

Difference in Interoception between Long-Distance Runners and Sprinters: An Event-related Potential Study

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ABSTRACT

HIRAO, T., T. VOGT, and H. MASAKI. Difference in Interoception between Long-Distance Runners and Sprinters: An Event-related Potential Study. *Med. Sci. Sports Exerc.*, Vol. 52, No. 6, pp. 1367–1375, 2020. **Purpose:** Interoception is a sense of the physiological state of one's body. Interoception that is generated by processing physiological information in the insular cortex plays an important role in achieving optimal performance in competitive sports. This study aimed to reveal the difference in interoceptive ability between long-distance runners and sprinters and its neural correlates by recording the stimulus-preceding negativity (SPN) that is generated from the insular cortex. Based on previous findings, we predicted that long-distance runners would show better interoceptive ability and larger SPNs compared with sprinters. **Method:** We used a questionnaire and a heartbeat counting task to evaluate the interoceptive sensitivity and accuracy, respectively, of both long-distance runners and sprinters. We recorded SPNs during the execution of a time estimation task where participants estimate 3 s by pressing a button. **Results:** Results of the questionnaire revealed that sprinters exhibited a higher interoceptive ability associated with attention control of their own bodies than did long-distance runners. Sprinters also showed a larger SPN over the left centroparietal regions compared with long-distance runners. **Conclusion:** In contrast to our prediction, sprinters exhibited a superior interoceptive ability and a greater activity of the insular cortex relative to long-distance runners. These results suggest that sprinters might be more susceptible to their internal bodily signals compared with long-distance runners, exhibiting greater activation of the anterior insula. **Key Words:** INTERNAL BODY SIGNALS, ATHLETES, COMPETITIVE SPORTS, STIMULUS-PRECEDING NEGATIVITY, INSULAR CORTEX, PERFORMANCE

Interoception is defined as the sense of the internal physiological state of one's own body (1,2). Afferent fibers are spread across the entire body and constantly convey physiological information about the body's state to the posterior part of the insular cortex (2). Interoceptive information is integrated with other types of information (e.g., exteroceptive information) in the middle insula and with motivational, social, and cognitive information in the anterior insula (3). Through

this processing, physiological information can broadly contribute to homeostatic processes and the sense of modulation of somatic feelings (2,4).

Previous studies have revealed that for athletes, interoception may be an essential sense that allows them to carefully attend to their own bodily signals (5). Afferent interoceptive information is used as a signal for athletes to modulate their exercise intensity (6). In line with these findings, it is plausible that interoceptive ability is crucial for athletes to achieve optimal performance in competitive sports. A previous study claimed that interoception is composed of three dimensions: interoceptive accuracy, interoceptive sensibility, and interoceptive awareness (7). Interoceptive accuracy is the objective precision of detecting internal signals. Interoceptive sensibility is a self-evaluation of subjective interoception. Interoceptive awareness is a metacognitive awareness, that is, being cognizant of the awareness of one's own internal physiological state. It is plausible that metacognitive awareness is unrelated to sporting performance; therefore, there is a possibility that the interoceptive accuracy and interoceptive sensibility contribute to an optimal performance of athletes.

However, few studies have examined interoception in relation to athletes' sophisticated performance, so the role of interoception in sports remains unclear. Studies in other fields have demonstrated

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that interoception is an important factor in maximizing performance in professional settings. Recent research has implied that interoceptive abilities are associated with the ability of market traders to make good decisions (8). In sport-related studies, more research is necessary to examine the relationship between interoceptive abilities and performance.

One investigative approach is to compare interoceptive abilities among athletes who play different sports. For example, in track and field, different competitive running distances may require different interoceptive abilities. It is assumed that long-distance runners use interoceptive information to continually monitor their running speed during a race to achieve an ideal pace. In contrast, interoceptive information may be of little value to sprinters in their competitive races, because they rely on short bursts of speed rather than continually monitoring their speed over time. These predictions were based on a previous study in which elite marathoners used an associative cognitive strategy to intensely focus on their internal sensations, then used a dissociative strategy to dissociate sensory input during a race (9). Moreover, a previous study (10) showed that long-distance runners who were more skilled in adjusting their running-pace were more attentive to their bodily states than runners who were less skilled in adjusting their running pace. Long-distance runners may develop a superior interoceptive ability to attend to their bodies during the experience of running long-distance races.

Elite runners who participate in endurance activities, such as adventure racers and military personnel, appeared to have superior interoceptive ability relative to control participants (11,12). Paulus et al. (11) reported that elite adventure racers did not show any performance deterioration in a simple stimulus-response task under aversive interoceptive conditions (i.e., bad respiratory sensation). Their insulae exhibited greater activation during the anticipation of the aversive interoceptive stimulus to maintain their performance under aversive conditions. The insular cortex is an important brain area for athletes' interoceptive processing in endurance sports. In the extreme environment of competitive races, elite adventure racers need to be aware of the state of their bodies to adjust their exercise intensity appropriately and thus demonstrate superior interoceptive function, which allows them to accurately anticipate and modulate the state of their bodies (11). Long-distance racing is representative for endurance sports. Long-distance runners may have a similar interoceptive ability to that of elite adventure racers because they are also required to monitor their bodily states continuously and adjust their exercise intensity during a race.

Thus, long-distance runners and sprinters both exhibit interoception; however, their interoceptive abilities are different. Using experimental tasks to measure brain activities, recent studies have shown that experience playing sports affects both behaviors and brain activities (13,14). Long-distance runners and sprinters, for example, exhibited different neural responses in the anterior cingulate cortex to erroneous behaviors (14). Given that interoception differs between long-distance runners and sprinters, it is plausible that the activation of the insular cortex would also differ between these two groups.

