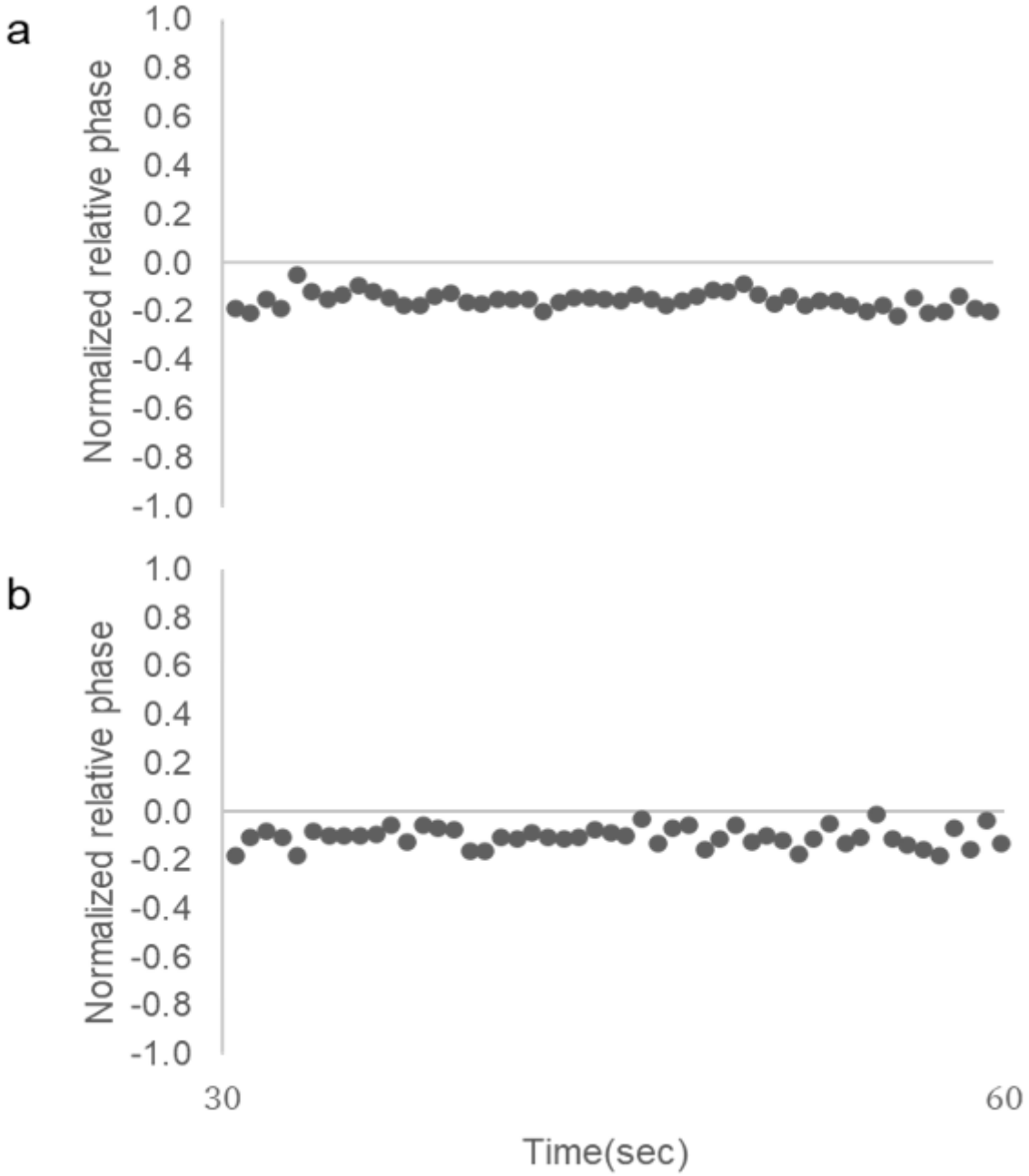

Figure 2

Phase-locking diagram

Note: This is a phase-locking diagram of participants at the 600 ms auditory stimulus interval. It was created by a time series of normalized relative phases, with an excerpt from the 30 second-interval to 60 seconds after the start of the measurement. (a) Phase-locked diagram of the original data. The delta of the normalized relative phase is small and shows a nearly horizontal direction. (b) Phase-locked diagram of the surrogate data. The delta is larger than that of the original data and shows variation.