



Sensorimotor simulation and distributed processing of biological motion: Insights from healthy and paraplegic adults

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Abstract

The processing of biological motion (BM), particularly the local motion cues tracing the movements of crucial joints, is vital for social interaction and human survival. While numerous studies have focused on the brain mechanisms underlying BM processing, the contribution of sensorimotor simulation at peripheral effectors remains unclear. In this study, we examined healthy adults and paraplegic spinal cord injury participants to investigate this issue. For healthy adults, both intact BM stimuli and local BM cues without global configuration induced a temporal dilation effect when sitting (sensorimotor simulation accessible), but not when standing (sensorimotor simulation temporarily hindered). In contrast, for participants with permanently hindered sensorimotor simulation, the temporal dilation effect was observed only with intact BM stimuli but not with local BM cues, indicating a robust reliance on sensorimotor simulation during the processing of local BM cues and a selective compensation based on global configuration cues for the permanent loss of sensorimotor simulation. These findings highlight the role of embodied cognition in the distributed processing of biological motion and suggest the importance of selective compensation under damaged sensorimotor circuits.

Keywords Biological motion · Sensorimotor simulation · Spinal cord injury · Functional compensation

Introduction

Successful processing of biological motion (BM; i.e., the dynamic motion produced by humans or other living creatures) is crucial to daily life (Blake & Shiffrar, 2007; Pavlova, 2012). The human brain has evolved specialized mechanisms for BM perception across both spatial and temporal domains (Troje & Chang, 2023; Shen et al., 2023a, 2023b; Shen et al., 2025; Yovel & O'Toole, 2016). In the spatial domain, the processing of upright BM shows higher accuracy or sensitivity in discriminating motion direction and detecting global form than that of inverted BM (Thomas & Shiffrar, 2010; Troje & Westhoff, 2006). In the temporal domain, upright BM is perceived as lasting longer than its inverted counterparts with the same duration (Cao et al., 2015; L. Wang & Jiang, 2012; Q. Wang et al., 2014). Such a temporal dilation effect might reflect a long-term evolutionary adaptation (Kaneko & Murakami, 2009; van Wassenhove et al., 2008). Extending the subjective duration of significant stimuli can enhance their temporal resolution, allowing us to process these signals more deeply per unit of objective time (Tse et al., 2004). In addition, the processing of dynamic

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and continuous motion information is intrinsically linked to temporal summation, as motion is conveyed through visual signals over time rather than at isolated moments. Compared with simple translational or apparent motion, the temporal summation of BM operates over much longer periods and is constrained by the number of ambulation cycles rather than the exposure duration per se (Beintema et al., 2006; Faivre & Koch, 2014; Neri et al., 1998). A recent EEG study also supports the specialized temporal processing of BM, showing significantly stronger cortical tracking of the higher-order temporal structure of BM (e.g., gait cycles) than that of its inverted counterpart (Shen et al., 2023b; Shen et al., 2025).

Numerous neuroimaging studies have depicted the cortical and subcortical brain network involved in BM processing—for example, the posterior superior temporal sulcus (pSTS), extrastriate body area (EBA), premotor, cerebellum, insula, and superior colliculus (Chang et al., 2018; Grossman & Blake, 2002; Jastorff & Orban, 2009; Lu et al., 2024; Saygin, 2007; Sokolov et al., 2012, 2018; Vaina et al., 2001; Y. Wang et al., 2022). However, previous studies have also found that action observation not only recruits the onlooker's brain but also activates the muscles involved in the actual execution of the observed action (Cavallo et al., 2012; Hardwick et al., 2018; Urgesi et al., 2006; Vargas et al., 2004). This phenomenon is known as sensorimotor simulation, where perceiving other people's actions covertly activates motor imitation in the observer (Barsalou, 1999; Jeannerod, 2001; Wilson & Knoblich, 2005). Disrupting sensorimotor simulation through body posture manipulation or spinal cord injury can modulate the spatial processing of body actions and static body posture in tasks of visual matching, direction discrimination, or detection (Arrighi et al., 2011; Fiori et al., 2014; Pernigo et al., 2012). However, little is known about whether and how sensorimotor simulation modulates BM perception in the temporal domain.

It is also worth noting that BM information consists of two key cues: global configuration cues depicting the body form of BM and local motion cues tracing the movements of crucial joints (Chang & Troje, 2009; Hirai & Senju, 2020; Troje & Westhoff, 2006; Y. Wang et al., 2018). Spatially scrambling the canonical point-light BM sequence disrupts the global configuration of BM while preserving local motion cues. Compared with global configuration cues, the processing of local motion cues—for example, spatially scrambled biological motion (SBM), lengthens perceived temporal duration (L. Wang & Jiang, 2012), gains preferential access to awareness (Sun et al., 2022), and is less affected by noise (Chang & Troje, 2009) but more influenced by genes (Y. Wang et al., 2018). Converging evidence from various tasks suggests an innate mechanism tuned to local BM cues in the human brain, which may serve as a life-detection system to perceive other living creatures (see reviews by Hirai & Senju, 2020; Lemaire & Vallortigara, 2022; Troje & Chang, 2023). The significance of local motion cues and the sensorimotor simulation hypothesis

raises the question of whether the life-detection system based on local BM cues extends beyond the brain to encompass the body.