Stimulus-preceding negativity (SPN) is a negative slow cortical potential that reflects the nonmotor anticipatory process for an upcoming stimulus event (15). Importantly, SPN is a useful index of assessing individuals' insular activity (16). The most often used task for recording the SPN is a time estimation task that is composed of a cue stimulus, a response, and a feedback stimulus. In this task, participants are asked to press a button whenever they feel that the designated time has elapsed, and the correctness of their time estimation is presented a few seconds after their response. During the time period between the response and the feedback, the SPN emerges as a brain activity related to the anticipation of feedback (15,17). Damen and Brunia (18) found that, in a time estimation task, a reduction in heart rate occurred with SPN before the presentation of feedback. Heartbeat perception (HBP) is thought to be an ability related to, or perhaps a part of, interoception (19). The amplitude of the SPN has been thought to include the anticipatory process for an interoceptive change in the time estimation task.

Studies using neuroimaging techniques have confirmed that the insular cortex is the main generator of SPN (16,20). In addition to neuroimaging studies, Kotani et al. (20) used a source analysis, constrained by functional magnetic resonance imaging, to investigate the physiological source of SPN in a time estimation task. Their study confirmed that the activation of the right anterior insula contributed to the SPN amplitudes preceding the feedback stimulus in the time estimation task. It has been proposed that the anterior insula integrates afferent interoceptive signals with predictions and provides visceral-interoceptive predictions (21). The amplitude of SPN can include afferent and efferent interoceptive processing during an anticipatory period.

The current study aimed to clarify the differences between the interoceptive abilities (i.e., interoceptive accuracy and sensibility) of long-distance runners and those of sprinters. We used both a questionnaire and a heartbeat counting task, one of the most common tasks used to accurately detect and evaluate a cardiovascular modulation (7), to assess interoceptive accuracy. We used a questionnaire (Multidimensional Assessment of Interoceptive Awareness, or MAIA) to evaluate interoceptive sensibility. We also used a time estimation task to record the SPN to investigate interoception-related brain activities. We hypothesized that the interoception of long-distance runners would be superior to that of sprinters because interoception is more important in competitive endurance races than in sprint races.

METHODS

Participants

A total of 32 runners on the track and field team at Waseda University participated in this study: 17 long-distance runners (2 female, 15 male; age, 19.65 ± 1.06 yr) and 15 sprinters (2 female, 13 male; age, 19.93 ± 1.03 yr). The long-distance runners' group included runners in the track and field competitions for the 3000-m steeplechase, 5000 m, half marathon, and full marathon. The sprinters competed in the 100-, 200-, and 400-m sprints, as well as the 110-m hurdles. Hand preference was assessed with the Edinburgh Handedness Inventory

(22). Long-distance runners and sprinters had mean handedness scores of 72.4 ± 47.5 and 70.9 ± 59.7 , respectively. This study was approved by the Ethics Committee of Waseda University, and informed consent was obtained from all participants.

Task

Time estimation task. Presentation software (Neurobehavioral Systems, Inc., Berkeley, CA; www.neurobs.com) that can present either visual or auditory stimuli in milliseconds was used to program the time estimation task. Numerous event-related potential studies have used the Presentation software because it precisely generates trigger signals for event-related potential averaging (e.g., Ref. (23)). At the beginning of the task, a fixation dot was displayed in the center of the display monitor. A sound cue was presented 1500 ms after the appearance of the fixation dot. Participants were required to respond when they estimated an elapsed time of 3 s by pressing a button with their right index finger. After their response, a feedback stimulus for their time estimation performance was presented at 1500 ms. In the feedback stimulus, a circle with a solid white line indicated a correct response, a minus sign indicated an undershoot response, and a plus sign indicated an overshoot response. An anticipation of 2500 ms was inserted between the response and the feedback presentation (Fig. 1A). A response within a correct time range—a window of 300 ms (i.e., correct range, 2850–3150 ms)—was considered correct. After the experiment, we collected the participant's self-reported introspection and confirmed that none of the participants explicitly noticed the existing trial-by-trial modulation of the correct time range.

The participants completed the time estimation task in conditions with and without feedback (FB and no-FB conditions, respectively). The time estimation task consisted of three blocks of 60 trials. The first two blocks were always in the FB condition, and the last block was in the no-FB condition.

Heartbeat counting task. After or before executing the time estimation task, all participants were asked to complete a heartbeat counting task (Fig. 1B). In this task, participants were instructed to focus on their own cardiac activity and count the number of heartbeats during intervals of three different durations (25, 35, and 45 s). Sound stimuli were used to indicate when participants should start and end their heartbeat counts. The task was composed of two blocks of three trials with three different intervals. The order of trials was randomized, which prevented participants from using their intuition to guess the answers. This task was used to assess interoceptive accuracy (24,25). An HBP score was calculated using the following formula:

$$\text{HBP score} = \frac{1}{6} \sum \left(1 - \frac{|\text{recorded heartbeats} - \text{counted heartbeats}|}{\text{recorded heartbeats}} \right)$$

Questionnaires. Before the execution of tasks, participants completed the MAIA (26). The MAIA is a multidimensional self-report measure of one's ability to comprehend the internal state of one's own body (interoceptive sensitivity). The MAIA was composed of 32 items divided into eight multidimensional concepts (noticing, not distracted, not worrying, attention regulation, emotional awareness, self-regulation, body listening, and trusting).

