Video Article

Bouncing Ball with a Uniformly Varying Velocity in a Metronome Synchronization Task

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URL: https://www.jove.com/video/56205
DOI: doi:10.3791/56205

Keywords: Behavior, Issue 127, Auditory, bouncing ball, gravity, modality, motion, velocity, sensorimotor synchronization, visual

Date Published: 9/21/2017

Citation: Huang, Y., Gu, L., Yang, J., Wu, X. Bouncing Ball with a Uniformly Varying Velocity in a Metronome Synchronization Task. *J. Vis. Exp.* (127), e56205, doi:10.3791/56205 (2017).

Abstract

Sensorimotor synchronization (SMS), a fundamental human ability to coordinate movements with external rhythms, has long been thought to be modality specific. In the canonical metronome synchronization task that requires tapping a finger along with an isochronous sequence, a well-established finding is that synchronization is much more stable to an auditory sequence consisting of auditory tones than to a visual sequence consisting of visual flashes. However, recent studies have shown that periodically moving visual stimuli can substantially improve synchronization compared with visual flashes. In particular, synchronization of a visual bouncing ball that has a uniformly varying velocity was found to be not less stable than synchronization of auditory tones. Here, the current protocol describes the application of the bouncing ball with a uniformly varying velocity in a metronome synchronization task. The usage of the bouncing ball in sequences with different inter-onset intervals (IOI) is included. The representative results illustrate synchronization performance of the bouncing ball, as compared with the performances of auditory tones and visual flashes. Given its comparable synchronization performance to that of auditory tones, the bouncing ball is of particular importance for addressing the current research topic of whether modality-specific mechanisms underlay SMS.

Video Link

The video component of this article can be found at https://www.jove.com/video/56205/

Introduction

Sensorimotor synchronization (SMS) refers to the coordination of movements (*e.g.*, finger taps) with an external rhythm, and is canonically studied using a simple metronome synchronization task in which the subject is required to tap a finger along with an isochronous sequence[1,2]. The superiority of the auditory over visual modality in metronome synchronization has been established for over a century: synchronization is much more stable to an auditory sequence consisting of auditory tones (**Figure 1A**) than to a visual sequence consisting of visual flashes (**Figure 1B**)[1]. This auditory advantage of metronome synchronization, however, has recently been challenged by studies employing periodically moving visual stimuli[3,4,5,6] (note that periodically moving visual stimuli refer to continuous movements). Hove *et al.* used a visual sequence composed of an up-down bar moving with a constant velocity, and found that synchronization of the up-down bar was more stable than synchronization of visual flashes, but was still less stable than synchronization of auditory tones[3,6]. Iversen *et al.* employed a bouncing ball that had a velocity varied according to a rectified sinusoid, and showed that synchronization of the bouncing ball was close to synchronization of auditory tones[5]. More recently, Gan *et al.* used a bouncing ball that had a uniformly varying velocity (*i.e.*, simulating the effect of gravity) (**Figure 1C**), and found that synchronization of the bouncing ball was not less stable than synchronization of auditory tones[4].

The purpose of the current protocol is to introduce a procedure to apply a bouncing ball with a uniformly varying velocity in a metronome synchronization task, as described in Gan *et al.*[4] The metronome synchronization task includes an auditory sequence composed of auditory tones (AT sequence, **Figure 1A**) and a visual sequence composed of visual flashes (VF sequence, **Figure 1B**), which are widely adopted in SMS studies[1]. The third type of sequence in the task is a visual sequence consisting of the bouncing ball (VB sequence, **Figure 1C**). Whereas modality-specific mechanisms have long been thought to underlay SMS, such as tighter connections between the auditory and motor cortices than between the visual and motor cortices[2], whether SMS is modality specific has recently drawn much research attention[1,7]. The bouncing ball as introduced in the present protocol is particularly useful for addressing the modality issue because of comparable synchronization performances of the bouncing ball and auditory tones. Moreover, metronome synchronization can be flexibly performed over a limited range of IOI (100-1,800 ms)[8]. To illustrate the application of the bouncing ball for different IOIs, the current protocol includes a 600-ms IOI (which is approximately the most preferred IOI), and a 900-ms IOI.