To address this issue, the study explored whether and how sensorimotor simulation influences the duration perception of BM and SBM by measuring the temporal dilation effect under three body states: sitting, standing, and paraplegic spinal cord injury (PSCI). First, we engaged healthy adults in duration discrimination tasks under both sitting and standing postures. Previous electromyography (EMG) studies reveal that standing, compared with sitting, significantly increases isometric muscle contraction in the back and lower limbs (Nicoletti & Läubli, 2018). Additionally, the amplitude of human soleus H-reflex was lower during standing than sitting, indicating suppression of the responsiveness of the monosynaptic reflex in the standing posture (Hayashi et al., 1992; Nakazawa et al., 2004). Together, compared with sitting, standing increases background muscle activity and suppresses the musculospinal pathway, leading to temporarily hindered sensorimotor simulation (Jeannerod, 2001). Thus, the standing posture allows us to investigate the influence of the *temporary hindrance of sensorimotor simulation*. If the sensorimotor system contributes to BM or SBM perception, the temporal dilation effect in the standing condition would decrease compared with the sitting condition, or even disappear. Consistent with this hypothesis, our results showed that the temporal dilation effects for both BM and SBM were evident in the sitting condition but disappeared in the standing condition, suggesting an online engagement of sensorimotor simulation during the processing of BM and SBM information.

Then, PSCI participants were recruited to perform the same task on BM and SBM while seated in their wheelchairs. These PSCI participants experience a permanent disconnection between the lower body and the brain, providing a unique opportunity to investigate the influence of *permanent deprivation of sensorimotor simulation* (Pernigo et al., 2012). We found that this permanent hindrance reduced the temporal dilation effect of SBM stimuli, further supporting the contribution of sensorimotor simulation to SBM processing. In contrast, BM stimuli exhibited a comparable temporal dilation effect to that of the healthy-sitting group, indicating a selective compensation based on global configuration cues in BM.

Methods

Participants

A two-tailed power analysis using G*Power 3 (Faul et al., 2007) indicated that a sample size of 15 participants would afford 80% power to detect a temporal dilation effect with a high effect size (Cohen's $d = 0.8$), based on the results of a previous study (L. Wang & Jiang, 2012). Two groups

of age- and gender-matched individuals agreed to participate in the study, including 20 healthy adults (three women, mean age $\pm SD = 32.10 \pm 6.27$ years), recruited from the local community of the university, and 20 participants with PSCI (three women, mean age $\pm SD = 32.50 \pm 5.04$ years), recruited from the local office of Disabled Persons' Federation. Two participants (one each from the healthy group and the PSCI group) were excluded from further analyses due to poor performance (see details in the Data Analysis section). All participants were right-handed with normal or corrected-to-normal vision and did not report head traumas or psychiatric disorders. They were naïve to the purpose of the study and gave informed consent according to procedures and protocols by the Ethics Committee of the university.

All PSCI participants reported the neurological level of lesions between C3 and L1, which were assessed through the American Spinal Injury Association Impairment Scale (ASIA; Ditunno et al., 1994), and were in accord with the International Standards for Neurological and Functional Classification of Spinal Cord Injury (Maynard et al., 1997). The onset of the traumatic event ranged from 0.67 to 16.75 (mean = 8.18 years, $SD = 5.71$ years) years before testing. All participants suffered from complete motor disability on their lower limbs but were able to move their arms and fingers against gravity with a full range of motion and thus perform the behavioral experiments. Additional demographic and clinical data are shown in Table 1 (see Supplementary Information).

Stimuli

All stimuli were generated and displayed using MATLAB (The MathWorks, Inc.) together with Psychtoolbox (Brainard, 1997; Pelli, 1997). Stimuli were point-light walker sequences derived from motion-captured data (Vanrie & Verfaillie, 2004). Each point-light walker depicts the motion of 13 dots attached to the major joints and the head of a human walker (Fig. 1a, left panel, GIF image see Fig. S1). Each motion stimulus subtended $107 \text{ pixels} \times 171 \text{ pixels}$. SBM stimuli (Fig. 1b, left panel, GIF image see Fig. S2) were created by randomizing the starting positions of each dot within a region approximating the intact BM sequences, aiming to investigate the perception of local motion without the constraints of global configuration cues. Inverted counterparts were generated by flipping the upright motion sequences vertically (Fig. 1a, right panel: inverted BM; Fig. 1b, right panel: inverted SBM), which were regarded as the control stimuli with matched low-level properties comparable to the BM stimuli (Shen et al., 2023b; Simion et al., 2008; Troje & Westhoff, 2006; Vallortigara & Regolin, 2006; Y. Wang et al., 2022).

Procedure

Participants sat or stood about 45 cm from a 14-in. (16:10 aspect ratio) LCD laptop monitor with a resolution of $1,024 \times 768$ pixels and a refresh rate of 60 Hz. The visual distance to the monitor was standardized by fixing the horizontal positions of both the monitor and the chair or wheelchair. Participants performed a duration discrimination task (Fig. 1c). At the start of each trial, a white fixation cross appeared on the screen with a random duration sampled from 1,000 ms to 1,500 ms. Then, an upright motion sequence and its inverted counterpart were presented successively. The order of presentation was counterbalanced across trials. One of the motion sequences was randomly selected as standard duration (1,000 ms), and the other was displayed for 400 ms, 600 ms, 800 ms, 1,000 ms, 1,200 ms, 1,400 ms, or 1,600 ms, leading to seven measurement conditions. A blank interval with a randomized duration of 400–600 ms was inserted between the two motion sequences. Participants were required to judge which motion sequence (the first or the second) appeared longer as accurately as possible. The stimulus content and its order were nonpredictive for the stimulus duration. All participants completed BM and SBM tests in two separate blocks on the same day, resulting in a total of 280 trials, with 20 trials for each measurement condition. The order of the BM and the SBM blocks was counterbalanced across participants.