Physiological recordings. The electroencephalogram (EEG) was recorded from 128 electrode sites using sintered Ag/AgCl active electrodes, according to the Biosemi-designed equiradial system montage using Biosemi ActiveTwo (Biosemi Inc., Amsterdam, the Netherlands). Electrooculograms and electrocardiograms (ECG) were recorded with six flat-type active electrodes. To monitor vertical eye movements, a pair of electrodes was placed at the left supraorbital and infraorbital sites. To monitor horizontal eye movements, another pair of electrodes was placed at the left and right outer canthi. Two electrodes, one on the skin over the left collarbone and another over the fifth rib, were placed across the heart to record the ECG. The data from all channels were digitized with 24-bit resolution at a

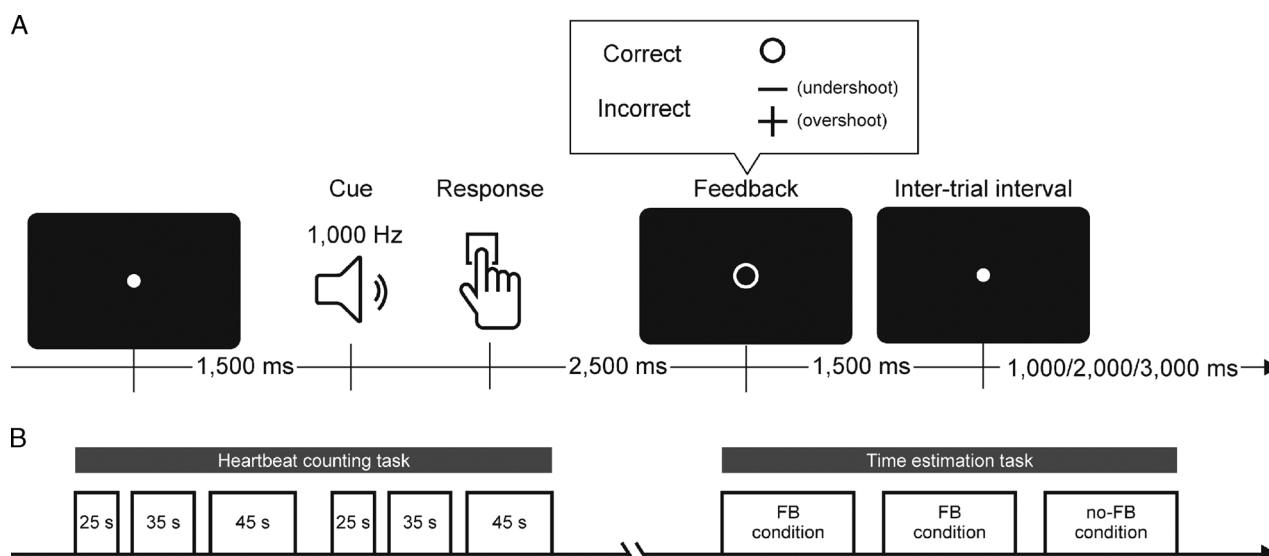


FIGURE 1—A, Schematic illustration of the time estimation task, in which the participant successfully estimated 3 s. B, Schematic illustration of the experimental procedure in which the execution order of the two tasks was counterbalanced between participants.

sampling rate of 1024 Hz. The EEG, electrooculogram, and ECG were recorded in both the time estimation and heartbeat counting tasks.

Data analysis. Brain Vision Analyzer 2 (Brain Products, Gilching, Germany) was used to process psychophysiological data. The EEG was re-referenced to the averaged mastoids. A low-pass filter of 30 Hz (roll-off: 24 dB per octave) was applied to calculate SPN in the time estimation task, and epochs of 4 s before and 1 s after feedback onset were extracted. Ocular movement artifacts were removed using the algorithm described by Gratton et al. (27), and the epochs in which EEG variations exceeded $\pm 80 \mu\text{V}$ were rejected. For the calculation of SPN, baselines were corrected to the time window of 200 ms before the response onset. In both the time estimation and heartbeat counting tasks, ECGs were band-pass filtered with 0.1–30 Hz (roll-off: 24 dB per octave). To obtain the heart rate, R-waves were detected to calculate interbeat intervals (18,28).

A temporospatial principal component analysis (PCA) was applied to pure SPN using a PCA toolkit (29). The temporospatial PCA is a technique used to decompose temporally and spatially overlapped electrocortical activities by calculating the temporal and spatial variance of cortical activity. We applied this technique to distinguish between the motor-related slow potentials elicited before the responses and the nonmotor slow potentials of feedback anticipation elicited after the responses. A temporal PCA with Promax rotation was first applied to the pure SPN data, which produced 13 temporal factors (TF) as the result of the scree plot. Spatial PCA with Infomax rotation was applied to each TF, which yielded two spatial factors (SF) for each TF.

Statistical analyses were conducted using IBM SPSS statistics, version 25 (IBM Corp., Ehningen, Germany). Participants' performance in the time estimation task, the heartbeat counting task, and the MAIA scores were subjected to independent *t*-tests to investigate a between-group difference. To separate the motor activation from the anticipatory activation, pure SPN was calculated by subtracting the waveforms in the no-FB condition from the waveforms in the FB condition. The pure SPN amplitudes were subjected to a three-way ANOVA with the within-subject factors of caudality (frontal/central/parietal) and hemisphere (left/right), and a between-subject factor of group (long-distance runners/sprinters). When *post hoc* tests were required, paired-sample *t*-tests with a Bonferroni correction were used for comparisons. When Mauchly's test revealed a violation of the assumption of sphericity, the degrees of freedom were adjusted using the Greenhouse–Geisser correction.

