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Perceived coordinated biological motion sequences warp time perception

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ABSTRACT

Collective motion requires coordinated movements of multiple individuals, such as people walking in the same direction and in temporal synchrony. It provides a salient social signal closely linked to coordinated group action and social cohesion. Previous research has shown that the human visual system is highly sensitive to such coordinated biological movement, efficiently representing multiple moving agents as a unified spatial entity. While coordinated biological motion also unfolds over time, it remains unclear how its temporal dynamics are processed. Here, we asked participants to complete a temporal comparison task using multiple point-light walkers, in which they indicated which of two sequentially presented displays (coordinated or uncoordinated) had a longer duration. The results revealed that coordinated biological motion sequences, defined by temporal synchrony (i.e., matched step phase) and spatial alignment (i.e., common walking direction), were perceived as shorter in duration than uncoordinated counterparts, in which both temporal synchrony and spatial alignment were disrupted. This effect persisted even when the biological motion was scrambled, but disappeared in static displays. Crucially, it was not attributable to low-level spatial perceptual organization, as it remained robust across varied stimulus configurations. Interestingly, this effect was absent in non-biological motion and object motion, suggesting that the change in perceived duration is specific to high-level bio-social signals. Moreover, the effect was stronger for temporal synchrony than for spatial alignment. These findings point to a specialized mechanism for time perception tuned to coordinated group movement, highlighting the influence of higher-order social dynamics on the subjective experience of time.

1. Introduction

Collective motion refers to the spatiotemporally coordinated actions that emerge when multiple individuals interact within shared environments (Parrish & Edelstein-Keshet, 1999; Warren, 2018). These patterns are widespread in everyday group activities: people walking together often spontaneously align their direction and synchronize their steps, and group dances involve intentionally coordinated and rehearsed movements (Suberry & Bodner, 2024; Sylos-Labini, d'Avella, Lacquaniti, & Ivanenko, 2018). Beyond its functional role in motor coordination, collective motion also provides vital cues for how we perceive groups and interpret social behavior (Shamay-Tsoory, Saporta, Marton-Alper, & Gvirts, 2019). Thus, perceiving biological group movements may be important for survival and social interaction.

It has been widely demonstrated that humans are highly attuned to detect collective behavior among multiple individuals (Cracco et al., 2022; Elias, Dyer, & Sweeny, 2016; Sweeny, Haroz, & Whitney, 2013). Behavioral findings suggest that observers can efficiently estimate the mean walking direction of briefly presented crowds of point-light walkers, despite variations in group size and individual headings, showing a tolerance to within-group variability that fosters the perception of a disorganized group as a unified Gestalt. This finding suggests that humans use ensemble-coding mechanisms to perceive collective motion with high sensitivity (Sweeny et al., 2013). In

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addition, synchrony can also facilitate holistic perceptual judgments of stimuli. Participants are more accurate in identifying emotional expressions when multiple faces change emotions synchronously (Elias et al., 2016). More interestingly, to facilitate perceptual judgments of coherence and synchrony, such holistic processing even modulates the perception of an individual embedded in a spatial context. Specifically, Cheng, Liu, Yuan, and Jiang (2022) found that participants' judgments of the walking direction of a central point-light walker were "attracted" by the directional information of surrounding walkers, thereby promoting the perception of a heterogeneous crowd as more homogeneous (Cheng et al., 2022). Taken together, these findings suggest that the visual system can efficiently integrate complex group information while tolerating a certain degree of local variation within the group to facilitate the perception of synchrony. Neuroimaging studies support these behavioral findings, further demonstrating that the human brain is highly sensitive to synchronous biological motion. EEG studies using the frequency tagging method indicate that when observers viewed four human agents performing either synchronous or asynchronous movements, synchronous group movements induced stronger neural responses (Cracco et al., 2022), particularly when the stimuli possessed human qualities (Alp, Nikolaev, Wagemans, & Kogo, 2017). In a subsequent study, participants observed four point-light walkers moving at a fixed pace, either in or out of synchrony (i.e., temporal synchrony) or in the same or in different walking directions (i.e., spatial alignment). The findings showed that neural responses were enhanced by temporal synchrony rather than spatial alignment (Cracco, Papeo, & Wiersema, 2024). In addition, fMRI results revealed that interpersonal synchrony could be decoded from activity within the social perception network. Especially, the right fusiform cortex responded more strongly to synchronous than to asynchronous motion (Tsantani, Yon, & Cook, 2024). Together, these findings indicate that the perception of coordinated group behavior is supported by specialized neural mechanisms that integrate dynamic information across multiple interacting individuals.

Accumulating studies have shown that humans are sensitive to coordinated group motion, whereby synchronously moving agents are perceived more efficiently as a cohesive social unit at the spatial level (Cheng et al., 2022; Sweeny et al., 2013). In fact, synchronous and asynchronous movement patterns also unfold over time, and this temporal dynamic shapes how they are perceived (Cracco et al., 2022; Cracco et al., 2024). These temporal dynamics allow observers to detect precise alignment in movement timing, anticipate others' actions, and maintain the perception of group cohesion over time. Thus, understanding the temporal processing of collective movements is essential. However, these investigations have predominantly focused on spatial aspects, leaving it unclear whether humans exhibit specialized processing for coordinated biological movements in temporal perception.

Temporal perception, a fundamental aspect of cognition, can be influenced by such factors (Grondin, 2010; Wittmann, 2013). One line of evidence suggests that perceptual grouping also influences temporal experience (Zhou, Yang, Zhang, Zhang, & Mao, 2015). For example, spatially grouped collinear stimuli are perceived as lasting longer than spatially shuffled counterparts (Xue, Yuan, & Jiang, 2025). In addition, Liverence and Scholl (2012) showed that dynamic displays segmented into fewer, more coherent event units result in longer perceived durations (Liverence & Scholl, 2012). These studies have primarily focused on low-level perceptual organization. However, it remains unclear how higher-order socially interactive stimuli with perceptual organization, such as synchronous group movement in humans, shape time perception. On the other hand, one well-documented phenomenon is that motion lengthens perceived duration: high-speed or smoothly moving stimuli are consistently perceived as lasting longer than static ones (Beckmann & Young, 2009; Brown, 1995; Kaneko & Murakami, 2009). Beyond low-level motion, the perception of bio-social information also modulates time perception. For instance, biological motion (BM) signals can elicit time dilation, with upright point-light walkers producing stronger effects than inverted ones (Wang & Jiang, 2012). Interestingly, previous research has found that participants perceived intentional social interactions as shorter in duration than non-interactive counterparts, with this time distortion effect modulated by individual social cognitive abilities and oxytocin levels (Liu, Yuan, Chen, Jiang, & Zhou, 2018). Synchronous group movements are a distinctive form of social interaction that typically involves larger groups of individuals, yet it is not established whether they affect time perception in a similar pattern.