All healthy participants completed the temporal discrimination tasks in two postures (i.e., sitting and standing). The procedures for the sitting and standing sessions were identical, except for the body postures. To avoid the practice or fatigue effect, the sitting and standing sessions were conducted at least 2 days apart, with the order counterbalanced across participants. To ensure a comparable visual distance between the sitting and standing postures, the monitor height in the standing condition was adjusted by stacking boxes on the desk until the participants' visual distance matched that of the sitting posture. Meanwhile, in standing sessions, to estimate the potential influence of the body shift on time discrimination, participants were required to stand on a Wii Balance Board (Clark et al., 2010) during the whole experiment except during breaks. The Wii Balance Board continuously monitored and recorded participants' event-related changes in the center of pressure (COP) in mediolateral and anteroposterior dimensions. The COP is a valid measure of body balance, representing the distribution of pressure on a two-dimensional surface (Clark et al., 2010; Eerland et al., 2011). One participant in the standing session had no COP recording due to a device connection error. The PSCI group completed the BM and SBM tasks in exactly the same way as healthy participants in the sitting posture. The only difference between the groups is that the healthy group sat in a regular chair while the PSCI group sat in a wheelchair. To

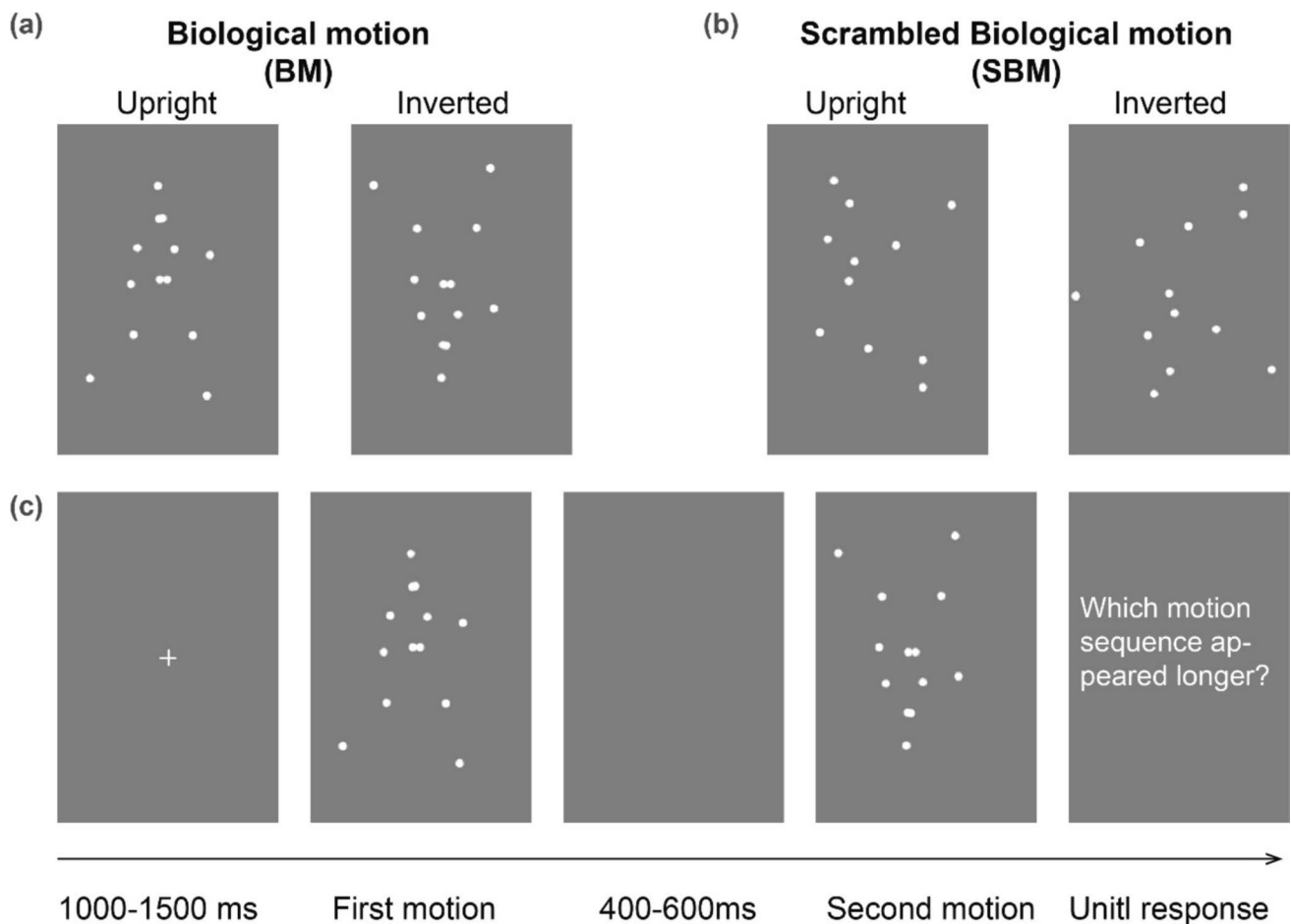


Fig. 1 Illustrations of stimuli and experimental procedures. **a** The static schematic of upright and inverted BM sequences. **b** The static schematic of upright and inverted SBM sequences. **c** The schematic representation of the paradigm for the example of a BM trial

summarize, we tested the temporal dilation effect of BM and SBM information in three conditions: the normal state of sensorimotor simulation (sitting), the temporary hindrance of sensorimotor simulation (standing), and the permanent deprivation of sensorimotor simulation (PSCI).