RESULTS

Time estimation task. The time range for the correct response in this task was adjusted; therefore, a correct rate of approximately 50% was produced in each group ($50.1\% \pm 1.9\%$ for long-distance runners vs $49.5\% \pm 2.6\%$ for sprinters). A *t*-test confirmed that no significant difference existed between the two groups ($t(30) = 0.74$, $P = 0.46$, $d = 0.26$; Fig. 2A). The heartbeat modulation during the anticipation phase of the task

is shown in Figure 2D. The difference in heartbeat between the FB and no-FB conditions was calculated, and the subtracted heartbeat data from the groups were subjected to independent *t*-tests. The sprinters had a significantly larger mean decrease in their heartbeat, which occurred before the feedback presentation, than did the long-distance runners (-500 to 0 ms: $t(30) = 2.37$, $P = 0.024$, $d = 0.83$; 0 to 500 ms: $t(30) = 2.33$, $P = 0.027$, $d = 0.82$; 500 to 1000 ms: $t(30) = 2.64$, $P = 0.013$, $d = 0.92$; 1000 to 1500 ms: $t(30) = 2.13$, $P = 0.042$, $d = 0.74$).

Heartbeat counting task. No significant difference in HBP scores between the groups was observed (0.85 ± 0.12 for long-distance runners vs 0.83 ± 0.09 for sprinters; $t(30) = 0.92$, $P = 0.36$, $d = 0.33$; Fig. 2B).

Questionnaires. Each group's scores in each subscale of the MAIA were compared using independent *t*-tests. Sprinters had a higher interoceptive ability of controlling their attention with respect to their own bodies than long-distance runners (attention regulation (MAIA subscale 4): 3.2 ± 0.5 (sprinters) vs 2.8 ± 0.4 (long-distance runners); $t(30) = 2.47$, $P = 0.020$, $d = 0.87$). No significant difference was found in any other subscale between the two groups (*t* values ≤ 1.91 , *P* values ≥ 0.065 , $d \leq 0.68$; Fig. 2C).

To investigate the differences in personality between long-distance runners and sprinters, independent *t*-tests were applied to compare their scores in each subscale of the NEO-FFI. No significant personality differences were found between the groups (*t* values ≤ 0.89 , *P* values ≥ 0.38 , $d \leq 0.31$).

SPN. Figure 3 shows grand-averaged SPN waveforms at six electrodes in each group. Pure SPN amplitudes were calculated by subtracting the waveforms in the no-FB condition from the waveforms in the FB condition. Pure SPN amplitudes were subjected to a three-way ANOVA of caudality–hemisphere–group, which showed that pure SPN had a typical preponderance of negativity in the right-hemisphere ($F(1,30) = 5.28$, $P = 0.029$, $\eta_p^2 = 0.15$). Moreover, an interaction between hemisphere and group was significant ($F(1,30) = 6.03$, $P = 0.020$, $\eta_p^2 = 0.17$). *Post hoc* tests showed that the SPN amplitude in the left hemisphere was greater among sprinters than among long-distance runners ($t(30) = 2.25$, $P = 0.032$, $d = 0.64$). Long-distance runners had right-hemisphere preponderance of negativity ($t(16) = 3.00$, $P = 0.009$, $d = 0.79$), but sprinters did not [$t(14) = 0.14$, $P = 0.89$, $d = 0.02$].

Correlation of SPN amplitudes with behavioral and physiological data. A Pearson correlation analysis revealed that attention regulation (MAIA subscale 4) was negatively correlated with SPN amplitudes at C3 and P3 (C3: $r = -0.49$, $P = 0.005$; P3: $r = -0.46$, $P = 0.008$). Figure 4 shows the correlations between SPN amplitudes and attention regulation scores. HBP scores in the heartbeat counting task and all other MAIA subscales were not significantly correlated with SPN amplitudes (*P* values ≥ 0.077).

It has been reported that SPN is associated with a decrease in heart rate (18). We investigated the relationship between a decrease in heart rate and SPN amplitudes, because the insular cortex (one of the generators of SPN) is a brain area where cardiovascular interoceptive information is processed. Nevertheless,