To address these issues, the present study employed a temporal comparison task. We first examined whether perceived duration differed between coordinated and uncoordinated biological motion using two standard durations (1000 ms and 500 ms). In human biological motion, coordination can be expressed through temporal synchrony, i.e., move in synchrony, and spatial alignment, i.e., common walking direction (Cracco et al., 2024; Warren, 2018). Thus, in this experiment, coordinated biological motion was defined by both temporal synchrony and spatial alignment, whereas uncoordinated biological motion was defined by differences in both temporal synchrony and spatial alignment. We found that the perceived duration of coordinated biological motion was shorter than that of uncoordinated biological motion. We then examined which of the two key components of biological motion, static body figure and local motion, plays the critical role in this effect. Furthermore, we examined whether this effect depends on low-level spatial perceptual organization by presenting four distinct stimuli that differed in spatial configuration while keeping local motion cues constant. In addition, we assessed the high-level biological specificity of the effect by testing whether it generalizes to non-biological and object-based motion. Finally, we investigated whether the effect is primarily driven by temporal synchrony or spatial alignment.

2. Method

2.1. *Experiment 1*

Experiment 1 first examined whether perceived coordinated biological motion influences subjective time. Participants were presented with coordinated and uncoordinated biological motion sequences with a standard duration of 1000 ms (Experiment 1a) and 500 ms (Experiment 1b), and were required to judge which sequence was perceived as longer.

2.1.1. *Method*

2.1.1.1. Participants. Sixteen college students (2 males, 14 females; M = 21.00 years, SD = 1.83) participated in Experiment 1a as paid volunteers. The sample size was determined based on a previous relevant study, which also investigated time perception using biological motion (Wang & Jiang, 2012). A two-tailed power analysis using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) confirmed that a sample size of 16 participants would afford more than 80% power (Cohen's $d = -0.94$, $\alpha = 0.05$). To avoid potential interference between experiments and prevent prior exposure from biasing perceptual interpretations, we recruited a new group of sixteen college students (4 males, 12 females; M = 22.75 years, SD = 2.17) to participate in Experiment 1b. All participants had normal or corrected-to-normal vision and did not have a history of neurological problems. This study was approved by the institutional review board of Nanjing Normal University (Protocol Number: NNU202402029).

2.1.2. *Stimulus*

Participants sat comfortably in a dim room, 56 cm from the computer screen (1920 × 1080 resolution, 60 Hz refresh rate). Stimuli were presented on the gray-background screen via MATLAB (MathWorks, Natick, MA, USA) and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The biological motion stimuli were point-light walker displays adopted from the Biological Motion Database (Vanrie & Verfaillie, 2004), consisting of

13 markers indicating the major joints of the actor (head, shoulders, elbows, wrists, hips, knees, and feet). Each stimulus display contained four walkers, which were located at each of the four corners in the central frame of the display. Each walker was positioned such that the center of the walker was located approximately 1.74° horizontally and 2.96° vertically from the central fixation point, forming a square layout around the center, with each point-light walker subtending a maximal vertical extent of 2.05° and a maximal horizontal extent of 4.09°.

In each trial, participants viewed two sequentially presented stimuli: one coordinated and one uncoordinated (see Supplementary Materials for example animations of the coordinated and uncoordinated stimuli). In the coordinated condition, the four point-light walkers were both spatially and temporally aligned. Specifically, in each trial, all four walkers were assigned the same azimuth angle. This common angle was randomly selected from −45°, −15°, 15°, and 45° on a trial-by-trial basis. The azimuth angle specified the orientation of the walker around the vertical axis, with negative values indicating that the walker faced left relative to the viewer and positive values indicating that it faced right. Moreover, they all began walking from the same initial frame of the biological motion sequence, resulting in both spatial alignment and temporal synchrony. In contrast, in the uncoordinated condition, each of the four walkers was assigned a different azimuth angle, randomly selected from the four values (i.e., one walker was set to −45°, one to −15°, one to 15°, and one to 45°, with the assignment randomized across four walkers). In addition, the initial frame of each walker's biological motion sequence was randomized independently, resulting in both spatial misalignment and temporal asynchrony. The biological motion stimuli were identical in Experiments 1a and 1b (see supplementary videos).

2.1.3. Procedure

In Experiment 1a, participants first completed a practice session to ensure they were acquainted with the temporal comparison task. In the main experiment, each trial of the temporal comparison task begins with a 1000-ms fixation at the center cross (1° × 1°), followed by two motion sequences, one coordinated and the other uncoordinated, with a blank screen (a randomized duration of 400–600 ms) between them to avoid a potential interference effect. One of the motion sequences (coordinated or uncoordinated, each in half of the trials in random order) is shown for 1000 ms, while the other (either coordinated or uncoordinated) is displayed for 400, 600, 800, 1000, 1200, 1400, or 1600 ms, with each duration being equally probable. In other words, the temporal difference between coordinated and uncoordinated motion sequences ranges from −600 ms to 600 ms, with a 200-ms step, forming 7 testing conditions. Participants are required to press one of two buttons to indicate which motion sequence (first or second) lasted longer. After making a response, the next trial begins immediately (see Fig. 1). The experiment consists of 4 blocks, each followed by a brief break. Each block consisted of 35 trials, resulting in a total of 140 trials, with 20 trials for each test condition.

In Experiment 1b, the procedure was identical to that of Experiment 1a, except for the presentation durations of the motion sequences. Specifically, one motion sequence (coordinated or uncoordinated, each in half of the trials in random order) is shown for 500 ms, while the other sequence is presented for 200, 300, 400, 500, 600, 700, or 800 ms. Accordingly, the temporal difference between coordinated and uncoordinated motion sequences ranges from −300 ms to 300 ms, with a 100-ms step.

2.1.4. Analysis

To quantify the temporal perception of biological motion, we constructed a psychometric curve for each observer. The independent variable (x) was defined as the physical duration difference between the coordinated and uncoordinated motion sequences ($x = \text{Duration}_{coord} - \text{Duration}_{uncoord}$), corresponding to the seven tested temporal-difference levels ranging from −600 ms to 600 ms in 200-ms steps in Experiment 1a (from −300 ms to 300 ms in 100-ms steps in Experiment 1b). Negative values of x indicate that the coordinated sequence was physically shorter than the uncoordinated sequence, whereas positive values indicate that it was physically longer. The dependent variable was the proportion of trials in which observers judged the coordinated motion sequence to be longer than the uncoordinated sequence. Then, psychometric curves were obtained by fitting the observed proportions as a function of the physical duration difference (x) with a Boltzmann sigmoid function. Curve fitting was performed in MATLAB (MathWorks, Natick, MA) using the *fit* function with a sigmoid model defined by *fittype*. The free parameters were estimated through nonlinear optimization to minimize the discrepancy between the predicted and observed response proportions. The fitted function was defined as: $f(x) = 1 / (1 + \exp[(x - x_0) / \omega])$. In this function, x_0 corresponds to the subjective equality point (PSE), which is the point at which the observer perceives the durations of the coordinated and uncoordinated sequences as equal. A positive PSE means that the coordinated biological motion sequence is perceived as shorter relative to the uncoordinated sequence, while a negative PSE indicates the opposite. The half-interquartile range of the fitted function ($DL = (x_{0.75} - x_{0.25})/2$) corresponds to the difference limen (DL), which is an indicator of temporal discrimination sensitivity. Here, $x_{0.75}$ represents the stimulus difference at which participants judge the coordinated motion sequences as longer with 75% probability, and $x_{0.25}$ represents the stimulus difference at which they make the same judgment with 25% probability. Smaller DL values indicate steeper psychometric slopes and higher temporal sensitivity. Bayes factor (BF_{10}) of the *t-test* was reported to further support the presence or absence of a difference (Hoijtink, Mulder, van Lissa, & Gu, 2019).