Data analysis

The proportion of longer responses to upright motion sequences was fitted with a Boltzmann sigmoid function (Eq. 1) for each participant (L. Wang & Jiang, 2012). The point of subjective equality (PSE) was the duration at which observers reported the upright motion sequence as longer at a proportion of 50%. A negative PSE suggested that the upright motion sequence is perceived longer (i.e., temporal expansion) compared with the inverted counterpart, whereas a positive PSE suggested the opposite. In addition, difference limen (DL) was defined as half the interquartile range of the fitted function. A small DL suggested a high temporal discrimination sensitivity (Wearden & Ferrara,

1996). Two participants (one each from the healthy group and the PSCI group) were excluded from further analyses due to poor goodness of fit (exceeded 3 *SDs*). Bayes factor (BF_{10}) of the *t* test was reported to further support the presence or absence of a difference (Hu et al., 2018).

$$F(x) = \frac{1}{1 + e^{-a(x-c)}} \quad (1)$$

Results

Healthy adults: Significant temporal dilation effect of both BM and SBM in the sitting posture

For the BM stimuli, a two-tailed, one-sample *t* test showed that sitting participants tended to judge the upright BM lasting longer compared with the inverted ones with identical physical duration (Fig. 2a). That is,

the upright BM stimuli induced a significant temporal dilation effect (Fig. 2b), $t(18) = 3.60$, $p = 0.002$, Cohen's $d = 0.83$, $BF_{10} = 19.87$. For the SBM stimuli, we observed a similar temporal dilation effect (Fig. 2c & d), $t(18) = 3.15$, $p = 0.006$, Cohen's $d = 0.72$, $BF_{10} = 8.56$. These results repeated previous findings that both BM and SBM lengthen perceived temporal duration relative to their inverted counterparts (L. Wang & Jiang, 2012).

Healthy adults: Temporal dilation effect of both BM and SBM disappeared in the standing posture

When these healthy participants were required to stand motionlessly (see the Methods section), the temporal

dilation effects for both BM and SBM disappeared, BM: Fig. 2b; $t(18) = 0.80$, $p = 0.433$, Cohen's $d = 0.18$, $BF_{10} = 0.32$; SBM: Fig. 2d; $t(18) = 0.04$, $p = 0.972$, Cohen's $d = 0.01$, $BF_{10} = 0.24$. Furthermore, the temporal dilation effect in the standing condition was significantly smaller than that in the sitting condition for both BM and SBM stimuli, BM: $t(18) = -2.15$, $p = 0.046$, Cohen's $d = -0.49$, $BF_{10} = 1.52$; SBM: $t(18) = -2.68$, $p = 0.015$, Cohen's $d = -0.61$, $BF_{10} = 3.63$. Consistently, an ANOVA on the temporal dilation effect, with body posture (sitting, vs. standing) and stimulus type (BM, vs. SBM) as within-participant variables, revealed a significant main effect of body posture, $F(1,18) = 6.69$, $p = 0.019$, $\eta_p^2 = 0.27$, with a smaller temporal dilation effect