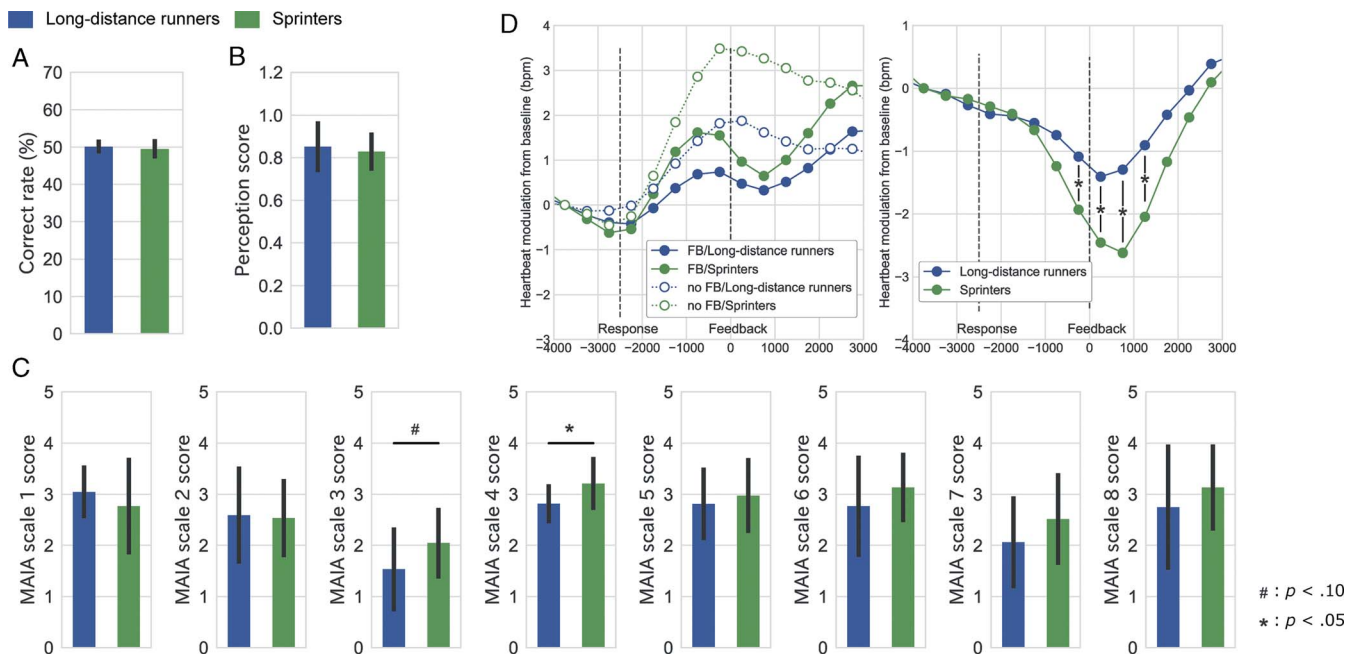


FIGURE 2—Behavioral and physiological findings. A, Results of the time estimation task. B, Perception scores in the heartbeat counting task. C, MAIA subscale scores. D, Modulation of heartbeat during the period, which was the same as a segment for the SPN. Bar graphs show means, and error bars indicate SD for each group. * $P < 0.05$. # $P < 0.10$.

the magnitude of the decrease in heart rate before the presentation of FB in the time estimation task was not significantly correlated with SPN amplitudes (P values ≥ 0.11).

PCA. Despite SPN reflecting nonmotor processing, the negative deflection of the SPN amplitude seemed to start before the response onset. We applied PCA to decompose temporally

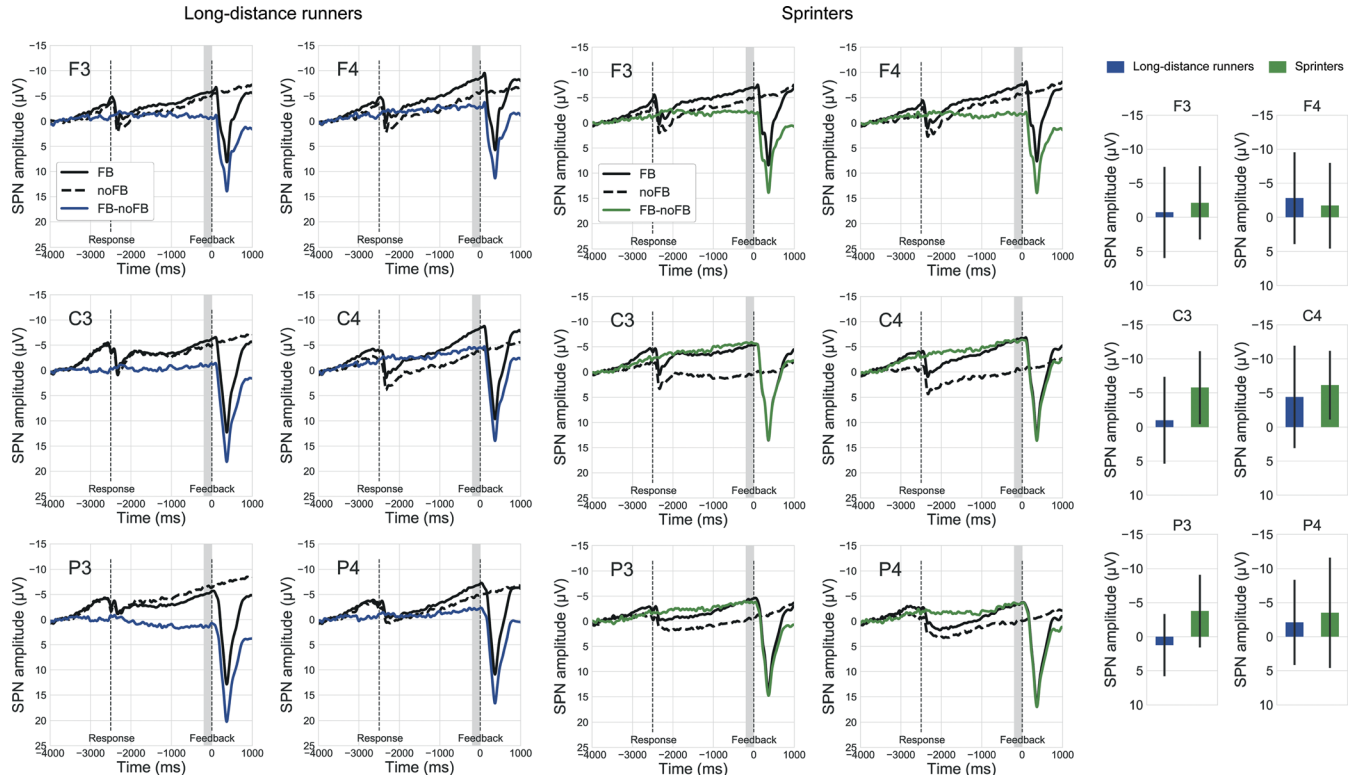


FIGURE 3—Pure SPN waveforms and topographies. The gray shadows in the waveforms indicate measured areas for SPN. The values of SPN amplitudes are shown as bar graphs on the right panel. Bar graphs indicate means, and error bars indicate SD for each group.

