The Role of Global Configuration and Local Motion in Beat Synchronization to Biological Motion

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Abstract

This study investigates the effects of global configuration and local motion on beat synchronization with biological motion using an improved beat synchronization paradigm. Experiment 1 demonstrated that synchronization stability was significantly higher when the global configuration was preserved than when it was disrupted; following configuration disruption, whether the directional biological properties of local motion were preserved or disrupted had no significant impact on synchronization stability. Experiment 2, under conditions of configuration disruption, compared three local motion states and revealed that disrupting either directional biological properties or speed variation biological properties yielded no significant difference in synchronization stability compared to the condition where local motion biological properties were retained. Experiment 3 uncovered an interaction effect: when the configuration remained intact, disrupting the biological properties of local motion speed variation significantly reduced synchronization stability; when the configuration was disrupted, no difference in synchronization performance emerged between preserving or disrupting local motion biological properties. The results support a Bayesian mechanism of "global prior-local likelihood matching" : a humanoid configuration activates a biological motion template as a strong prior, and when local motion retains biological properties, the likelihood matches the prior, resulting in minimal prediction errors, reduced sensorimotor timing load, and optimal synchronization stability; when global configuration is disrupted, the strong prior cannot be established, the brain becomes insensitive to local motion biological properties, and thus synchronization performance converges regardless of whether local biological properties are preserved. The study demonstrates that global configuration dominates prior generation, while local biological properties only modulate sensorimotor timing when a prior exists, providing new evidence for the hierarchical processing mechanism of biological motion perception.

Full Text

Preamble

Title: The Influence of Global Configuration and Local Motion on Beat Synchronization with Biological Motion

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Abstract

This study investigated the effects of global configuration and local motion on beat synchronization with biological motion using an improved beat synchronization paradigm. Experiment 1 revealed that synchronization stability was significantly higher when global configuration was preserved compared to when it was disrupted. After configuration disruption, neither preserving nor destroying the biological nature of local motion direction significantly affected synchronization stability. Experiment 2, conducted under disrupted configuration, compared three local motion conditions and found that synchronization stability did not differ significantly between conditions that preserved local motion biological properties and those that destroyed either directional or speed variation biological properties. Experiment 3 uncovered a significant interaction: when global configuration remained intact, disrupting the biological nature of local speed variation significantly reduced synchronization stability; however, when configuration was disrupted, synchronization performance showed no difference between preserved and destroyed local motion biological properties.

These results support a Bayesian mechanism of "global prior–local likelihood matching." The human form configuration activates biological motion templates as strong priors. When local motion retains biological properties, the likelihood matches the prior, yielding minimal prediction error, reduced sensorimotor timing load, and optimal synchronization stability. When global configuration is disrupted, strong priors cannot be established, and the brain becomes insensitive to local motion biological properties. Consequently, synchronization performance converges regardless of whether local biological properties are preserved. This study demonstrates that global configuration dominates prior generation, while local biological properties only modulate sensorimotor timing when priors exist, providing new evidence for hierarchical processing mechanisms in biological motion perception.

Keywords: biological motion, beat synchronization, global configuration, local motion

1. Introduction

Biological motion (BM) refers to the holistic movement behaviors of humans or animals in space (Jiang & Wang, 2011). Research on biological motion typically employs point-light walker sequences as stimuli, which display the dynamic changes of major human joints (Johansson, 1973). Studies have shown that people can easily detect point-light walker sequences and extract extensive information about the moving agent, such as action orientation, gender, identity, emotion, and intention. Research indicates that humans possess the capacity to process biological motion as early as two days after birth, demonstrating the ability to recognize point-light walker sequences and showing preferential looking (Bertenthal, 1993). This ability improves with age, approaching adult levels by age 5 (Pavlova et al., 2001) and remaining robust into old age (Norman et al., 2004). Thus, biological motion processing represents a fundamental cognitive capacity in humans, characterized by early emergence, rapid development, and long-term maintenance throughout the lifespan.

1.1 Biological Motion Beat Synchronization and Its Evolutionary Significance

Biological motion inherently contains rhythm. This rhythm sometimes emerges from the repetition of single actions (e.g., alternating footsteps during walking) and sometimes from the repetition of action combinations (e.g., the recurring pattern of turn, spin, and pivot in waltz). The ability to synchronize one’ s actions with the beat of biological motion rhythm is a fundamental human capacity known as biological motion beat synchronization, which constitutes a sensorimotor synchronization process based on biological motion. Sensorimotor synchronization refers to the process by which humans coordinate their actions with temporal regularities in sensory input (typically manifested as beats in a sequence), with the underlying mechanism being a timing process based on real-time coupling between sensory and motor systems. Beat synchronization with biological motion stimuli holds significant practical implications for human survival. For instance, unified movements in dance enhance performance impact, while synchronized marching in military formations boosts morale and deters enemies. Furthermore, Jordania’ s (2011) Audio-Visual Intimidating Display model proposes that organized, rhythmic group synchronization in early humans could signal unity and strength to predators, while individual participation in such synchronized actions could reduce fear and pain, suggesting important evolutionary significance for biological motion beat synchronization.