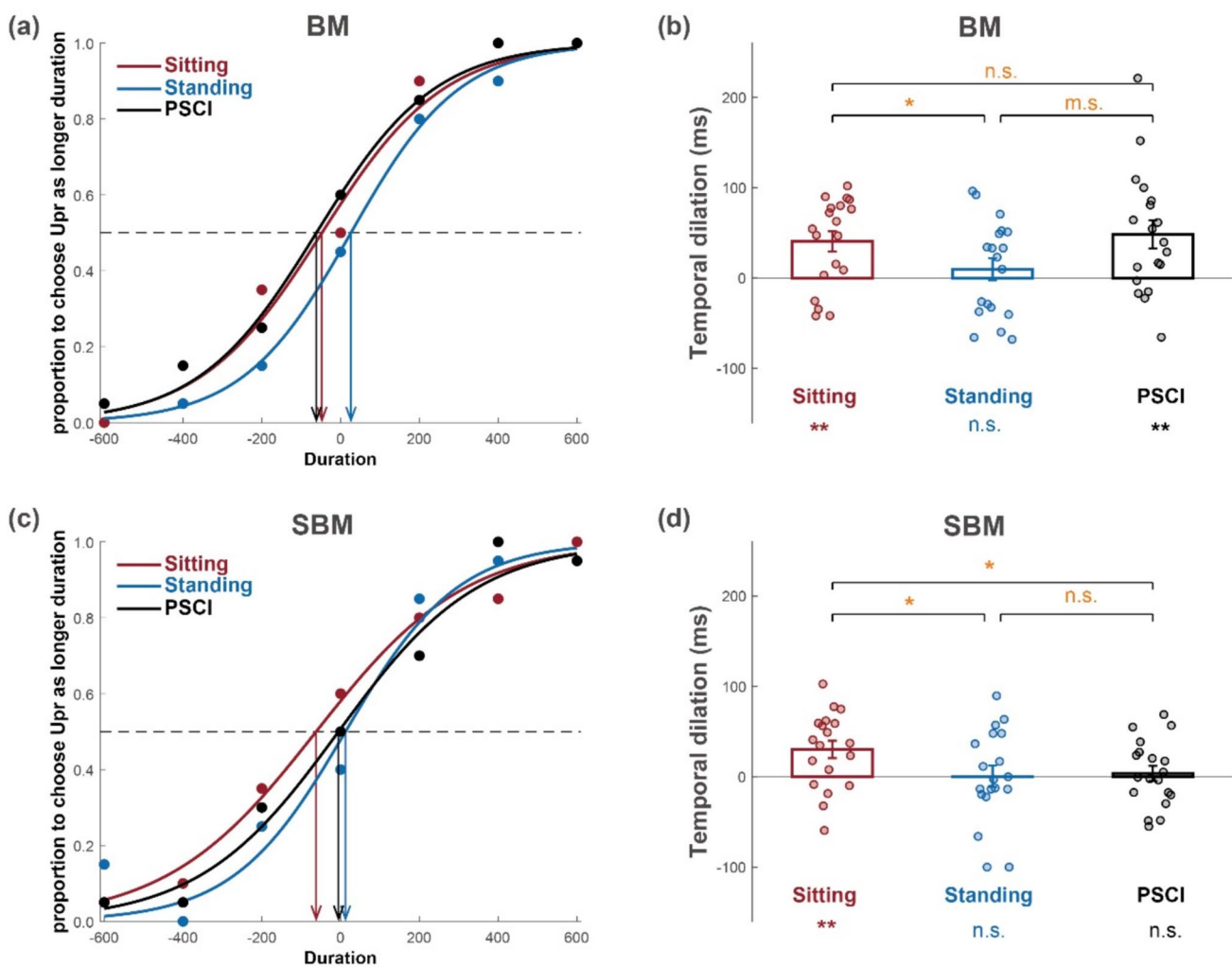


Fig. 2 Availability of sensorimotor simulation modulates the temporal dilation effect. Typical individual data in BM (a) and SBM (c) conditions. Filled dots represented the raw proportions of longer responses to upright motion sequences as a function of the differences between the presentation durations of the two stimuli (upright vs. inverted). Solid curves were fitted functions based on the raw proportions. The dotted horizontal line represented the 50% proportion

of longer responses to upright stimuli. The colorful arrows indicate the PSE in each condition, respectively. The temporal dilation effects (i.e., $-1 \times \text{PSE}$) of BM and SBM stimuli are shown in (b) and (d), respectively. Error bars represent ± 1 standard error of means. Hollow dots represented individual data in each condition. *: $p < 0.05$; **: $0.01 < p < 0.001$; m.s.: $0.05 < p < 0.1$; n.s.: $p > 0.1$. (Color figure online)

in the standing condition than that in the sitting condition. The main effect of stimulus type, $F(1,18) = 0.91$, $p = 0.354$, $\eta_p^2 = 0.05$, and the interaction between body posture and stimulus type, $F(1,18) = 0.01$, $p = 0.937$, $\eta_p^2 < 0.01$, were not significant, further demonstrating that a standing posture equally impaired the processing of BM and SBM. The two-tailed paired-sample *t*-test showed that the difference limens (DLs) were not significantly different between the sitting and standing conditions, BM: $t(18) = 0.03$, $p = 0.977$; Cohen's $d = 0.01$, $BF_{10} = 0.24$; SBM: $t(18) = -0.88$, $p = 0.390$; Cohen's $d = 0.20$, $BF_{10} = 0.34$, suggesting that the differences in the temporal dilation effects between body postures cannot be attributed to discrimination sensitivity.

Meanwhile, the absence of the temporal dilation effect in the standing condition cannot be explained by a body shift in the standing posture. The mental timeline theory posits that left (right) space is associated with a relatively short (longer) temporal duration (Vallesi et al., 2008). Furthermore, body posture variations, such as leaning to the left (Eerland et al., 2011), potentially shift attention into left space and shrink size estimation, a cognitive domain hypothesized to share a common "magnitude" system with temporal and numerical processing (Walsh, 2003). To eliminate potential influences of body postural variation on temporal judgments via a similar attentional shift mechanism, we required all participants to perform the task while standing upright on a Wii Balance Board. Our results showed that participants adhered to this requirement. For most participants, the COPs of the body along the mediolateral and anteroposterior directions remained stable across different periods of a trial (i.e., fix, stim1, blank, stim2, resp; for a typical participant's data, see Fig. 3a). To further exclude any potential influence of COP shifts on temporal dilation effects, we performed trial-based COP shift analysis to identify and exclude participants with excessive within-trial COP shift. Specifically, we calculated the maximum COP shift (i.e., pairwise COP difference) across the five periods (i.e., fix, stim1, blank, stim2, resp) at the trial level for each participant and each condition. Four participants, whose average maximum within-trial COP shift exceeded two standard deviations from the group mean (Fig. 3b), were excluded. We then repeated the one-sample *t* test on the temporal dilation effect for the rest of participants and found that neither BM nor SBM exhibited a significant temporal dilation effect in the standing condition, Fig. 3c; BM: $t(13) = 1.05$, $p = 0.313$, Cohen's $d = 0.28$, $BF_{10} = 0.43$; SBM: $t(13) = 0.46$, $p = 0.655$, Cohen's $d = 0.12$, $BF_{10} = 0.30$. Therefore, the COP shift could not explain the absence of the temporal dilation effect in the standing condition.