2.1.5. Results

In Experiment 1a, one-sample t-test showed that the PSE was significantly greater than zero ($M \pm SD = 82.39 \pm 41.33$; Fig. 2), t (15)

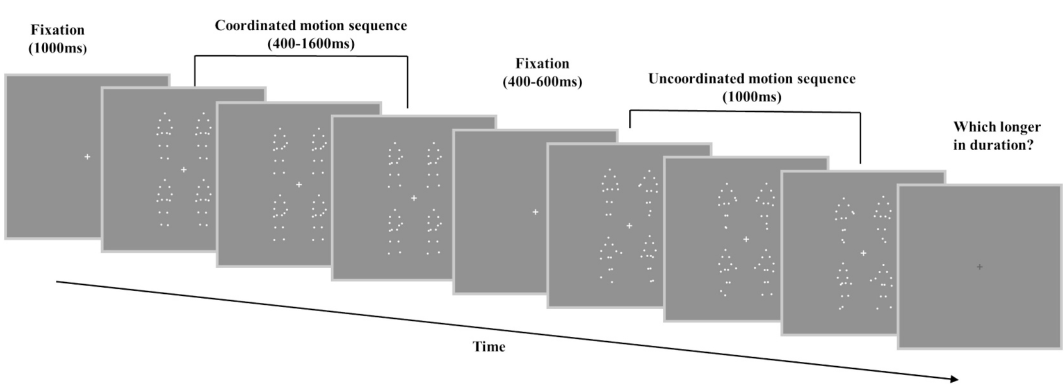

Fig. 1. Experimental procedure for Experiment 1a. Schematic representation of the temporal comparison task in the 1000-ms biological motion condition.

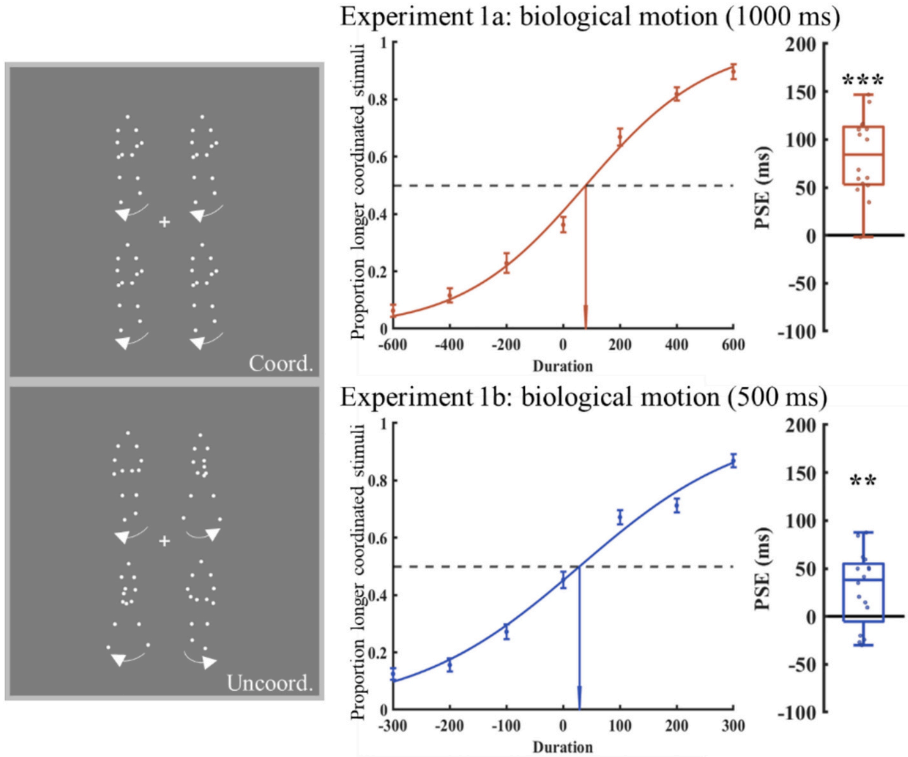

Fig. 2. Stimuli and results from Experiments 1a and 1b. The left panels illustrate the coordinated (Coord.) and uncoordinated (Uncoord.) biological motion stimuli used in both experiments. The stimuli were identical across Experiment 1a and 1b, differing only in their presentation durations. The middle panels show psychometric functions for coordinated versus uncoordinated biological motion sequences as a function of the physical duration difference in the 1000-ms (Experiment 1a, red) and 500-ms (Experiment 1b, blue) standard-duration. The curves illustrate the proportion of "longer" judgments as a function of the temporal offset, and the inset arrows display significantly positive points of subjective equality (PSEs). The right panels depict individual and mean PSE values. Error bars represent ±1 standard error of the mean, and dots denote individual data points for each condition. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$= 7.97$, $p < 0.001$, d $= 1.99$, 95% CI for the mean difference [60.37, 104.40], $BF_{10} = 19{,}490.00$. Specifically, results showed that the proportion of "longer" judgments was generally larger under the uncoordinated condition than under the coordinated condition, reflecting participants' tendency to perceive coordinated sequences as shorter compared to uncoordinated ones in the 1000-ms standard-duration.

In Experiment 1b, one-sample t-test showed that the PSE was significantly greater than zero (M ± SD = 28.88 ± 38.75; Fig. 2), t (15) $= 2.98$, $p < 0.01$, d $= 0.75$, 95% CI for the mean difference [8.24, 49.53], $BF_{10} = 5.80$. These results suggest that participants were more likely to judge coordinated sequences as shorter in duration than uncoordinated sequences in the 500-ms standard-duration, replicating the same effect observed in Experiment 1a.

2.2. Experiment 2

Experiment 1 revealed that coordinated biological motion sequences were perceived as shorter in duration than uncoordinated sequences across different temporal intervals. To identify the mechanism underlying this effect, Experiment 2 further isolated the static body form and local motion of biological motion by respectively presenting static figure (Experiment 2a) and scrambled motion (Experiment 2b), in order to test which component is critical for the time distortion effect observed in Experiment 1.

2.2.1. Method

Sixteen college students (6 males, 10 females; M = 22.25 years, SD = 3.26) were recruited to participate in Experiment 2a. To avoid potential interference between experiments, specifically cross-contamination between the static form and scrambled motion manipulations, these were tested in separate experiments. Thus, we recruited a different group of sixteen college students (8 males, 8 females; M = 23.06 years, SD = 2.35) to participate in Experiment 2b.