1.2 Current Status of Biological Motion Beat Synchronization Research

Research on biological motion beat synchronization remains relatively scarce. Su (2016a) employed dance movements containing two metrical periodicities as experimental stimuli to investigate biological motion rhythm synchronization. In these dance movements, the torso bounced once per beat while the limbs moved once every two beats, creating two distinct metrical levels. Results showed that participants could freely choose either metrical level as the beat for synchronization, consistent with findings in the auditory domain. Su (2016b) also discovered a “subdivision effect”in biological motion rhythm synchronization similar to that observed in auditory rhythm synchronization: when the beat represented by leg movements was subdivided by the addition of torso movements, participants' synchronization accuracy and stability both improved. These studies on human dance movement synchronization focused on complex rhythms containing multiple metrical levels, leaving the investigation of beat synchronization with single repetitive biological motions (e.g., walking, jumping jacks) largely unexplored. Such biological motion beat synchronization represents an important form of sensorimotor synchronization.

Using EEG technology, Shen et al. (2023) recorded brain responses to gait cycles (the cycle formed by alternating left and right foot movements during walking) and step cycles (the cycle formed by each individual step) while participants viewed human walking movements. The gait cycle provides information about the phase relationship between left and right limb movements, which the step cycle lacks. They found that at the frequency corresponding to the gait cycle (1 Hz), cortical neural oscillatory activity showed an inversion effect: upright biological motion stimuli elicited significantly stronger neural entrainment than inverted stimuli. In contrast, at the frequency corresponding to the step cycle (2 Hz), both upright and inverted biological motion stimuli elicited strong neural entrainment with no significant difference between them. These results suggest that the brain' s rhythmic neural activity encoding of gait cycles exhibits biological motion processing specificity. Although Shen et al. (2023) did not require participants to perform explicit synchronization actions with the biological motion beat, the phenomenon where high-excitability phases of brain neural oscillations align with the occurrence of external periodic events is known as implicit synchronization, which may form the basis of beat synchronization (Repp & Su, 2013). This suggests that the biological motion-specific effects of walking movement processing discovered by Shen (2023) at the neural oscillation level may also manifest at the behavioral level (i.e., beat synchronization).

1.3 The Roles of Global Configuration and Local Motion in Biological Motion Perception

For biological motion, global configuration and local motion represent important information from two distinct levels. Local motion refers to the trajectory and velocity information provided by the movement of each point-light, whereas global configuration refers to the body shape information formed by integrating the positional information of all points in the point-light walker sequence (Jiang & Wang, 2011). Compared to the low-level physical information provided by local motion (such as velocity and trajectory), global configuration constitutes higher-order information. Both global configuration and local motion characteristics of biological motion influence related perceptual processes (Sun et al., 2022; Wang et al., 2010).

Global configuration plays an independent and critical role in biological motion perception. Bertenthal and Pinto (1994) found that when target joint points were masked by multiple distractor points with identical motion trajectories but random spatial positions, observers could still detect upright point-light walkers in a present/absent judgment task, while detection rates for inverted displays dropped to chance level. This demonstrates that human body form is perceived directly as an emergent global property rather than through initial detection and subsequent combination of local features. The inversion effect further supports the global processing view. Similar to face perception (Yin, 1969), vertically rotating biological motion stimuli by 180 degrees significantly impairs performance in target detection, action recognition, and direction discrimination tasks (Bertenthal & Pinto, 1994; Dittrich, 1993), an effect attributed to disruption of global structural information rather than damage to local motion information. Technological dissociation studies provide more direct evidence. Beintema and Lappe (2002) used limited-lifetime techniques to remove local motion information while preserving static configuration information, finding that observers could still recognize walking direction, with performance correlating with the number of point-lights (providing configuration information) rather than presentation duration (providing local motion information). This supports a template-matching model based on shape information accumulation, which posits that the visual system stores a library of static postural templates of the human body and recognizes biological motion by matching input point-light positions with these static templates (Lange et al., 2006). Neuroimaging research further reveals the neural basis of this mechanism: Thompson et al. (2005) found that the superior temporal sulcus (STS) showed stronger activation for intact walkers than for walkers with scrambled limbs and torsos, regardless of whether stimuli were partially occluded (which disrupts local features and continuous visibility of joint connections), indicating that the STS employs holistic body configuration models rather than local feature tracking to process biological motion. These findings collectively demonstrate that global configuration plays a crucial role in biological motion perception.

Local motion information also plays an independent and important role in biological motion perception. Mather et al. (1992) manipulated the inter-frame intervals and number of blank frames in point-light sequences, finding that observers' ability to perceive biological motion was impaired as these intervals increased. Since increasing inter-frame intervals disrupts local motion information (i.e., the processing of each point' s motion trajectory) while leaving global shape information processing unaffected, this indicates that local motion information is essential for biological motion processing. Inversion effects based on local motion challenge single-factor explanations of the phenomenon. Troje and Westhoff (2006) discovered an inversion effect independent of global structural information: using scrambled biological motion sequences (which disrupt global structure while preserving local motion), observers could still discriminate human walking direction but failed to do so when the sequences were inverted.

Further research showed that inverting only the two point-lights representing the feet was sufficient to produce this effect, which depends on the vertical gravitational acceleration of foot movements, demonstrating that local motion itself contains specific biological information. These results indicate that biological motion perception is not a unitary phenomenon but rather a multi-level phenomenon involving different processing mechanisms (structure-based and local motion-based), with local motion information capable of functioning independently of global configuration to make important contributions to biological motion perception.