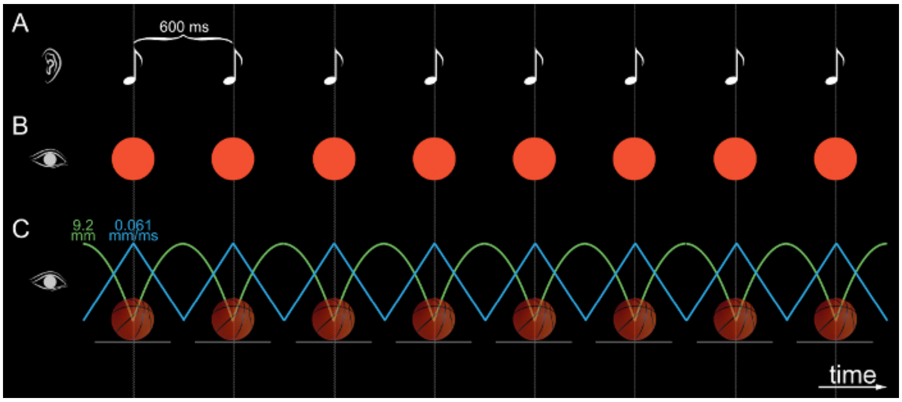

Figure 1: Illustration of the stimuli. The subject taps along with an isochronous sequence, which is composed of auditory tones (**A**: the AT sequence), visual flashing balls (**B**: the VF sequence), or a visual bouncing ball (**C**: the VB sequence). In **C**, the velocity and trajectory of the bouncing ball are plotted as functions of time and are indicated by blue and green lines, respectively. The movement distance of the bouncing ball is 9.2 mm and the peak velocity at the bouncing point (*i.e.*, at the lowest ball position) is 0.061 mm/ms. Eight events in a 600-ms IOI sequence are shown. Please click here to view a larger version of this figure.

Protocol

This protocol was approved by the Institutional Review Board of Psychology Department of Sun Yat-Sen University.

NOTE: A custom program "BouncingBall"[9] is provided for accomplishing this protocol. Extracting the file "BouncingBall.zip" generates a directory "BouncingBall", which contains auditory and visual stimuli files (see Section 1 below), a script "BouncingBall_run.m" for programming of stimulus presentation and response recording (see Section 2 below) and presenting stimuli and recording responses (see Section 3 below), and a script "BouncingBall_analyze.m" for programming of data analyses (see Section 4 below) and performing data analyses (see Section 5 below).

1. Preparation of Auditory and Visual Stimuli

NOTE: The "BouncingBall" directory contains generated stimuli. Readers can use or modify the stimuli as required.

1. Use software in which auditory tones can be generated, to create a pure tone of 600 Hz and 50 ms duration.
2. Use software in which visual images can be generated, to create an image of an orange ball with a transparent background.
3. Use a smartphone with a camera to take a picture of an orange basketball, and use software in which visual images can be generated, to create an image of the basketball with a black background.

2. Programming of Stimulus Presentation and Response Recording

NOTE: The programming of stimulus presentation and response recording is already implemented in the script "BouncingBall_run.m" in the directory "BouncingBall", which can be opened and edited using a text edit software. Readers can set up or modify the settings as required, following the comments in the script.

1. Set up the background color as black.
2. Set up each sequence to have 55 events (54 IOIs). For practice (see below), set up the event number as 20.
3. Set up each sequence to be repeated 6 times. For practice, set up the repetition number as 2.
4. Setup the IOI to be 600 ms or 900 ms.
5. **Construct the AT sequence.**
    1. Present the pure tone every IOI.
    2. Permanently display an orange ball of 1.74 cm in diameter (subtended a visual angle of 1.66°) and a white bar of 3.54 cm x 4.06 cm. Present the ball at the center of the computer screen and display the bar 0.92 cm below the bottom edge of the ball.
    NOTE: The orange ball and the bar are presented to keep visual settings as consistent as possible between the AT sequence and the visual sequences, and to keep the subject fixating on the ball and maintaining attention on the auditory task.
6. **Construct the VF sequence.**
    1. Have the orange ball flash every IOI, *i.e.*, it lasts for 50 ms and disappears for the remaining IOI time.
7. **Construct the VB sequence.**
    1. Replace the orange ball with the realistic orange basketball.
    2. Let the ball continually move 0.92 cm (movement distance) down and touch the white bar, and then move up to the initial position.
    NOTE: The velocity of the ball is uniformly varied with a constant acceleration. The acceleration is 0.20 m/s^2 for the 600-ms IOI or 0.09 m/s^2 for the 900-ms IOI. The ball reaches its peak velocity when touching the bar. Use different accelerations for different IOIs.
8. Record and save the time when the subject presses the responding key on a computer keyboard.