The procedure and analysis were identical to those in Experiment 1a, but the stimuli were replaced. Specifically, in Experiment 2a, each of the four static point-light walkers was a single frame selected from the biological motion sequence, namely the frame corresponding to the longest gait cycle (see Fig. 3). This manipulation preserved the global body form while eliminating dynamic motion information. In the coordinated condition, the display consisted of four identical static point-light walkers, all taken from the same frame of the biological motion sequence and shown at the same azimuth angle. In the uncoordinated condition, the display consisted of four different static point-light walkers, created by varying both the azimuth angle and the initial frame selected from the biological motion sequence across the four figures. In other words, the coordinated condition presented four identical static stimuli, whereas the uncoordinated condition presented four different static stimuli (see Fig. 3).

In Experiment 2b, the scrambled stimuli were created by spatially rearranging the dot positions of the original biological motion displays used in Experiment 1a, while preserving the local motion trajectories of each individual dot. This manipulation disrupted the global structure of each walker by randomly displacing the trajectories across the display area in the same way, thereby eliminating the percept of an articulated figure (Cheng, Yuan, & Jiang, 2024; Wang & Jiang, 2012). The four stimuli shared an identical configuration (a difference from Experiment 3b that will be described in detail below). The uncoordinated condition was manipulated in the same way as described above. The presentation durations for the coordinated and uncoordinated conditions were kept identical to those used in Experiment 1a.

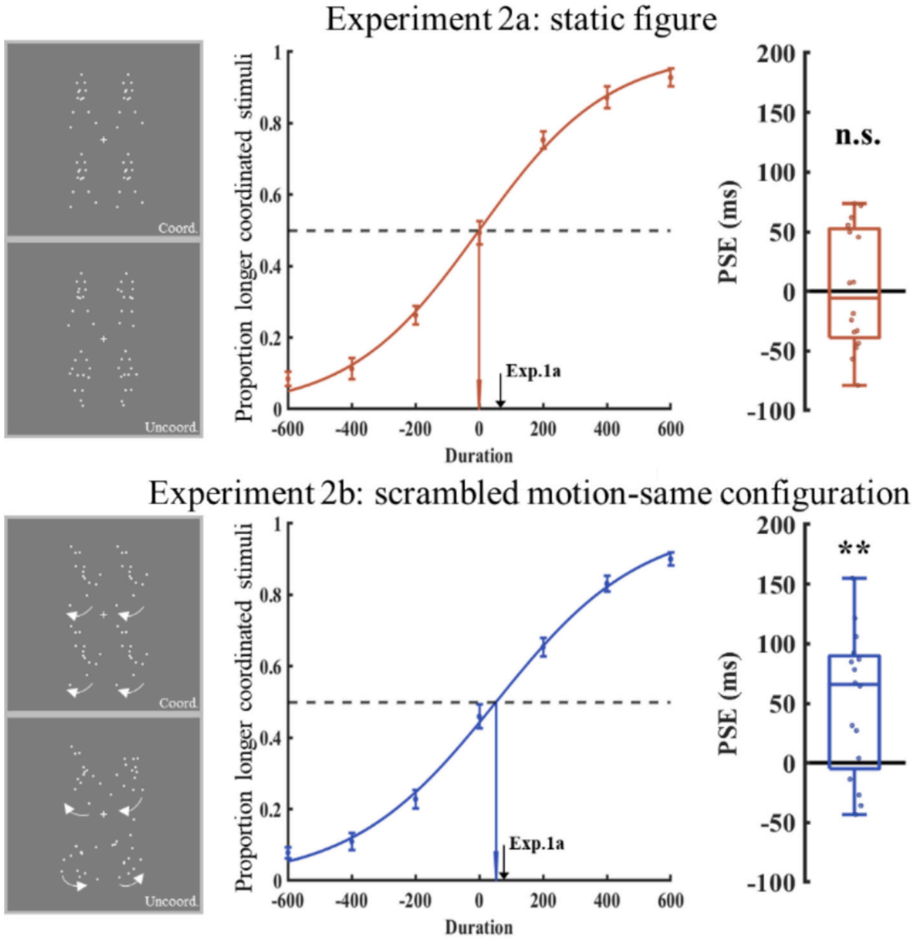

Fig. 3. Stimuli and results from Experiments 2a and 2b. The left panels illustrate the stimuli used in both experiments. The middle panels show the psychometric functions for coordinated versus uncoordinated sequences as a function of physical duration difference. The curves indicate the proportion of "longer" judgments as a function of temporal offset. The inset arrows mark the PSEs in Experiments 2a and 2b, and the short black arrow indicates the mean PSE obtained in Experiment 1a. The right panels depict individual participant PSEs and the group mean. $^{**}p < 0.01$, n.s., not significant.

2.2.2. *Results*

In Experiment 2a, one-sample *t*-test showed that the PSE did not significantly differ from zero (M ± SD = 2.30 ± 50.84; Fig. 3), $t\,(15) = 0.18$, $p = 0.859$, d = 0.05, 95% CI for the mean difference [−24.79, 29.39], $BF_{10} = 0.26$. We also conducted a cross-experiment comparison with Experiment 1a and found that the PSE for intact BM was significantly larger than that for the static form stimuli, $t\,(30) = 4.89$, $p < 0.001$, d = 1.73, 95% CI for the mean difference [46.63, 113.50], $BF_{10} = 565.10$. These findings indicate that static body form alone was insufficient to modulate perceived duration.

In Experiment 2b, the PSE was significantly greater than zero (M ± SD = 49.96 ± 59.97; Fig. 3), $t\,(15) = 3.33$, $p < 0.01$, d = 0.83, 95% CI for the mean difference [18.00, 81.91], $BF_{10} = 10.54$. Participants were more likely to judge uncoordinated scrambled motion as lasting longer than coordinated scrambled motion. A cross-experiment comparison with Experiment 1a showed that the difference in PSE between intact BM and scrambled motion did not reach statistical significance, $t\,(30) = 1.78$, $p = 0.085$, d = 0.63, 95% CI for the mean difference [−4.75, 69.62], $BF_{10} = 1.10$. The Bayes factor was close to 1, indicating only anecdotal evidence and warranting cautious interpretation of this comparison. This result further demonstrated that the observed temporal distortion effect in Experiment 1 may reflect an intrinsic sensitivity of the human visual system to local (i.e., scrambled) motion signals.

2.3. *Experiment 3*

Results from Experiment 2 demonstrated that local motion cues, rather than static body form, altered the perceived duration of coordinated and uncoordinated biological motion. However, one possible alternative explanation is that the effect arose simply because the four identical motion sequences in the coordinated condition formed a highly organized spatial pattern, whereas those in the uncoordinated condition did not. In this view, the observed temporal distortion may have been driven solely by this spatial regularity. To rule out this possibility, Experiments 3a and 3b used two complementary approaches to test whether the effect observed in Experiment 1a could be attributed solely to the spatial organization of the display. Specifically, we asked whether the same effect would still emerge when the spatial configuration was disrupted (i.e., the configuration of the four stimuli was no longer identical in the coordinated condition).