1.4 Potential Roles of Global Configuration and Local Motion in Biological Motion Beat Synchronization

The roles of global configuration and local motion in biological motion beat synchronization remain unexplored. In the aforementioned Shen (2023) study, the comparison of neural oscillation strength elicited by upright versus inverted biological motion at the gait cycle frequency could not dissociate the unique contributions of global configuration and local motion information to biological motion beat synchronization, as inversion simultaneously disrupts both types of information. From a Bayesian perception framework, the process of biological motion beat synchronization may follow a "global prior–local likelihood matching" mechanism. On one hand, based on the "global precedence principle" in visual processing (Navon, 1977; Kimchi, 1994; Navon, 2003), global configuration information may be processed prior to local motion information when biological motion enters the observer' s visual field. Within the Bayesian perception framework, intact human configuration can activate stored biological motion templates in the brain, forming strong prior expectations about movement temporal structure (Lange et al., 2006; Lange & Lappe, 2006). These priors provide observers with a framework for organizing and predicting local motion information (Adams et al., 2013; Keller & Mrsic-Flogel, 2018). Therefore, we expect global configuration information to enhance beat-based sensorimotor timing, manifested as improved biological motion beat synchronization.

On the other hand, the biological nature of local motion determines the quality of its likelihood information. Previous studies have found that beat synchronization performance is optimal when following a ball bouncing with realistic motion trajectory compared to uniform or sinusoidal motion (Gan et al., 2015; Zhou et al., 2020). For local motion in biological motion, constrained jointly by gravity and biomechanics (Cavagna et al., 1977; Troje & Westhoff, 2006), local motion patterns possess biological characteristics. When local motion maintains biological properties, the sensory likelihood information it provides matches the biological motion prior highly, minimizing prediction error and yielding optimal biological motion beat synchronization performance. When local motion patterns are disrupted, prior-likelihood matching decreases, prediction error increases, and beat-based sensorimotor timing is consequently affected, reducing biological motion beat synchronization stability.

More importantly, global configuration and local motion may interactively influence biological motion beat synchronization based on the “global prior-local likelihood matching” mechanism. When global configuration is intact, strong priors are successfully activated, and the biological nature of local motion determines the degree of matching between likelihood information and priors: when local motion maintains biological properties and matches existing template predictions, prior-likelihood matching is high, sensorimotor timing load is low, and synchronization performance is optimal; when local motion is disrupted, matching decreases and synchronization stability is reduced. However, when global configuration information is disrupted, existing templates for human movement cannot be activated, strong priors for biological motion cannot be established or are only weakly activated, and the brain relies primarily on bottom-up sensory input for timing, reducing sensitivity to changes in local motion biological properties. Consequently, the difference in synchronization performance between preserved and disrupted local motion biological properties may be minimal.

1.5 Research Questions and Design

This study aimed to investigate the independent and interactive roles of global configuration and local motion in biological motion beat synchronization, revealing the hierarchical processing principles of biological motion sensorimotor timing. Through three progressive experiments, we systematically dissociated the effects of global configuration and local motion on beat synchronization and explored how they jointly influence sensorimotor synchronization performance. Experiment 1 examined the role of global configuration in biological motion beat synchronization (standard BM stimuli vs. scrambled BM stimuli) and investigated the effect of local motion by destroying directional biological properties through inversion (scrambled BM stimuli vs. inverted scrambled BM stimuli). Experiment 2, under the premise of disrupted global configuration, examined differences in biological motion beat synchronization performance after destroying local motion information biological properties through different methods. Specifically, we compared synchronization stability across three stimulus conditions: scrambled BM (preserving local motion biological properties), inverted scrambled BM (destroying local motion directional biological properties), and scrambled uniform BM (destroying local motion speed variation biological properties). Building on Experiments 1 and 2, Experiment 3 tested whether an interaction exists between global configuration and local motion effects on biological motion beat synchronization by comparing synchronization stability across four stimulus conditions: standard BM, scrambled BM, standard uniform BM, and scrambled uniform BM.

The innovations of this study are twofold. First, it is the first to investigate factors influencing sensorimotor timing based on biological motion, systematically examining the independent and interactive effects of global configuration and local motion in biological motion beat synchronization, thereby filling a research gap in this domain. Second, theoretically, it is the first to incorporate biological motion beat synchronization within a Bayesian perception framework, proposing a hierarchical processing mechanism of "global prior-local likelihood matching" that offers a novel explanatory perspective for biological motion processing theories.

2. Experiment 1: The Role of Global Configuration and Local Motion in Biological Motion Beat Synchronization

Experiment 1 disrupted global configuration information by spatially scrambling point-light positions and destroyed the biological nature of local motion information by inverting joint point-lights to mirror-flip motion vector directions. Specifically, by comparing beat synchronization stability between standard BM and scrambled BM conditions, we investigated the role of global configuration information in biological motion beat synchronization. By comparing scrambled BM and inverted scrambled BM conditions, we examined the role of local motion information in biological motion beat synchronization while controlling for global configuration information.

2.1 Methods

2.1.1 Sample Size Planning We used G*Power 3.1 to estimate sample size. This study aimed to examine the effects of global configuration (standard BM vs. scrambled BM) and local motion (scrambled BM vs. inverted scrambled BM) on biological motion beat synchronization.

For the global configuration effect, Troje et al. (2006) found a performance difference of 0.19 between standard and scrambled BM conditions in a direction discrimination task, corresponding to Cohen' s d = 1.14. Sun et al. (2017) reported a difference of 0.36 between these conditions in a motion detection task, corresponding to Cohen' s d = 0.8. Based on these effect sizes, the required sample sizes were calculated as 13 and 20 participants, respectively, for a two-tailed test at $\alpha = 0.05$ with power = 0.95.