3. Experimental Procedure

NOTE: Presenting stimuli and recording responses are accomplished by typing "BouncingBall_run(SequenceType, IOI, ScreenX, ScreenY, isFormal)" in the command window of the software. "ScreenX" and "ScreenY" refer to the width and height of the computer screen in cm, respectively. The tapping data are automatically recorded in the file "SequenceType_IOI_ScreenX_ScreenY.mat" by the program. IsFormal refers to whether the experiment is the formal experiment or the practice.

1. Ask the subject to sit in front of a computer screen with a 60-cm viewing distance and wear a headset.
2. Give the subject the written informed consent form to sign.
3. **Give the subject the written experiment instructions.**
    1. In the instructions, explain the metronome synchronization task to the subject: tap (on a keyboard key using their index finger of their preferred hand) in synchrony with the tones in the AT sequence, the flashing balls in the VF sequence, and the moments when the bouncing ball moves to the lowest position (*i.e.*, touches the bar) in the VB sequence.

4. **Open the software.**
NOTE: The software continuously runs and its command window stays open. Typing the Bouncingball_run command in the command window will run the stimulus presentation and return to the command window when the stimulus presentation is finished.
5. **Ask the subject to practice with the 600 ms IOI AT, VF, and VB sequences twice to become familiar with the stimuli and task.**
NOTE: The practice was the same as the below formal experiment except: (1) The order of the three sequence types is not changed across the subjects; (2) Each sequence is repeated 2 times; and (3) Each sequence has 20 events.
    1. Type "Bouncingball_run('AT', 600, 53.1, 29.8, 0)" in the command window and then press the 'Enter' key, to perform the practice of the AT sequence.
    NOTE: The screen size was 53.1 cm x 29.8 cm in Gan *et al.*[4], but the readers should assign the size according to the screen that they use. When the experiment program is running, the subject is performing the task described in the experiment instructions. In addition, the sequence presentation is self-paced, *i.e.*, the subject presses the space bar to start a sequence.
    2. Type "Bouncingball_run('VF', 600, 53.1, 29.8, 0)" in the command window and then press the 'Enter' key, to perform the practice of the VF sequence.
    3. Type "Bouncingball_run('VB', 600, 53.1, 29.8, 0)" in the command window and then press the 'Enter' key, to perform the practice of the VB sequence.

6. **Ask the subject to conduct the experiment. Counterbalance the orders of IOI types and sequence types among subjects.**
NOTE: Below is the procedure for one subject.
    1. Type "Bouncingball_run('AT', 600, 53.1, 29.8, 1)" in the command window and then press the 'Enter' key, to perform the 600-ms IOI AT sequence.
        1. Note that the subject will tap on a keyboard key using the index finger in synchrony with the tones in the AT sequence.

    2. Type "Bouncingball_run('VF', 600, 53.1, 29.8, 1)" in the command window and then press the 'Enter' key, to perform the 600-ms IOI VF sequence.
        1. Note that the subject will tap on a keyboard key using the index finger in synchrony with the flashing balls.

    3. Type "Bouncingball_run('VB', 600, 53.1, 29.8, 1)" in the command window and then press the 'Enter' key, to perform the 600-ms IOI VB sequence.
        1. Note that the subject will tap on a keyboard key using the index finger in synchrony with the moments when the bouncing ball moves to the lowest position (*i.e.*, touches the bar).

    4. Type "Bouncingball_run('AT', 900, 53.1, 29.8, 1)" in the command window and then press the 'Enter' key, to perform the 900-ms IOI AT sequence.
        1. Note that the subject will tap on a keyboard key using the index finger in synchrony with the tones in the AT sequence.

    5. Type "Bouncingball_run('VF', 900, 53.1, 29.8, 1)" in the command window and then press the 'Enter' key, to perform the 900-ms IOI VF sequence.
        1. Note that the subject will tap on a keyboard key using the index finger in synchrony with the flashing balls.