2.3.1. *Method*

A new group of sixteen college students (8 males, 8 females; M = 21.00 years, SD = 2.00) were recruited to participate in Experiment 3a. In addition, we recruited a different group of sixteen college students (4 males, 12 females; M = 21.19 years, SD = 2.04) to participate in Experiment 3b.

The procedure and analysis were identical to those in Experiment 1a, except that the four stimuli were changed. In Experiment 3a, the diagonal pairs were identical, with one pair depicting intact biological motion and the other depicting scrambled motion in the coordinated condition. Although they differed in form, they shared the same motion pattern under the coordinated condition. In the uncoordinated condition, the four stimuli still comprised one pair of intact figures and one pair of scrambled figures, but their orientations and walking phases were not aligned.

In the coordinated condition of Experiment 3b, all four stimuli were different scrambled motions: their configurations differed because each was independently generated through randomization; however, they shared the same temporal phase and walking direction. In the uncoordinated condition, the four stimuli were also different scrambled motions and they differed in both temporal phase and walking direction (see Fig. 4).

2.3.2. Results

In Experiment 3a, one-sample *t*-test showed that the PSE was significantly greater than zero (M ± SD = 93.64 ± 76.89; Fig. 4), $t\,(15) = 4.87$, $p < 0.001$, d = 1.22, 95% CI for the mean difference [52.67, 134.60], $BF_{10} = 152.70$. A cross-experiment comparison with Experiment 1a showed that there was no significant difference in PSE between intact BM and intact-scrambled motion, $t\,(30) = -0.52$, $p = 0.610$, d = −0.18, 95% CI for the mean difference [−55.83, 33.31], $BF_{10} = 0.37$. These results indicate that even when the four stimuli in the coordinated condition were not identical, coordinated motion was still perceived as shorter in duration than uncoordinated motion, which further suggests that spatial configuration was not the primary driver of the observed change in perceived duration between coordinated and uncoordinated motion.

In Experiment 3b, one-sample t-test showed that the PSE was significantly greater than zero (M ± SD = 75.13 ± 51.71; Fig. 4), $t\,(15) = 5.81$, $p < 0.001$, d = 1.45, 95% CI for the mean difference [47.58, 102.70], $BF_{10} = 737.10$. Participants again tended to judge uncoordinated sequences as longer than coordinated sequences. A cross-experiment comparison with Experiment 1a showed that there was no significant difference in PSE between intact BM and scrambled motion-different configuration, $t\,(30) = 0.44$, $p = 0.664$, d = 0.16, 95% CI for the mean difference [−26.54, 41.05], $BF_{10} = 0.36$. This finding replicates the pattern observed in Experiment 3a and provides stronger evidence that the perceptual shortening of coordinated sequences cannot be explained solely by differences in spatial configuration.

2.4. Experiment 4

Across the first three experiments, we consistently found that coordinated biological motion sequences were perceived as shorter than uncoordinated sequences. This effect may be driven by local motion cues and could not be attributed solely to spatial organization. However, up to this point, all stimuli retained biological characteristics. It therefore remains unclear whether the observed temporal distortion effect reflects a mechanism specific to biological motion processing or a more general consequence of coordinated movement. To address this question, Experiment 4 replaced biological motion stimuli with non-biological motion (Experiment 4a) and object motion (Experiment 4b) displays to assess whether the temporal distortion effect is specific to higher-level biological signals.

2.4.1. Method

We tested sixteen college students (6 males, 10 females; M = 22.13

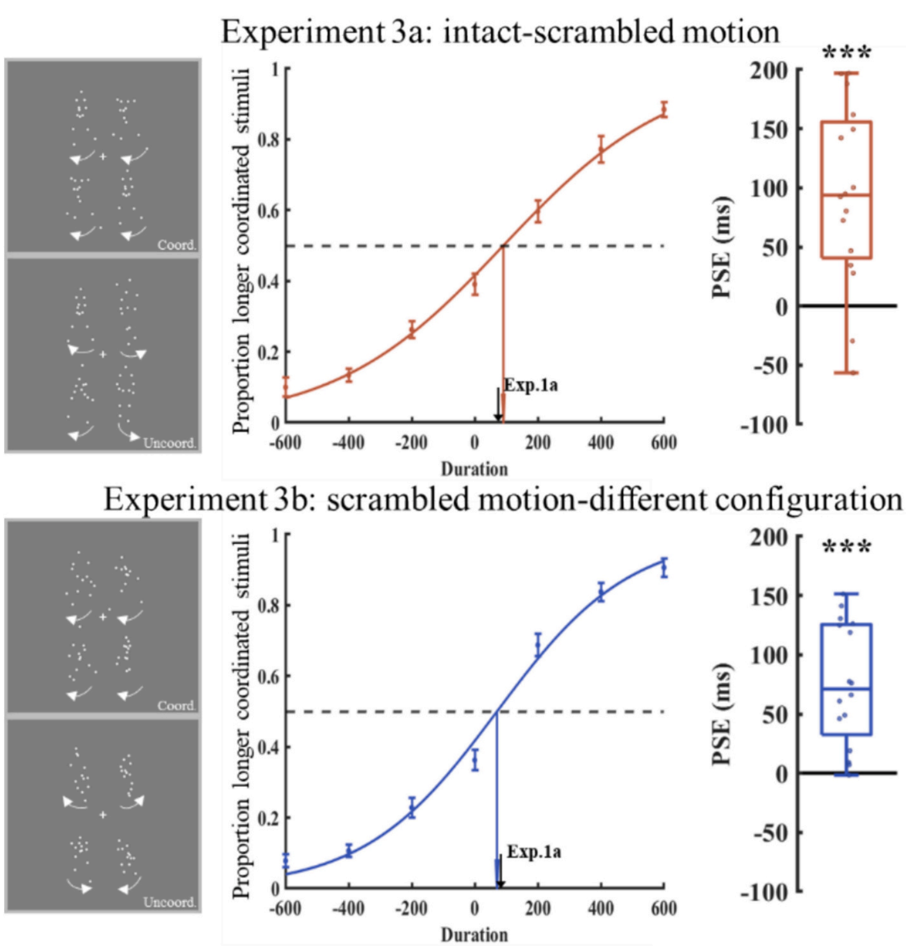

Fig. 4. Stimuli and results from Experiment 3a and 3b.

years, SD = 2.39) in Experiment 4a, and a new group of sixteen college students (9 males, 7 females; M = 21.63 years, SD = 2.42) participated in Experiment 4b.