For the local motion effect, Troje et al. (2006) found a performance difference of 0.38 between scrambled and inverted scrambled BM conditions, corresponding to Cohen' s d = 1.59. Based on this effect size, the required sample size was 8 participants for a two-tailed test at $\alpha = 0.05$ with power = 0.95.

Considering both types of effects, we determined that each experiment should include no fewer than 20 participants to ensure adequate statistical power. Based on this estimation, Experiment 1 planned to recruit 30 participants, which satisfied the statistical power requirements.

2.1.2 Participants Thirty Chinese university students (24 females, mean age = 19.6 years, SD = 1.5) participated in the experiment. All participants were healthy, with normal hearing and vision (or corrected-to-normal vision), right-handed, and had no history of mental illness. They received compensation after completing the experiment. This study was approved by the Research Ethics Committee of the School of Psychology at Shandong Normal University. All participants in Experiment 1 signed informed consent forms prior to participation and received compensation afterward.

2.1.3 Stimuli Stimuli were programmed and presented using MATLAB 2016b and Psychophysics Toolbox Version 3 (PTB-3) on a monitor with a resolution of 1920$×$1080 and a refresh rate of 100 Hz.

We designed three types of visual motion stimulus sequences with equal temporal intervals: standard BM, scrambled BM, and inverted scrambled BM (see Figure 1 [Figure 1: see original paper]). Stimuli were created based on biological motion data provided by Van Boxtel and Lu (2013) (file name: Walker.txt, hereafter referred to as the original animation). Standard BM stimuli contained 13 points distributed across the head (1 point), shoulders (2 points), hips (2 points), elbows (2 points), wrists (2 points), knees (2 points), and ankles (2 points). The standard BM stimulus size was 4.76°$×$2.86°. In standard BM, each forward step of the left or right foot constituted an independent step cycle, while the alternating movement of both feet formed a higher-order gait cycle. A complete gait cycle required one full walking loop, for example, starting with the left foot stepping forward, followed by the right foot stepping, until the left foot was ready to step forward again (Shen et al., 2023). The original animation contained 133 frames. Since frame 98 represented the moment when the left foot landed, we designated this frame as the first frame of our experimental animation. Consequently, one stimulus cycle in our experimental animation extended from frame 98 of the original animation to frame 97 of the next cycle (constituting one gait cycle). To ensure equal duration between left foot landing to right foot landing and right foot landing to left foot landing, we removed frame 67 from the original animation (which showed minimal change from frames 66 and 68, so its removal did not affect motion continuity). After removal, each step cycle contained 66 frames with a duration of 660 ms. We used the step cycle as the beat interval for following the biological motion stimulus, setting the beat rate at 660 ms/beat, which approximates humans' preferred beat rate (approximately 600 ms/beat) (Repp, 2005).

Scrambled BM stimuli were created by randomly scrambling the starting positions of each point-light in the standard BM stimulus while preserving their motion patterns, thereby disrupting global configuration information while retaining local motion information. Inverted scrambled BM stimuli were created by mirror-flipping the scrambled BM stimuli along the horizontal axis, disrupting both global configuration information and the biological nature of local motion information by altering motion direction. The height and width of scrambled and inverted scrambled BM stimuli were identical to those of standard BM stimuli. The frame selection method, cycle definition criteria, and beat interval (660 ms) were consistent with the standard BM stimulus.

During visual motion stimulus presentation, a fixation point remained at the center of the screen (see Figure 2 [Figure 2: see original paper]). The fixation point was an inverted brown solid equilateral triangle subtending 0.38°, positioned 2.38° above the lowest point of the stimulus motion trajectory. Four red dots (0.18°) were continuously presented around the visual motion stimulus (at the four vertices of the stimulus' s virtual rectangular bounding box). The virtual rectangle (3.35°$×$5.72°) determining the positions of the four red dots was centered on the fixation point with sides parallel to the screen edges; the virtual rectangle itself was not displayed during the experiment.

2.1.4 Procedure Participants sat 60 cm from the display screen. The three stimulus conditions (standard BM, scrambled BM, and inverted scrambled BM) were presented in separate blocks, with block order counterbalanced across participants. Each block consisted of practice sessions (Practice 1 and Practice 2) followed by the formal experiment.

For visual motion stimuli containing multiple moving points, we could not arbitrarily designate a specific state as the beat occurrence moment because different participants might perceive the "beat point" differently. For instance, some might perceive the moment when the left foot lands as the beat point, while others might perceive the beat point as when other joints reach inflection points in their motion. Therefore, this study employed an improved beat synchronization paradigm. In Practice 1, we used an auditory guide sequence to first establish the beat tempo for participants, who were then required to maintain this tempo during the subsequent visual motion stimulus sequence and voluntarily choose which motion state corresponded to beat occurrence. Specifically, in each trial of Practice 1, an auditory guide sequence (containing 5 beat intervals) was presented first, followed by a 2-s black blank screen. After the blank screen, the visual motion stimulus sequence for the current block was presented (containing 14 beat intervals). Throughout this process, participants were required to maintain fixation and synchronize their tapping with the stimulus sequence. While performing the beat synchronization task, participants also completed a peripheral red dot change detection task. Practice 1 contained two trials. After completing Practice 1, if participants reported that they could stably synchronize with the visual motion stimulus sequence, they proceeded to Practice 2; otherwise, they returned to Practice 1 for additional practice. Practice 2 also contained two trials, with each trial identical to Practice 1 except for the absence of the auditory guide sequence. After completing practice, participants entered the formal experiment for that block.