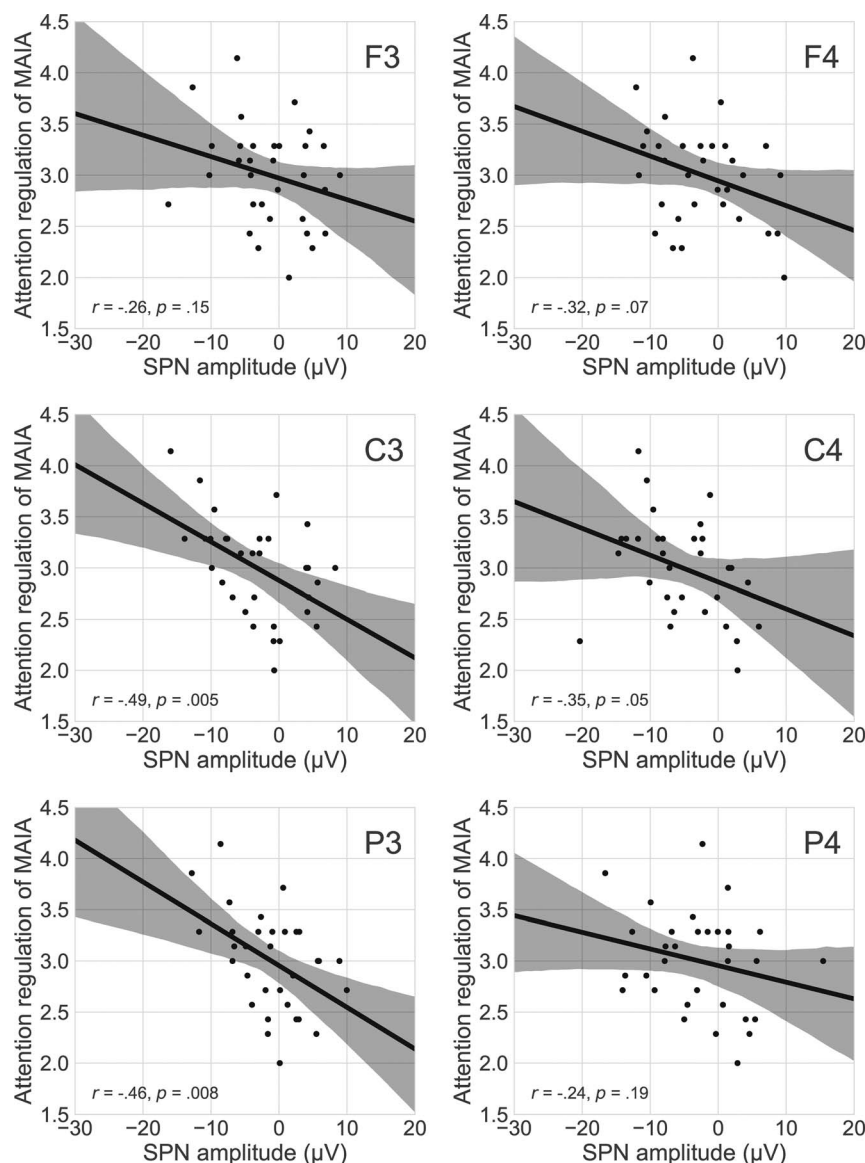


FIGURE 4—Correlations between scores on MAIA, subscale 4 (attention regulation), and SPN amplitudes at six electrode positions. The gray shadows represent 95% confidence intervals.

or spatially overlapped electrocortical activities. A temporal PCA was used to decompose pure SPN data into one response-related motor (TF04), two anticipation-related nonmotor (TF01 and TF05), and four feedback-related factors (Fig. 5). After the temporal PCA, a spatial PCA was applied to each TF, which resulted in two SF for each TF.

Pearson correlations between the first SF in each TF and the attention-regulation MAIA scores were calculated. Attention regulation was negatively correlated with the anticipation-related factors (TF01SF01: $r = -0.48$, $P = 0.006$; TF05SF01: $r = -0.47$, $P = 0.007$), but not significantly correlated with the motor response-related factor (TF04SF01: $r = -0.33$, $P = 0.065$).

Arousal level during the anticipatory phase. A two-way ANOVA with one between-measures (group) factor and one repeated-measures (condition) factor was used to analyze

the power of an α frequency range of 8–13 Hz on the occipital scalp area during the anticipatory phase. It is known that α power in the occipital area is related to the level of arousal (e.g., Ref. (30)). The α power was found to be significantly higher in the no-FB condition than in the FB condition ($F(1,30) = 16.5$, $P < 0.001$, $\eta_p^2 = 0.36$), but there was no significant group difference ($F(1,30) \leq 0.001$, $P = 0.99$, $\eta_p^2 \leq 0.001$).

DISCUSSION

The main purpose of this study was to clarify whether sprinters and long-distance runners have different interoceptive abilities. We compared the SPN amplitudes, which reflect the activity of the insular cortex, including interoceptive information processing, of both kinds of runners.