The procedure and analysis were identical to those in Experiment 1a, except that the stimuli were replaced with nonbiological motion and object motion. The coordinated manipulation was identical to that used in the previous experiments. In Experiment 4a, the stimuli are created by eliminating the dynamic biological features inherent in the original BM sequences. To achieve this, we disrupted the phase coherence of BM by randomizing the starting motion phase of each dot. Furthermore, we removed the natural velocity profile of the BM stimuli by assigning each dot a constant speed, set to its average speed throughout the motion. These manipulations preserved the motion trajectories of the dots while completely stripping away the dynamic biological cues, including any gravity-dependent acceleration signals. In Experiment 4b, the stimuli consisted of four stereoscopically rotating spheres (i.e., object motion), each composed of 100 dots and projected onto a 2D plane. Notably, the dots were not uniformly distributed across the spherical surface. Analogously, we manipulated spatial misalignment by randomly assigning each of the four spheres to different azimuth orientations (−45°, −15°, 15°, or 45° around the vertical axis) and temporal misalignment by varying their initial dot positions (see Fig. 5).

2.4.2. Results

In Experiment 4a, one-sample *t*-test showed that the PSE was not significantly different from zero (M ± SD = −39.26 ± 142.47; Fig. 5), $t(15) = -1.10$, $p = 0.288$, d = −0.28, 95% CI for the mean difference [−115.20, 36.66], $BF_{10} = 0.43$. There was no significant difference in perceived duration between coordinated and uncoordinated non-biological motion. In addition, we conducted a cross-experiment comparison with Experiment 1a and found that the PSE for intact BM was significantly larger than that for the non-BM, $t(30) = 3.28$, $p = 0.003$, d = 1.16, 95% CI for the mean difference [45.91, 197.40], $BF_{10} = 14.24$, suggesting that the effect observed previously may depend on biological motion information.

In Experiment 4b, one-sample t-test revealed the PSE was not significantly different from zero (M ± SD = −10.96 ± 51.25; Fig. 5), $t(15) = -0.86$, $p = 0.406$, d = −0.21, 95% CI for the mean difference [−38.27, 16.35], $BF_{10} = 0.35$. There was no significant difference in perceived duration between coordinated and uncoordinated object motion. A cross-experiment comparison with Experiment 1a showed that the PSE for intact BM was significantly larger than that for the object motion, $t(30) = 5.67$, $p < 0.001$, d = 2.01, 95% CI for the mean difference [59.73, 127.00], $BF_{10} = 3{,}921.00$, further supporting the possibility that the effect is specific to higher-level motion signals.

2.5. Experiment 5

Across Experiments 1–4, we simultaneously manipulated temporal synchrony and spatial alignment. Although both factors may have contributed to the observed effect, we sought to determine which played the more critical role. Experiment 5 therefore employed a within-subject design to dissociate these two factors by separately manipulating temporal synchrony and spatial alignment in separate blocks. This design allowed us to directly compare their relative contributions and determine which component primarily accounts for the observed distortions in subjective time perception.

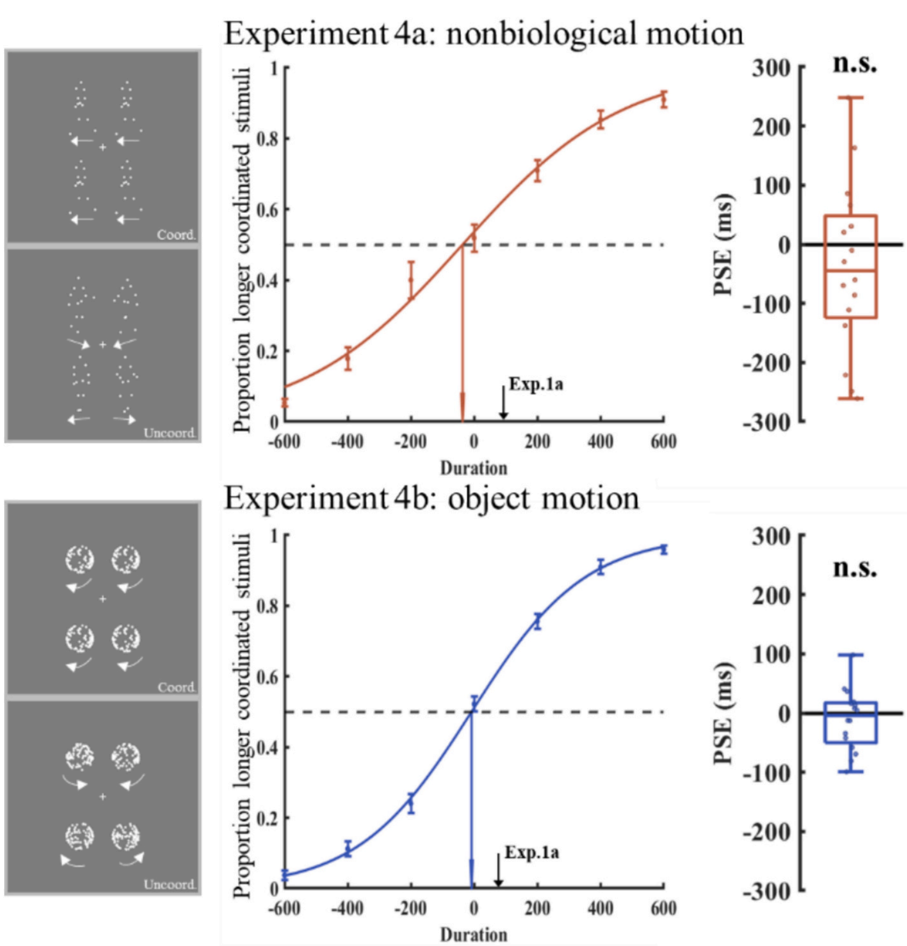

Fig. 5. Stimuli and results from Experiment 4a and 4b.

2.5.1. Method

Sixteen college students (6 males, 10 females; M = 22.13 years, SD = 2.45) participated in Experiment 5. The procedure and analysis were identical to those in Experiment 1a. The coordinated condition in Experiment 5 was also identical to that used in Experiment 1a, whereas the uncoordinated condition was modified to manipulate temporal synchrony and spatial alignment independently. In the (disrupting) temporal synchrony block, the uncoordinated condition was created by independently randomizing only the initial frame of each walker's biological motion sequence, while their overall walking direction remained consistent, thereby disrupting temporal synchrony. In the (disrupting) spatial alignment block, the uncoordinated condition was generated by assigning each of the four walkers a different azimuth value (using the same values as in the previous experiments), while the temporal phase of their movements was kept aligned, thereby disrupting spatial alignment.