PSCI group: Temporal dilation effect of SBM but not BM disappeared in the PSCI group

The contrast between sitting and standing postures in healthy adults indicated that the temporary hindrance of sensorimotor simulation equally reduced the sensitivity to BM and SBM processing. In contrast, the permanent deprivation of sensorimotor simulation in the PSCI group revealed a distinct impact on BM and SBM processing. Specifically, the temporal dilation effect in the PSCI group disappeared in the SBM condition, Fig. 2d; $t(18) = 0.47$, $p = 0.661$, Cohen's $d = 0.12$, $BF_{10} = 0.26$, but remained significant in the BM condition, Fig. 2b; $t(18) = 3.11$, $p = 0.006$, Cohen's $d = 0.71$, $BF_{10} = 7.91$.

DLs were not different between the BM and SBM conditions, $t(18) = -0.05$, $p = 0.963$; Cohen's $d = 0.01$, $BF_{10} = 0.24$, implying that the different temporal dilation effect between the BM and the SBM conditions in PSCI group cannot be attributed to discrimination sensitivity. Meanwhile, we found no significant correlation between the years since lesion onset and the magnitude of the temporal dilation for both the BM and SBM conditions, Fig. S3; BM: $r = -0.147$, $p = 0.547$; SBM: $r = -0.033$, $p = 0.894$. There might be a quick development of the selective compensation for intact BM stimuli in PSCI participants (see more in the Discussion section). There was also no significant correlation between the level of spinal injury and the magnitude of the temporal dilation for both the BM and SBM conditions (p values > 0.05).

The contrast between the healthy group and the PSCI group

Compared with sitting-healthy participants, PSCI participants showed a weaker temporal dilation effect in the SBM condition but a comparable temporal dilation effect in the BM condition, SBM: $t(36) = -2.08$, $p = 0.044$, Cohen's $d = -0.68$, $BF_{10} = 1.66$; BM: $t(36) = 0.41$, $p = 0.684$, Cohen's $d = 0.13$, $BF_{10} = 0.34$; two-tailed independent sample *t* test, further demonstrating the disappearance of temporal dilation effect in SBM but not in BM after spinal cord injury.

Additionally, compared with standing-healthy participants, the PSCI group showed a comparable and non-significant temporal dilation effect in the SBM condition, $t(36) = 0.228$, $p = 0.821$, Cohen's $d = 0.07$, $BF_{10} = 0.32$, indicating a general impairment in SBM processing regardless of spinal cord injury or standing posture. However, in the BM condition, the PSCI group exhibited a significant temporal dilation effect that is slightly larger than that of sitting, healthy participants, $t(36) = 1.951$, $p = 0.059$, Cohen's $d = 0.63$, $BF_{10} = 1.36$, suggesting that the temporal dilation in BM processing only disappeared under the standing posture of the healthy group.