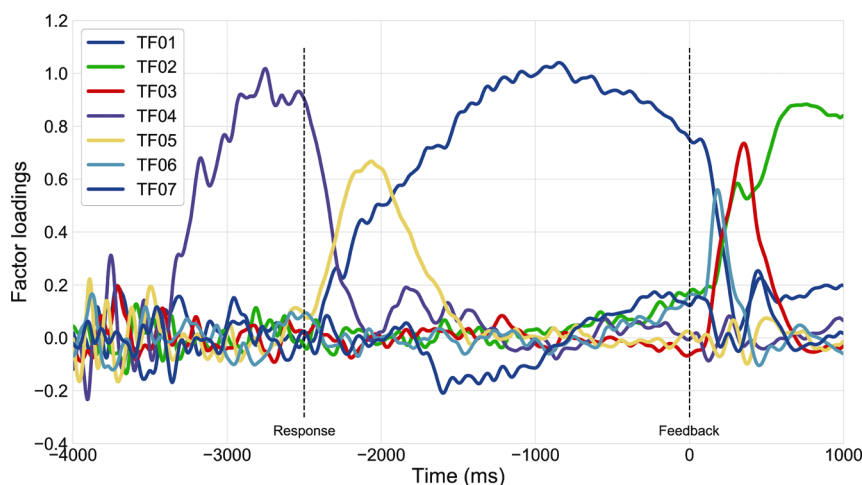


FIGURE 5—Factor loadings of seven TF that had a factor loading of more than 1%. Factor loadings represent the correlation between each SF and the pure SPN waveform.

One aspect of interoceptive ability (interoceptive accuracy) involves noticing physiological changes inside the body. To assess the difference in interoceptive accuracy between long-distance runners and sprinters, both groups performed a heart-beat counting task. Cardiovascular activity is projected onto the right insula, and this area has a crucial role in processing this information (31). We presumed that the long-distance runners would have higher interoceptive accuracy compared with sprinters. However, inconsistent with our expectation, HBP scores did not significantly differ between the groups. This suggests that there is no difference in their ability to notice cardiovascular activity and that interoceptive accuracy did not substantially differ between the groups.

Also inconsistent with our prediction, the questionnaire results revealed that sprinters had a higher level of attention regulation. Sprinters were better able to maintain and control their attention to bodily sensations compared with long-distance runners (26). Attention regulation is an interoceptive ability that the sprinters may have acquired through their own experiences. The importance of interoceptive information relative to exteroceptive information differs between long-distance runners and sprinters. In long-distance races, runners need to pay attention to both types of information, but exteroceptive information is not valuable to sprinters. In other words, long-distance running might share characteristics with open-skill sports, whereas sprinting exhibits characteristics of closed-skill sports. These different playing characteristics may affect the interoceptive ability of each type of runner. A previous study found that suitable attention direction, based on intrinsic motor imagery ability, could affect the process of motor learning (32). In their study, individuals who tended to use kinesthetic motor imagery reported having experience with closed-skill sports in general, whereas individuals who tended to use visual motor imagery reported experiences with open-skill sports. Athletes in open- and closed-skill sports acquire sensory-cognitive skills related to their specific sport domain (33). These results implied that individuals playing sports that required closed-skills could develop the ability to pay attention

to their bodies and sustain that attention throughout their playing experience.

We also aimed to examine the differences in the neural correlates of interoception between long-distance runners and sprinters. Consistent with the results of interoceptive abilities, sprinters had greater SPN amplitudes compared with long-distance runners. The only significant difference in SPN between the two groups was found in the left hemisphere. Moreover, SPN amplitudes in the left central and parietal regions were negatively correlated with attention regulation.

The greater SPN of sprinters can be ascribed to higher activity in their left insula. A functional magnetic resonance imaging study found different functions of insulae between hemispheres. The left insula processed behavioral adaptation to maximize monetary gain, and the right insula processed the salience of outcomes (34). In the context of reward and punishment, although the SPN had a general preponderance in the right hemisphere in the punishment condition, the preponderance in the right hemisphere was diminished in the reward condition (35). These results indicated that the left insula was activated for reward anticipation, and this process was evidenced on the left side of the scalp as SPN. We observed a difference in the SPN amplitude over the left hemisphere between sprinters and long-distance runners; however, we did not manipulate any experimental reward. Given that the interoceptive system provides information for evaluating rewards (36), participants might have interpreted the presentation of correct feedback as their reward.

Another possible explanation for the SPN result is the involvement of the left precentral gyrus. The insula acts as a high-level integration hub, and the anterior insular cortex is a brain area that is interconnected with several other regions (37). The SPN difference in the left hemisphere could be produced by the activation of other brain regions as well as activation in the insular cortex. It has been reported that the left precentral gyrus (Brodmann area 9), as well as the bilateral insular cortex, contributed to a negative deflection of SPN during the anticipatory phase of a time estimation task (20). Activations

of dipoles located in the left anterior insula and left precentral gyrus had a left-lateralized distribution on the scalp (20). Although there is a motor-related area in the precentral gyrus, activation in this area during the anticipatory phase was not related to motor activation because activations in the primary motor cortex (BA4), primary sensory cortex (BA1–3), and premotor cortex (BA6) were absent during the anticipation of the feedback stimulus. The left precentral gyrus can be a crucial brain area for interoception. A previous study investigated the differences in brain structure between meditators and healthy controls. Group differences in brain gyration were found in the left precentral gyrus, right fusiform gyrus, right cuneus, and bilateral anterior insula (38). The results of that study indicated that meditation training could modulate the left precentral gyrus and the left insular cortex. Considering that the attention regulation of interoception is an essential ability for meditation (39), the SPN difference between groups in our study could have been caused by a different activation in the left precentral gyrus.