2.5.2. Results

One-sample *t*-test showed a significant positive PSE in the (disrupting) temporal synchrony block (see Fig. 6; M ± SD = 92.67 ± 44.30), $t(15) = 8.37$, $p < 0.001$, d = 2.09, 95% CI for the mean difference [69.06, 116.30], BF_{10} = 33,475.72, as well as in the (disrupting) spatial alignment block (M ± SD = 21.04 ± 34.04), $t(15) = 2.47$, $p < 0.05$, d = 0.62, 95% CI for the mean difference [2.90, 39.18], BF_{10} = 2.53, indicating reliable distortions in perceived duration in both blocks. Moreover, this effect was significantly greater for (disrupting) temporal synchrony condition than for (disrupting) spatial alignment, $t(15) = 6.73$, $p < 0.001$, d = 1.68, 95% CI for the mean difference [48.95, 94.29], BF_{10} = 3167.00. A cross-experiment comparison with Experiment 1a showed that there was no significant difference in PSE between intact BM and the (disrupting) temporal synchrony condition, $t(30) = -0.68$, $p = 0.503$, d = −0.24, 95% CI for the mean difference [−41.21, 20.65], BF_{10} = 0.40. In contrast, the PSE for intact BM was significantly larger than that for the (disrupting) spatial alignment, $t(30) = 4.58$, $p < 0.001$, d = 1.62, 95% CI for the mean difference [34.01, 88.68], BF_{10} = 268.80. Together, these findings demonstrate that both temporal synchrony and spatial alignment can warp perceived duration, with temporal synchrony exerting a stronger influence.

3. Discussion

Given that collective motion is transmitted through visual input across time rather than at single, static fragments, processing dynamic and continuous motion information necessarily depends on temporal summation (Cracco et al., 2022; Cracco et al., 2024). The present study investigated the temporal processing of coordinated and uncoordinated biological motion. To facilitate understanding of the experimental logic, we summarize the experimental manipulations and key results across the five experiments below (see Table 1). We demonstrated that the perceived duration of coordinated biological motion is shorter than that of uncoordinated motion under both the 1000-ms and 500-ms standard duration. Further, we found that the effect is driven primarily by local biological motion cues, rather than static body form. Critically, this effect remained when the four agents had distinct configurations, suggesting that this difference in perceived duration was not entirely attributable to spatial perceptual organization. Interestingly, the effect vanished when the stimuli were replaced with non-biological motion and object motion, indicating that it is specific to high-level biological signals. Last, our findings suggest that temporal synchrony contributes more substantially than spatial alignment to shaping perceived duration. These findings extend existing research on the perception of collective behavior by showing that coordinated biological motion not only shapes the spatial integration of group motion but also influences the temporal structure of subjective experience.

Time perception is not absolute but rather significantly influenced by the properties of external stimuli. Studies have shown that perceived duration increases with greater stimulus size (Xuan, Zhang, He, & Chen, 2007) and luminance (Sperandio, Savazzi, Marzi, & Gregory, 2008). Likewise, dynamic stimuli, such as those that are moving, looming, or flickering, are generally perceived as lasting longer than static or receding stimuli (Brown, 1995; Kanai & Watanabe, 2006; Roelofs & Zeeman, 1951; van Wassenhove, Buonomano, Shimojo, & Shams, 2008). These distortions arise because salient or dynamic events can signal threats or require rapid responses, which enhances attentional capture and elicits physiological arousal. This leads to the accumulation of more temporal pulses and prolongs event processing time (Droit-Volet, Mermillod, Cocenas-Silva, & Gil, 2010; Grassi & Pavan, 2012;

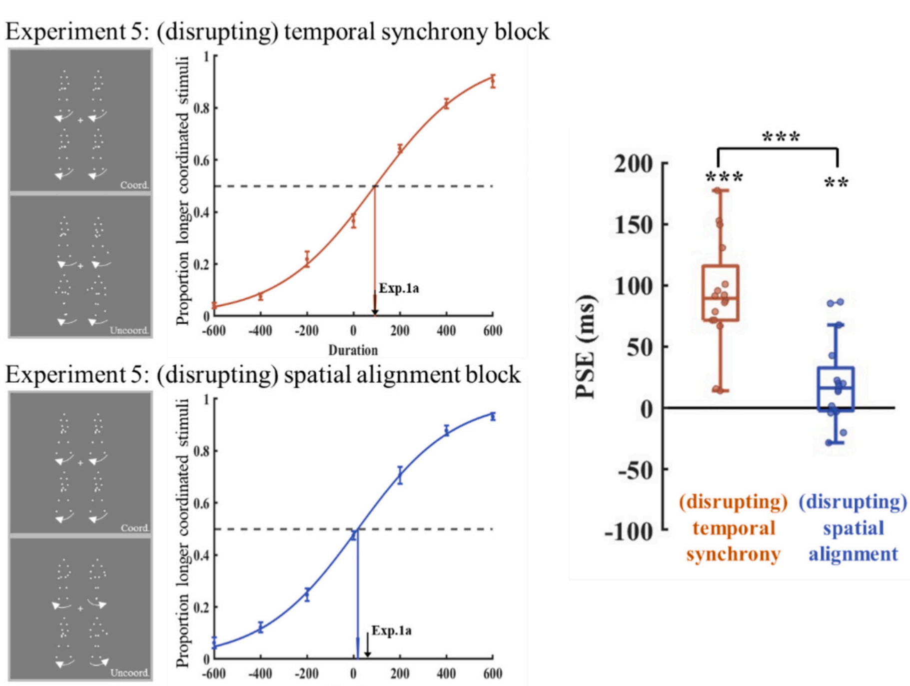

Fig. 6. Stimuli and results from Experiment 5.

Table 1
Summary of experimental manipulations and key results across experiments.

Experiment	Sample Size	Manipulated factor	Stimulus type	PSE Comparison	Result
Exp. 1a	16	Presentation duration	BM (1000 ms)	Coord vs. Uncoord	$p < 0.001$
Exp. 1b	16		BM (500 ms)	Coord vs. Uncoord	$p < 0.01$
Exp. 2a	16	Biological motion components	Static figure	Coord vs. Uncoord	$p = 0.859$
Exp. 2b	16		Scrambled motion-same configuration	Coord vs. Uncoord	$p < 0.01$
Exp. 3a	16	Spatial organization	Intact and scrambled motion	Coord vs. Uncoord	$p < 0.001$
Exp. 3b	16		Scrambled motion-different configuration	Coord vs. Uncoord	$p < 0.001$
Exp. 4a	16	Biological signals	Nonbiological motion	Coord vs. Uncoord	$p = 0.288$
Exp. 4b	16		Object motion	Coord vs. Uncoord	$p = 0.406$
Exp. 5	16	Coordination components	BM with (disrupting) temporal synchrony	Coord vs. Uncoord	$p < 0.001$
			BM with (disrupting) spatial alignment	Coord vs. Uncoord	$p < 0.05$

Sugarman, McGlinchey, & Fortenbaugh, 2021; van Wassenhove, Wittmann, Craig, & Paulus, 2011). Beyond these low-level stimulus properties, higher-level biosocial stimuli also exert a distinct regulatory influence on time perception. For example, Wang and Jiang (2012) first found that the perceived duration of upright biological motion sequences was significantly longer than that of inverted sequences, indicating that a special mechanism of time perception is tuned to life motion signals (Wang & Jiang, 2012). In addition, it was found that when the two postures could be plausibly integrated into a continuous motion sequence, participants perceived the duration of body picture pairs as shorter than in the control conditions. The findings suggest that the brain integrates two static images through temporal binding, giving rise to the experience of continuous biological motion (Orgs & Haggard, 2011). Furthermore, time perception is systematically modulated by social interaction information. Burra and Kerzel (2021) found that when gaze was directed toward the observer, participants underestimated the duration compared to when gaze was averted (Burra & Kerzel, 2021). In addition, researchers found that the subjective duration of the communicative motion sequence was significantly shorter than the noncommunicative motion sequence. However, in conditions where the social intention was eliminated (such as spatially swapped and temporally delayed), the time distortion effect disappeared (Liu et al., 2018). Based on previous studies, we have further extended the time perception of the social relationships within groups. Specifically, coordinated biological movements are perceived as shorter in duration than uncoordinated movements. This suggests that temporal perception is not only shaped by dyadic social cues, such as gaze or communicative intentions, but also by higher-order collective motion. Such findings highlight that human temporal processing is finely attuned to spatiotemporally aligned group behaviors.