    6. Type "Bouncingball_run('VB', 900, 53.1, 29.8, 1)" in the command window and then press the 'Enter' key, to perform the 900-ms IOI VB sequence.
        1. Note that the subject will tap on a keyboard key using the index finger in synchrony with the moments when the bouncing ball moves to the lowest position (*i.e.*, touches the bar).

4. Programming of Data Analyses

NOTE: The programming of data analyses is already implemented in the script "BouncingBall_analyze.m" in the directory "BouncingBall", which can be opened and edited using a text edit software. Readers can set up or modify the settings as required, following the comments in the script. The raw synchronization data are a sequence of tap times. Use a circular method to analyze the variable periodic synchronization data, which has been detailed in[4,5,10]. Here, the present protocol describes a procedure to analyze the stability (R) of synchronization, using the circular statistics toolbox (*e.g.*, CircStat toolbox[11]), as described in Gan *et al.*[4]

1. Omit the taps to the first five events in the tap sequence because synchronization typically requires a few taps to stabilize.
2. **Compute asynchrony.**

1. For each tap sequence, calculate asynchrony as the difference between the time of a tap and the time of the corresponding event onset, resulting in a sequence of asynchronies.
NOTE: It is better to exclude invalid taps for each sequence. Invalid taps include missing tap (*i.e.*, there is no tap during the -1/2 to +1/2 IOI interval around an event) and multiple taps (*i.e.*, when there is more than one tap during the -1/2 to +1/2 IOI interval).
2. Convert the times (ms) of asynchronies into angles (degree) by asynchrony*(360/IOI). Then use function *circ_ang2rad*[11] to convert degrees into radians, which results in the relative phase (RP) on a unit circle.

3. **Compute synchronization stability (R).**
    1. For each asynchrony sequence, use function *circ_var*[11] to calculate the variance (S) of the RPs.
    2. Compute R using R = 1 - S.
    NOTE: R is the length of the resultant (*i.e.*, average of vectors) of the RPs, ranging from 0 (unstable tapping with uniformly distributed RPs) to 1 (perfectly stable tapping with a unimodal distribution of RPs).
    3. For each sequence type, calculate the mean value of the RPs of the 6 trials, as the R of that sequence type of that subject.

5. Performing Data Analyses

NOTE: Below is the analysis of data from one subject collected as introduced above. Performing data analyses is accomplished by typing "Bouncingball_analyze(RecordedFile)" in the command window of the software, which returns the mean and standard deviation (SD) of the stability.

1. For the 600-ms IOI AT sequence, type "Bouncingball_analyze('AT_600_53.1, 29.8.mat')" in the command window and then press the 'Enter' key.
2. For the 600-ms IOI VF sequence, type "Bouncingball_analyze('VF_600_53.1, 29.8.mat')" in the command window and then press the 'Enter' key.
3. For the 600-ms IOI VB sequence, type "Bouncingball_analyze('VB_600_53.1, 29.8.mat')" in the command window and then press the 'Enter' key.
4. For the 900-ms IOI AT sequence, type "Bouncingball_analyze('AT_900_53.1, 29.8.mat')" in the command window and then press the 'Enter' key.
5. For the 900-ms IOI VF sequence, type "Bouncingball_analyze('VF_900_53.1, 29.8.mat')" in the command window and then press the 'Enter' key.
6. For the 900-ms IOI VB sequence, type "Bouncingball_analyze('VB_900_53.1, 29.8.mat')" in the command window and then press the 'Enter' key.