In the formal experiment, each visual motion stimulus condition block contained 16 trials. Except that each trial sequence contained 24 beat intervals, all other settings were consistent with Practice 2.

2.1.5 Analysis We included trials without red dot color changes in each visual motion stimulus condition for repeated measures ANOVA, with stimulus type as the independent variable and the standard deviation of participants' inter-tap intervals (ITI) as the dependent variable (Repp, 2005). Smaller ITI standard deviation indicates higher beat synchronization stability. Specifically, ITI refers to the time interval between participants’ consecutive key presses. We calculated the dependent variable using the following steps: (1) excluded the first 5 taps in each trial to eliminate initial synchronization instability (Repp, 2005); (2) calculated the standard deviation of remaining tap intervals within each trial; (3) averaged the standard deviations across formal experiment trials as the final dependent variable. ITI standard deviation is a classic measure in beat synchronization research, with lower values indicating higher synchronization stability, meaning participants can more consistently maintain the target rhythm (Repp, 2005; Repp & Su, 2013).

Data exclusion criteria were as follows: (1) We calculated participants’ accuracy on the red dot change detection task for each visual motion stimulus condition. Low accuracy on this task suggests that participants may not have allocated attention to the global visual motion stimulus. If a participant’ s accuracy in any stimulus condition fell below 75%, all data from that participant were excluded (Slotboom et al., 2017). (2) The auditory guide beat interval was 660 ms. If a participant in any stimulus condition failed to tap at the guided rate (ITI mean $<$ 600 ms or $>$ 700 ms), all data from that participant were excluded. This criterion was based on Patel et al.’ s (2005) report of ITI mean variability under visual flicker conditions: in an “800 ms stimulus interval, 800 ms beat interval” condition, individual differences in participants’ ITI means ranged from 775-825 ms (approximately \$±\$3.1% of the target value); in a “400 ms stimulus interval, 800 ms beat interval” condition, excluding one extreme value, ITI means ranged from 750-850 ms (approximately \$±\$6.2% of the target). Considering that our task required participants to voluntarily choose a motion state in the biological motion as the beat point after auditory guidance, imposing higher cognitive load, we set the acceptable ITI range at 600-700 ms (approximately \$±\$9.1% deviation from the 660 ms target). (3) ITI standard deviation reflects tapping interval stability; extremely high values typically indicate failure to find a stable beat point, attentional distraction, task misunderstanding, or extreme motor coordination deficits. We excluded extreme data beyond the boundary of the group mean + 3 standard deviations for the ITI standard deviation measure. According to these criteria, all participants in Experiment 1 met the inclusion standards.

2.2 Results

A one-way repeated measures ANOVA revealed significant differences in biological motion beat synchronization stability across stimulus types, $F(2, 58) = 4.60$, $p = 0.014$, $p^2 = 0.14$. Bonferroni post-hoc tests showed that: (1) beat synchronization stability in the standard BM condition ($M = 0.05$, $SD = 0.01$) was significantly higher than in both the scrambled BM condition ($M = 0.05$, $SD = 0.01$), $p = 0.004$, and the inverted scrambled BM condition ($M = 0.05$, $SD = 0.01$), $p = 0.033$; (2) there was no significant difference in beat synchronization stability between the scrambled BM and inverted scrambled BM conditions, p = 0.387 (see Figure 3 [Figure 3: see original paper]).

2.3 Discussion

Experiment 1 results showed that beat synchronization stability was significantly higher in the standard BM condition compared to both scrambled and inverted scrambled BM conditions, indicating that global configuration information facilitates sensorimotor synchronization induced by biological motion stimuli. This result aligns with expectations. However, the absence of a significant difference in beat synchronization stability between scrambled and inverted scrambled BM conditions was unexpected. Compared to scrambled BM, inverted scrambled BM only altered the direction of local motion vectors (e.g., acceleration, velocity, displacement) without changing the temporal patterns of these vectors' magnitudes, which may have preserved biological cues that could assist beat synchronization. Therefore, Experiment 2 aimed to disrupt the biological nature of local motion information by eliminating point-light acceleration.

3. Experiment 2: Effects of Different Methods of Disrupting Local Motion Biological Properties on Beat Synchronization

Experiment 1 revealed the facilitating effect of global configuration information on biological motion beat synchronization. However, because inversion only changed the direction of local motion vectors while preserving their speed variation patterns, substantial biological information in local motion may have remained. To address this limitation, Experiment 2 introduced scrambled uniform BM stimuli: based on scrambled BM stimuli, we preserved each point-light' s trajectory while eliminating motion acceleration, making each point' s velocity constant at its original mean rate. This method disrupts the biological nature of local motion information in terms of speed variation patterns.

Specifically, by comparing beat synchronization stability across scrambled BM, inverted scrambled BM, and scrambled uniform BM conditions, we investigated how different methods of disrupting local motion biological properties affect biological motion beat synchronization.

3.1 Methods

3.1.1 Sample Size Planning Sample size calculation was based on the same effect size estimation as Experiment 1, yielding a required sample size of no fewer than 20 participants. Based on this estimation, Experiment 2 planned to recruit 30 participants, which satisfied the statistical power requirements.