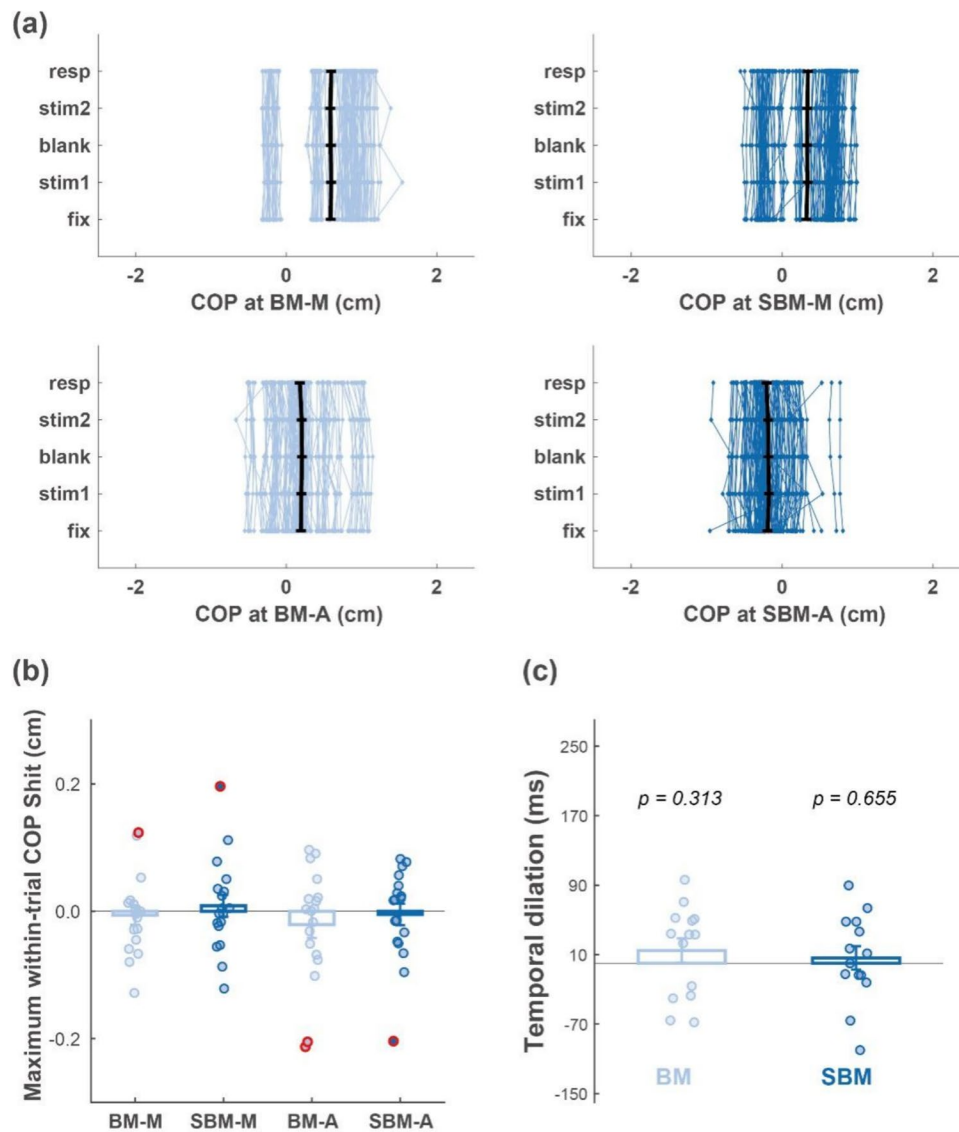


Fig. 3 Center of pressure in standing posture. **a** A typical individual's data depicted the instantaneous values of the observers' center of pressure (COP), in standing posture across five periods of a trial (i.e., fix, stim1, blank, stim2, resp) for each stimulus type (BM, left panels; SBM, right panels) and COP direction (M for mediolateral, upper panels; A for anteroposterior, lower panels). 'fix' was the period when the white fixation was presented on the screen. 'stim1' was the first motion sequence and 'stim2' was the second one. 'blank' was the blank screen between the two motion sequences. 'resp' was the response period. Light lines depicted the COPs for each trial.

Discussion

The current study tested the temporal dilation effect induced by BM (consisting of global configuration and local motion cues) and SBM (only local motion cues) information under three conditions of sensorimotor simulation: available, temporarily hindered, and permanently

deprived. A significant temporal dilation effect was observed for both BM and SBM stimuli only when healthy adults were sitting (sensorimotor simulation accessible), but not when they were standing (sensorimotor simulation temporarily hindered). For PSCI participants (sensorimotor simulation permanently disabled), the temporal dilation effect was observed only for the intact BM stimuli

but not for the SBM stimuli. These findings highlight the engagement of online sensorimotor simulation during BM perception and distinguish its different roles in BM and SBM processing.

In the sitting posture of healthy adults, both the BM and SBM stimuli induced significantly longer perceived durations relative to their inverted counterparts. These findings were consistent with previous studies (Cao et al., 2015; L. Wang & Jiang, 2012; Q. Wang et al., 2014) that used the same temporal discrimination task under sitting conditions in healthy adults. By contrast, for the same healthy adults in the sitting condition, when sensorimotor simulation was temporarily hindered via standing posture (Hayashi et al., 1992; Nakazawa et al., 2004; Nicoletti & Läubli, 2018), the temporal dilation effect vanished for both the BM and SBM conditions. The different results between sitting and standing postures suggest that online sensorimotor simulation is essential for the temporal processing of human motion signals, which is consistent with many well-established effects showing that the sensorimotor system is actively involved in either the perception or production of human body actions (Arrighi et al., 2011; Bosbach et al., 2006; Hardwick et al., 2018; Pernigo et al., 2012). More importantly, extending previous studies focusing on intact BM (Arrighi et al., 2011), the current findings fill the gap in understanding sensorimotor reliance for the processing of local motion cues in BM. These findings, for the first time, provide direct evidence supporting the notion that the life-detection system, driven by local motion cues, engages embodied cognition.

Besides the temporary hindrance of sensorimotor simulation induced by standing posture, the permanent deprivation due to PSCI also disturbed the processing of SBM. This finding reinforces the sensorimotor reliance for the processing of local motion cues. Interestingly, the PSCI group showed a significant dilation effect for the intact BM stimuli that was not observed in the healthy group under the standing posture, even though both groups were unavailable to sensorimotor simulation. These results suggest a potential compensation for the temporal processing of intact BM under permanent loss (i.e., PSCI) rather than temporary loss (i.e., standing posture) of sensorimotor simulation. Unlike the standing posture, PSCI participants suffer from a permanent somatomotor disconnection between the body and the brain (Freund et al., 2011; Henderson et al., 2011; Wrigley et al., 2009), with brain reorganization potentially occurring as early as 6 months after injuries (Hou et al., 2016; Solstrand Dahlberg et al., 2018). This provides neurophysiological foundations supporting functional compensations for perceptual or behavioral impairments after injury. Therefore, the PSCI's temporal dilation for BM stimuli observed in the current study might reflect a behavioral-level compensation for the specific processing of BM information relative to its inverted counterpart, even though the

perceptual sensitivity for BM per se was not comparable to healthy controls (Arrighi et al., 2011). The absence of the dilation effect in SBM stimuli suggests that the compensation observed in BM stimuli mainly resulted from its global configuration cues, implying a form-based compensation. Such compensation was also observed in a hand laterality task based on the stimuli of static figures (Fiori et al., 2014).