Representative Results

One of the best-known results in SMS studies is that metronome synchronization is much more stable to an auditory sequence consisting of auditory tones than to a visual sequence consisting of visual flashes[1], suggesting modality-specific mechanisms of SMS[2]. However, recent studies have shown that periodically moving visual stimuli can substantially improve synchronization compared to visual flashes[3,4,5,6], and synchronization of a visual bouncing ball that has a uniformly varying velocity was found to be not less stable than synchronization of auditory tones[4]. The representative results are examples from a published work of our group[4]. There were 15 subjects in the experiment. A two-way repeated measures analysis of variance (ANOVA, with Greenhouse-Geisser corrections) with the factors sequence type (three sequence types) and IOI type (two IOI types) revealed a statistical main effect of sequence type ($F_{2,28}$ = 16.77, p = 0.001, *partial*η^2 = 0.55). The main effect of IOI type ($F_{1,14}$ = 0.88, p = 0.364, *partial* η^2 = 0.06) and interaction between the two factors ($F_{2,28}$ = 0.88, p = 0.401, *partial* η^2 = 0.06) were not statistically significant. The comparison of the stability between sequence types (t-test, with Bonferroni corrections) showed that for both 600-ms and 900-ms IOIs, the synchronization of the bouncing ball was much more stable than synchronization of visual flashes (600-ms IOI: t_{14} = 3.96, $p_{correccted}$ = 0.006, *Cohen's d* = 1.02; 900-ms IOI: t_{14} = 4.28, $p_{correccted}$ = 0.006, *Cohen's d* = 1.11), and was not less stable than synchronization of auditory tones (600-ms IOI: t_{14} = 2.95, $p_{correccted}$ = 0.066, *Cohen's d* = 0.76; 900-ms IOI: t_{14} = 2.06, $p_{correccted}$ = 0.348, *Cohen's d* = 0.53) (**Figure 2**).

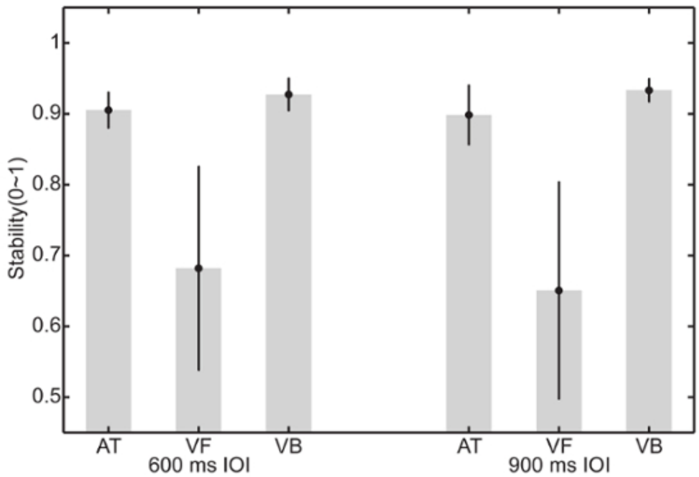

Figure 2: Synchronization stability (R) for the AT, VF, and VB sequences of 600-ms and 900-ms IOIs. Error bars indicate ± 95% confidence intervals. Other conventions are as in **Figure 1**. The figure is adapted from **Figure 2** in Gan *et al.*[4] (which is published under a Creative Commons Attribution 4.0 International License). Please click here to view a larger version of this figure.

Discussion

This protocol illustrates how to examine a bouncing ball with a uniformly varying velocity in a metronome synchronization task. Given its comparable synchronization performance to that of auditory tones, the bouncing ball is of particular importance for addressing the current research topic of whether SMS is modality specific.

The critical step in the current protocol is to introduce the uniformly varying velocity of the bouncing ball, and step-by-step instructions are provided to carry out the synchronization task and to analyze the synchronization data. The present protocol also illustrates how to use the bouncing ball for different IOIs by adopting different accelerations. Here it should be mentioned that the usage of the bouncing ball should be limited for IOIs not less than 300 ms. Gan *et al.*[4] have shown that the bouncing ball with a 300-ms IOI was too fast and looked unnatural to subjects, and was thus difficult to tap with the ball.

The bouncing ball is a useful tool for studying SMS and timing processing. While in this protocol the bouncing ball is illustrated in a simple metronome synchronization task and the representative results are from a behavioral study with normal subjects, future work could adopt the bouncing ball in investigation of: (1) synchronization to more complex rhythm sequences in which the metronome (or beat, in the musical context) is required to be extracted from complex sequences[12,13]; (2) perception of a timing deviation in a metronome[13,14]; (3) neural mechanisms underlying SMS[6]; and (4) patients with timing deficits, *e.g.*, Parkinson's patients[15,16].

Disclosures

The authors have nothing to disclose.

Acknowledgements

This work was supported by National Natural Science Foundation of China (31371129).

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