The present findings can be interpreted within two classic accounts of time perception: the attentional-gate account and the coding efficiency account. According to the attentional-gate model, the internal clock comprises a pacemaker, an attention-controlled gate, and an accumulator. The perceived duration of an interval depends on the number of pulses that successfully pass through the gate and are accumulated (Zakay & Block, 1996). Thus, the increased attentional demand may enhance the rate of information processing (Tse, Intriligator, Rivest, & Cavanagh, 2004; Zakay & Block, 1996). In the present study, uncoordinated biological motion contained multiple less predictable motion streams, as the four point-light walkers differed in walking direction and step phase. These less predictable and less coherent motion streams may have attracted more distributed attentional resources, allowing more temporal pulses to be accumulated and thereby making uncoordinated displays appear longer in duration than coordinated displays. In addition, the coding-efficiency account offers an alternative perspective. According to this account, stimuli that are encoded more efficiently, such as predictable or perceptually organized stimuli, tend to be perceived as shorter in duration (Eagleman & Pariyadath, 2009; Noguchi & Kakigi, 2006). It has been found that when group behavior is synchronized, ensemble coding effectively integrates individual-level noise, significantly reducing perceptual uncertainty (Sweeny & Whitney, 2014). Consistent with this view, when local elements are integrated into a coherent Gestalt, observers may become less sensitive to changes in individual components (Poljac, de-Wit, & Wagemans, 2012). In the present study, the shorter perceived duration of coordinated biological motion can be understood as a natural outcome of efficiency-based neural coding strategies that minimize computational costs.

However, whereas the present study used dynamic biological-motion stimuli, Xue et al. (2025) used static chunked stimuli and showed that collinear arrangements led to duration overestimation (Xue et al., 2025). This finding suggests that collinearity may attract more attentional resources by enhancing the overall organization and perceptual salience of the stimulus. Thus, perceptual grouping may influence time perception through multiple mechanisms, depending on whether it reduces processing demands or increases stimulus salience. Notably, although the attentional-gate account and coding-efficiency account offer plausible explanations for the observed temporal distortion, the present design does not allow us to determine which account is more appropriate. Because participants judged the relative duration of coordinated and uncoordinated biological motion, we cannot determine whether the effect reflects temporal compression for coordinated biological motion, temporal expansion for uncoordinated biological motion, or both. Further behavioral and neuroimaging studies are therefore needed to distinguish between these accounts and clarify the underlying mechanisms.

More importantly, our results showed that coordinated and uncoordinated object motion and other non-biological stimuli, which lack biologically meaningful kinematic features, did not alter perceived duration. This absence of an effect suggests that spatiotemporal coherence alone may be insufficient to produce the observed temporal distortion. Instead, the effect may depend on the bio-social significance carried by coordinated biological agents. For example, group coordination in biological motion may convey cues to shared intentionality, social cohesion, or affective relevance (Raafat, Chater, & Frith, 2009; Vicary, Sperling, von Zimmermann, Richardson, & Orgs, 2017; Wilson & Gos, 2019), which may further enhance attentional engagement or coding efficiency brought by the spatiotemporal coherence among agents (Cracco et al., 2022; Sweeny et al., 2013). This interpretation is also consistent with EEG frequency-tagging evidence showing that neural responses to motion coordination can be dissociated from responses to human form in multiple point-light dancers, indicating that synchrony and social relevance may contribute separately to the perception of group movement (Alp et al., 2017). Thus, the present findings indicate that the temporal distortion observed for coordinated biological motion may depend on the interaction between efficient integration and social meaning carried by biological agents. In contrast, coordinated and uncoordinated non-biological motion may differ in perceptual organization, but such differences may not carry sufficient bio-social relevance to produce a reliable change in perceived duration.

In addition, we found that the effect of coordinated group movement on perceived duration persisted in scrambled motion sequences. This pattern is highly consistent with prior findings, all of which demonstrate that the visual system remains highly sensitive to local motion cues (Chang, Ban, Ikegaya, Fujita, & Troje, 2018; Lu et al., 2024; Troje & Westhoff, 2006). For instance, even under spatially scrambled conditions, biological motion can elicit strong visual search asymmetries, suggesting that such kinematic cues function as "pre-attentive" features that are rapidly detected (Wang, Zhang, He, & Jiang, 2010). The temporal dilation effect in biological motion persists under spatially scrambled conditions but disappears under non-biological conditions (Wang & Jiang, 2012). Likewise, we found local foot motion signals elicited a marked increase in pupil size (Cheng et al., 2024). Interestingly, our results suggest that even when four scrambled motion cues differ in their coherent forms, the local biological kinematics they convey still retain enough information to facilitate efficient processing (Hirai & Senju, 2020), leading to the observed temporal effect. This indicates that the temporal effect is not determined solely by spatial grouping, but rather relies on the intrinsic spatiotemporal structure of multiple local motion cues. Finally, our finding that temporal synchrony produces a stronger effect is consistent with a recent study by Cracco et al. (2024), who showed that brain responses preferentially coupled to the walkers' movements when they moved in temporal synchrony, indicating that temporal rather than spatial alignment plays an important role in processing biological motion groups (Cracco et al., 2024).

In conclusion, the current study clearly demonstrates that coordinated biological motion sequences can shape subjective time perception. This effect is not produced by static body information alone and persists in scrambled motion, indicating that local motion cues are critical for this effect. In addition, the effect could not be merely attributed to spatial perceptual organization. Importantly, the effect disappears in the non-biological and object motion sequences, suggesting that the effect cannot be attributed to low-level stimulus factors. Moreover, temporal synchrony plays a more prominent role than spatial alignment in shaping the observed effect. Together, these findings suggest that the human visual system is particularly sensitive to the temporal synchrony and spatial alignment of group biological motion, highlighting the importance of collective motion as a fundamental social cue in shaping subjective time.

CRediT authorship contribution statement

Yuhui Cheng: Writing – original draft, Visualization, Software, Investigation, Data curation, Conceptualization. **Jiazhen Wu:** Software, Investigation, Data curation. **Yao Bian:** Investigation. **Xiangyong Yuan:** Writing – review & editing. **Yi Jiang:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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Data availability

All data and code in this study are made available at doi:10.57760/sciencedb.28812.

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