3.1.2 Participants Thirty Chinese university students (25 females, mean age = 19.5 years, SD = 1.3) participated in the experiment. All participants were healthy, with normal hearing and vision (or corrected-to-normal vision), right-handed, and had no history of mental illness. They received compensation after completing the experiment. This study was approved by the Research Ethics Committee of the School of Psychology at Shandong Normal University. All participants in Experiment 2 signed informed consent forms prior to participation and received compensation afterward.

3.1.3 Stimuli We used biological motion data from the Van Boxtel and Lu (2013) biological motion toolbox to create three types of stimuli: scrambled BM, inverted scrambled BM, and scrambled uniform BM. The scrambled and inverted scrambled BM stimuli were identical to those in Experiment 1. The scrambled uniform BM stimulus was created by preserving each point-light’ s motion trajectory while removing motion acceleration, making each point’ s velocity constant at its original mean rate. The auditory guide sequence was identical to that used in Experiment 1.

3.1.4 Procedure The procedure was identical to that of Experiment 1.

3.1.5 Analysis The analysis method and data exclusion criteria were identical to those in Experiment 1. One participant met exclusion criterion (2): ITI means in both inverted-scrambled BM and uniform-scrambled BM conditions exceeded the upper limit of 700 ms. Two participants met exclusion criterion (3): ITI standard deviation exceeded the group mean by three standard deviations. Data from these three participants were excluded, leaving a final sample of 27 participants (23 females) for data analysis.

3.2 Results

A one-way repeated measures ANOVA revealed no significant differences in biological motion beat synchronization stability across stimulus types, $F(2, 52) = 1.23$, $p = 0.297$, $p^2 = 0.05$ (see Figure 4 [Figure 4: see original paper]).

3.3 Discussion

Experiment 2 found no significant differences in biological motion beat synchronization stability among scrambled BM, inverted scrambled BM, and scrambled uniform BM conditions, indicating that when global configuration information is disrupted, whether local motion information is destroyed has no significant effect on synchronization stability. All three stimulus types had disrupted global configuration information. Global configuration information may provide observers with a framework for organizing and processing local motion information, thereby facilitating the prediction and capture of periodic spatiotemporal information in biological motion and enhancing beat synchronization stability. When global configuration information is disrupted, biological motion cannot provide a processing framework for organizing local motion information, so the effect of local motion information on beat synchronization may only occur when global configuration information remains intact. This hypothesis was tested in Experiment 3.

4. Experiment 3: Interactive Effects of Global Configuration and Local Motion on Beat Synchronization

The results of Experiment 2 indicated that manipulating local motion information alone (preserving or destroying its biological properties) did not significantly affect biological motion beat synchronization performance. This finding suggests that local motion information may only function under specific conditions, with the integrity of global configuration information being a potential key factor. Based on this, Experiment 3 systematically examined the interactive effects of global configuration and local motion information on biological motion beat synchronization.

Experiment 3 employed a 2 × 2 factorial design, manipulating global configuration (preserved vs. disrupted) and local motion (preserved vs. disrupted) to create four experimental conditions: (1) standard BM stimulus (preserved global configuration, preserved local motion); (2) scrambled BM stimulus (disrupted global configuration, preserved local motion); (3) standard uniform BM stimulus (preserved global configuration, disrupted local motion); and (4) scrambled uniform BM stimulus (disrupted global configuration, disrupted local motion). By comparing beat synchronization stability across these four conditions, we could clarify the interactive effects of the two types of information.

4.1 Methods

4.1.1 Sample Size Planning Sample size calculation was based on the same effect size estimation as Experiment 1, yielding a required sample size of no fewer than 20 participants. Based on this estimation, Experiment 3 planned to recruit 35 participants, which satisfied the statistical power requirements.

4.1.2 Participants Thirty-five Chinese university students (28 females, mean age = 19.4 years, SD = 1.2) participated in the experiment. All participants were healthy, with normal hearing and vision (or corrected-to-normal vision), right-handed, and had no history of mental illness. They received compensation after completing the experiment. This study was approved by the Research Ethics Committee of the School of Psychology at Shandong Normal University. All participants in Experiment 3 signed informed consent forms prior to participation and received compensation afterward.

4.1.3 Stimuli We used biological motion data from the Van Boxtel and Lu (2013) biological motion toolbox to create four types of stimuli: standard BM, scrambled BM, standard uniform BM, and scrambled uniform BM. Standard and scrambled BM stimuli were identical to those in Experiment 1. Scrambled uniform BM stimuli were created as in Experiment 2. Standard uniform BM stimuli were created by preserving each point-light’ s motion trajectory while removing motion acceleration, making each point’ s velocity constant at its original mean rate. The auditory guide sequence was identical to that used in Experiment 1.

4.1.4 Procedure The procedure was identical to that of Experiment 1.

4.1.5 Analysis The analysis method and data exclusion criteria were identical to those in Experiment 1. Two participants met exclusion criterion (3): ITI standard deviation exceeded the group mean by three standard deviations. Data from these two participants were excluded, leaving a final sample of 33 participants (27 females) for data analysis.