The distinct compensation pattern observed in this study supports the notion that there are two relatively independent neural and cognitive components for the processing of local motion and global configuration in BM (Chang & Troje, 2009; Hirai & Senju, 2020; Thompson & Baccus, 2012; Troje & Westhoff, 2006; Vangeneugden et al., 2014; L. Wang & Jiang, 2012; Y. Wang et al., 2018). Specifically, local motion processing operates at an early stage of visual processing (L. Wang et al., 2010) and is less affected by learning experience (Chang & Troje, 2009). A twin study further demonstrated that the individual variation in local motion processing can be accounted for by genetic contribution, whereas global configuration processing is largely shaped by the environment (Y. Wang et al., 2018). These distinctions are also supported by the anatomical and functional dissociations between body form and body motion processing (Jastorff & Orban, 2009; Vangeneugden et al., 2014). Body form is mainly processed in the extrastriate body area (EBA), whereas body motion is mainly processed in pSTS, premotor, MT, and MST (Chang et al., 2018; Saygin, 2007; Thompson & Baccus, 2012; Vangeneugden et al., 2014). For PSCI participants with massive somatic deafferentation and motor deafferentation, the function of EBA (mainly responsible for global configuration processing) is enhanced to compensate for the altered activity in the motor cortex after spinal cord injury (Solstrand Dahlberg et al., 2018; van Nuenen et al., 2012). Meanwhile, the ability to process global configuration information (e.g., body form) is mainly acquired through learning (Chang & Troje, 2009; Y. Wang et al., 2018). The daily exposure to global configurations and accumulation of learning experience might speed up the establishment of the compensation. In contrast, the lower plasticity of local motion processing (Chang & Troje, 2009; Y. Wang et al., 2018) limits its potential compensation after spinal cord injury. Thus, PSCI participants tend to establish a compensation strategy based on form cues rather than local motion cues to process life motion signals, as evidenced by a significant temporal effect for BM but not SBM observed in the current study, and by better performance in form-related versus motion-related tasks reported in a previous study (Pernigo et al., 2012). Together, these findings highlight the role of sensorimotor reliance in local motion processing and the selective compensation involved in global configuration processing. In particular, the sensorimotor reliance for local motion processing may partially explain why genes can account for the individual ability in local BM processing (Y.

Wang et al., 2018). Specifically, monozygotic twins share highly similar physiological bases, and apart from potential similarities in brain responses, the motion simulations in their peripheral effectors when observing BM may also be remarkably alike. This issue merits further investigation using a combination of electromyography and neuroimaging techniques to provide direct neural and physiological evidence for the existence of an innate life motion detector (Troje & Westhoff, 2006) and its dependency on embodied cognition.

Even if we observed functional compensation in PSCI participants, no correlation between the years since the injury onset and the magnitude of the temporal dilation effect was found. The absence of correlation in the present study could be explained by too many years since the injury onset (mean = 8.18 ± 5.71 years; see Table 1 in Supplementary Information), while the time required for functional compensation is relatively short. On the one hand, brain reorganization could occur as early as 6 months after spinal cord injuries (Hou et al., 2016; Solstrand Dahlberg et al., 2018). On the other hand, humans are born as experts in perceiving life motion signals (Bardi et al., 2011, 2014; Simion et al., 2008). Such an inherent advantage and the repeated accumulation in daily experience may allow us to process BM to the highest level very quickly. Therefore, it is likely that PSCI participants only need a short period to achieve the highest compensation for the processing of global structure information in BM stimuli. Similarly, Arrighi et al. (2011) did not find any significant correlation between perceptual sensitivity and time since injury (0.75–15 years) either (Arrighi et al., 2011). Future studies should recruit more participants with shorter durations since injury and measure their brain reorganizations to provide more behavioral and neural evidence for the functional compensation hypothesis. Meanwhile, the different contributions of sensorimotor simulation on the temporal processing of intact BM and its local motion signals can be investigated in more action types.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.3758/s13423-025-02689-3>.

Author contribution Li Shen, Xiaorong Cheng, Zhao Fan, and Xianfeng Ding contributed to the design of the study.

Li Shen, Zhangjing Ma, Hexing Zhong, and Xiaofei Jiao collected the data.

Li Shen and Zhangjing Ma analyzed the data under the supervision of Zhao Fan and Xiaorong Cheng.

Li Shen, Ying Wang, Yi Jiang, Zhao Fan, Xiaorong Cheng, and Xianfeng Ding contributed to the writing of the manuscript.

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Data Availability All data and supplementary information generated during the current study are made available (<https://www.scidb.cn/en/s/6vQfYf>), and materials used during the study are available from the corresponding author upon request.

6vQfYf), and materials used during the study are available from the corresponding author upon request.

Code availability The code for generating the figures are available (<https://www.scidb.cn/en/s/6vQfYf>).

Declarations

Conflicts of interest The authors declare no competing interests. The authors declared no competing interest relevant to the content of this article.

Ethics approval The protocols of the research were approved by the institutional review board of the Ethics Committee of Central China Normal University.

Consent to participate Participants provided written, informed consent before the experiments.

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