4.2 Results

As shown in Figure 5 [Figure 5: see original paper], a two-way repeated measures ANOVA revealed a significant main effect of global configuration, F(1, 32) = 10.12, p = 0.003, $p^2 = 0.24$, with higher beat synchronization stability when global configuration was preserved than when it was disrupted. The main effect of local motion was not significant, F(1, 32) = 0.41, p = 0.525, $p^2 = 0.01$. The interaction between global configuration and local motion was significant, F(1, 32) = 4.32, p = 0.046, $p^2 = 0.12$. Further simple effects analysis revealed that when global configuration was preserved, beat synchronization stability was significantly higher in the local acceleration condition (M = 0.05, SD = 0.02) than in the local uniform condition (M = 0.05, SD = 0.02), F(1, 32) = 4.63, p = 0.039, $p^2 = 0.13$. When global configuration was disrupted, there was no significant difference in beat synchronization stability between local acceleration (M = 0.05, SD = 0.02) and local uniform (M = 0.05, SD = 0.02) conditions, F(1, 32) = 1.34, p = 0.256, $p^2 = 0.04$.

4.3 Discussion

Experiment 3 found a significant interactive effect of global configuration and local motion on biological motion beat synchronization stability: when global configuration information was preserved, disrupting the biological nature of local motion information significantly reduced synchronization stability; when global configuration information was disrupted, destroying local motion biological properties had no significant effect on synchronization stability. This interaction indicates that the effect of local motion information on beat synchronization depends on the integrity of global configuration. When the complete human form configuration is present, the biological nature of local motion becomes a key factor affecting synchronization performance; when global configuration is disrupted, the effect of local motion biological properties disappears. This hierarchical processing pattern supports the “global prior-local likelihood matching” mechanism within the Bayesian predictive coding framework: global configuration activates biological motion priors, and local motion information as likelihood evidence promotes synchronization when it matches the prior; when priors are absent, local information loses its matching template, and its biological features no longer affect synchronization performance.

5. General Discussion

This study employed an improved beat synchronization paradigm to investigate the effects of global configuration and local motion on biological motion beat synchronization through three progressive experiments.

First, Experiment 1 found that preserving global configuration significantly enhanced biological motion beat synchronization stability. This finding is consistent with previous research demonstrating the important facilitating role of global configuration information in tasks such as biological motion detection, direction discrimination, and biologicalness rating (Chang & Troje, 2008; Shiffrar et al., 1997; Bertenthal & Pinto, 1994; Beintema et al., 2006). Global configuration may provide a prior template for organizing and processing local motion information, which strengthens individuals' predictive abilities and improves the accuracy of beat capture.

Second, Experiments 1 and 2 investigated the independent role of local motion information. Experiment 1 found no significant difference in beat synchronization stability between inverted scrambled and scrambled biological motion. Since inversion only altered the direction of local motion vectors while preserving speed variation patterns, and since speed variation patterns themselves may contain rich biological information, Experiment 2 employed a more stringent manipulation—eliminating acceleration changes in point-light motion to create scrambled uniform BM stimuli, thoroughly destroying the biological nature of local motion in the temporal dimension. Results showed no significant differences in synchronization stability across the three conditions (scrambled, inverted scrambled, scrambled uniform). Both experiments consistently demonstrated that local motion information cannot independently influence beat synchronization performance when global configuration is absent.

These results appear to contrast with previous findings. For example, Troje and Westhoff (2006) found that observers could judge movement direction from scrambled biological motion, and Hirai et al.' s (2003) ERP research showed that the brain still exhibited specific responses to local biological motion under scrambled conditions. However, these studies differ critically from the present research in task nature—previous studies primarily used perceptual judgment tasks (e.g., direction discrimination), whereas this study employed a sensorimotor synchronization task requiring continuous temporal prediction and motor execution. The processing demands also differ: perceptual tasks may only require detecting the presence of local motion features, whereas beat synchronization requires precisely extracting and utilizing temporal information to guide action output. This suggests that without the prior template provided by global configuration, the biological features of local motion may be insufficient to support stable sensorimotor coordination.

Finally, Experiment 3 further examined the interactive effects of global configuration and local motion on biological motion beat synchronization. The results revealed a significant interaction: when global configuration information was preserved, disrupting the biological nature of local motion information significantly reduced synchronization stability; when global configuration information was disrupted, whether local motion biological properties were destroyed had no significant effect on synchronization stability.

This "global-dependency" pattern of local information processing discovered in our study aligns with the theoretical mechanism of "global prior–local likelihood matching." Specifically, the intact human form configuration enables the brain to establish strong biological motion prior expectations. Under this condition, local motion preserving biological features (e.g., natural acceleration changes) serves as likelihood information that highly matches prior expectations, minimizing prediction error and facilitating stable sensorimotor synchronization. Conversely, disrupting local motion biological properties (e.g., uniform motion) violates expected biological motion patterns, generating larger prediction errors and impairing synchronization performance. When global configuration is disrupted, the brain cannot establish effective biological motion priors and loses the reference standard for evaluating local motion biological properties. In this situation, the brain' s sensitivity to different local motion features decreases significantly, causing synchronization performance across various local motion conditions to converge.

Our findings resonate with similar phenomena in other domains. Gan et al. (2015) found that a ball accelerating downward in the direction of gravity produced more stable beat synchronization than a uniform-motion ball, but Zhou et al. (2020) discovered this advantage disappeared when motion was against gravity. This pattern strikingly mirrors our results: the direction of gravity activates physical motion priors, just as human form configuration activates biological motion priors; only when priors exist can expected local features promote synchronization. This cross-domain consistency supports a general principle of perception-action systems: prior knowledge modulates the processing weight of sensory information.

Neural pathway theories provide an alternative explanatory framework for our findings at the mechanistic level. The traditional dual-pathway model distinguishes between a ventral "what" pathway (V1 → V4 → IT, processing object shape and recognition) and a dorsal "where/how" pathway (V1 → MT → parietal cortex, processing spatial location and motion) (Ungerleider & Mishkin, 1982). Recent research has proposed a third visual pathway projecting from V1 via MT/V5 to the superior temporal sulcus (STS), specialized for processing dynamic social information such as biological motion (Pitcher & Ungerleider, 2021). Notably, Gilaie-Dotan et al. (2015) found that patients with severe ventral pathway damage could still perceive biological motion normally, indicating that biological motion processing has a unique neural basis. Based on this neuroanatomical evidence, our findings may reflect functional division of labor and interaction patterns among different visual pathways when processing biological motion. Global configuration may establish a spatiotemporal representation framework for biological motion through rapid global processing (likely involving higher visual areas such as STS), providing organizational principles and expected structures for subsequent fine processing. Local motion information (e.g., joint acceleration changes) is continuously processed in motion-sensitive areas such as MT/V5, but its behavioral impact depends on whether it can be integrated into the representation framework established by global configuration. When global configuration is scrambled, although local motion features are still encoded by the visual system, the lack of an organizational framework prevents these features from being effectively transformed into temporal prediction signals that guide sensorimotor synchronization.

This explanation aligns with recent understanding of visual pathway interactions—pathways are not independent parallel processors but exhibit extensive interconnections and functional integration. Global configuration information may modulate the efficiency or weight of local motion processing through top-down feedback connections, with this modulatory effect disappearing when configuration is disrupted. Importantly, this neural architecture-level explanation and the Bayesian "global prior-local likelihood matching" explanation actually describe different levels of the same phenomenon—the former focusing on implementation mechanisms, the latter on computational principles.

Although this study proposes a Bayesian framework of "global prior-local likelihood matching" to explain our results, two key limitations remain. First, we lack direct validation through quantitative Bayesian modeling. Our paradigm cannot quantify the strength of priors provided by global configuration, the likelihood functions of local motion, or their dynamic integration process. Future research should construct formal Bayesian models, manipulate stimulus uncertainty to estimate the relative precision of priors and likelihoods, and use model comparison to quantitatively evaluate different theoretical hypotheses. Second, we lack neuroimaging evidence. Although we speculate that the STS may be responsible for global configuration recognition and prior generation while MT/V5 encodes local motion information, this functional division and its interaction mechanisms require verification. Future studies could combine the spatial resolution of functional magnetic resonance imaging with the temporal resolution of magnetoencephalography or electroencephalography, use model-based analyses to predict neural activity from internal variables of Bayesian models, and employ causal intervention techniques such as TMS to verify the functional roles of key brain regions, thereby deepening understanding of the mechanisms underlying biological motion sensorimotor coordination.

In summary, this study has several theoretical implications. First, it validates the domain generality of hierarchical processing mechanisms. Through sensorimotor synchronization experiments, we demonstrated that intact human form configuration serves as a strong prior representation that can top-down organize local motion information, significantly reducing uncertainty in sensorimotor timing and thereby enhancing synchronization stability. This shows that the global precedence principle in information processing applies not only to traditional perceptual judgment tasks (Johansson, 1973; Navon, 1977; Blake & Shiffrar, 2007) but also extends to the domain of sensorimotor temporal coordination, deepening our understanding of the generality of hierarchical processing mechanisms in biological motion. Second, it provides behavioral evidence that deepens the Bayesian predictive coding mechanism. The finding that "the effect of local motion biological properties depends on prior activation" aligns with the prior-likelihood weighting mechanism in the Bayesian framework, indicating that high-quality sensory information can optimize temporal prediction only under strong prior constraints. This pattern echoes findings that gravity direction prior information facilitates temporal prediction (Gan et al., 2015; Zhou et al., 2020), suggesting a universal prior-modulation principle in sensorimotor synchronization.

Additionally, this study has practical implications in two main areas. First, it informs the design of innovative neurorehabilitation systems. Based on the finding that "intact human form configuration can serve as a strong prior to stabilize sensorimotor synchronization," we can develop virtual reality (VR)-based neurorehabilitation systems. Such systems would use virtual humanoid animation guides conforming to biological motion characteristics, enabling patients to perform gait coordination training in immersive environments. Combining visual action matching with real-time feedback and employing a progressive training strategy of "global precedence, local refinement" could guide patients to gradually optimize gait rhythm and effectively reduce gait variability and synchronization errors. Second, it enriches diagnostic techniques for Autism Spectrum Disorder (ASD). Since ASD patients exhibit specific deficits in global processing of biological motion (Klin & Jones, 2008; Kaiser et al., 2010), comparing performance on sensorimotor synchronization tasks between standard and scrambled BM conditions could capture global processing deficits and enhance the sensitivity and specificity of early ASD screening.

6. Conclusion

Beat synchronization stability with biological motion is jointly regulated by global configuration and local motion. Preserving global configuration information facilitates biological motion beat synchronization stability. When global configuration information is preserved, disrupting the biological nature of local motion information significantly reduces synchronization stability compared to preserving local motion biological properties. When global configuration information is disrupted, whether local motion biological properties are destroyed has no significant effect on synchronization stability.

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Note: Figure translations are in progress. See original paper for figures.