We obtained pure SPN by subtracting the SPN in the no-FB condition from the SPN in the FB condition. In theory, this subtraction should cancel out movement-related cortical potentials, such as the readiness potential preceding a button response; however, it seemed that the SPN of sprinters showed a slight difference in readiness potential between the FB and no-FB conditions. It has been reported that the negative slope of the readiness potential preceding a purposeful response was greater than that preceding a nonpurposeful response (30). We used a temporospatial PCA to temporally and spatially decompose overlapped components of ERPs (40). The PCA results revealed one response-related, two anticipatory, and four feedback-related components. The two anticipatory components are consistent with a previous study (43), in which SPN was composed of at least two temporal components when a temporal PCA was applied. The statistical analyses of SPN showed that the results for SPN were the same as the anticipatory components of PCA (TF01SF01 and TF05SF01), but that there was no significant difference in the response-related

component. These PCA results suggested that the negative shift of SPN amplitudes in the current study began immediately before the motor response. The onset of right anterior insular activation was found to occur before the response onset in the time estimation task (20). The timing of the initiation of a negative deflection might indicate that the activity in the right insular cortex influenced the SPN in the current study.

The heart rate results in our study indicated that sprinters had a higher magnitude of heart rate reduction preceding the presentation of the feedback stimulus compared with the long-distance runners. It has been reported that the anterior insula is involved in interoceptive predictions (21). The SPN is associated with a decrease in heart rate, which is one type of interoceptive modulation (18). Although we examined the relationship between heart rate reduction and SPN amplitude, no significant correlation was found. This result suggests that SPN did not reflect the amount of interoceptive change, but rather the ability to pay attention to interoceptive change during the anticipatory phase.

In conclusion, our results showed that sprinters had a superior ability to pay attention to their internal bodily signals compared with long-distance runners. Furthermore, sprinters had greater brain activation in their perception of interoceptive change than did long-distance runners. The features of the sprint race, namely, that instantaneous force is required, may have an effect on the interoceptive ability of sprinters.

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All authors report no conflict of interest related to this article.

REFERENCES

1. Critchley HD, Wiens S, Rotshtein P, et al. Neural systems supporting interoceptive awareness. *Nat Neurosci*. 2004;7(2):189–95.
2. Craig AD. Interoception: the sense of the physiological condition of the body. *Curr Opin Neurobiol*. 2003;13(4):500–5.
3. Craig AD. How do you feel—now? The anterior insula and human awareness. *Nat Rev Neurosci*. 2009;10(1):59–70.
4. Rasmussen T, Milner B. The role of early left-brain injury in determining lateralization of cerebral speech functions. *Ann N Y Acad Sci*. 1977;299:355–69.
5. Philippe RA, Seiler R. Sex differences on use of associative and dissociative cognitive strategies among male and female athletes. *Percept Mot Skills*. 2005;101(2):440–4.
6. St Clair Gibson A, Noakes TD. Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *Br J Sports Med*. 2004;38(6):797–806.
7. Garfinkel SN, Seth AK, Barrett AB, Suzuki K, Critchley HD. Knowing your own heart: distinguishing interoceptive accuracy from interoceptive awareness. *Biol Psychol*. 2015;104:65–74.
8. Kandasamy N, Garfinkel SN, Page L, et al. Interoceptive ability predicts survival on a London trading floor. *Sci Rep*. 2016;6:1–7.
9. Morgan WP, Pollock ML. Psychologic characterization of the elite distance runner. *Ann N Y Acad Sci*. 1977;301(1):382–403.
10. Takai K. Cognitive strategies and recall of pace by long-distance runners. *Percept Mot Skills*. 1998;86(3):763–70.
11. Paulus MP, Flagan T, Simmons AN, et al. Subjecting elite athletes to inspiratory breathing load reveals behavioral and neural signatures of optimal performers in extreme environments. *PLoS One*. 2012;7(1):e29394.
12. Paulus MP, Potterat EG, Taylor MK, et al. A neuroscience approach to optimizing brain resources for human performance in extreme environments. *Neurosci Biobehav Rev*. 2009;33(7):1080–8.

13. Hülsmüller T, Strüder HK, Mierau A. Visual but not motor processes predict simple visuomotor reaction time of badminton players. *Eur J Sport Sci.* 2018;18(2):190–200.
14. Maruo Y, Murphy TI, Masaki H. Long-distance runners and sprinters show different performance monitoring—an event-related potential study. *Front Psychol.* 2018;9:1–9.
15. Brunia CH, Damen EJ. Distribution of slow brain potentials related to motor preparation and stimulus anticipation in a time estimation task. *Electroencephalogr Clin Neurophysiol.* 1988;69(3):234–43.
16. Böcker KB, Brunia CH, van den Berg-Lenssen MM. A spatiotemporal dipole model of the stimulus preceding negativity (SPN) prior to feedback stimuli. *Brain Topogr.* 1994;7(1):71–88.
17. Brunia CH, van Boxtel GJ. Anticipatory attention to verbal and non-verbal stimuli is reflected in a modality-specific SPN. *Exp Brain Res.* 2004;156(2):231–9.
18. Damen EJ, Brunia CH. Changes in heart rate and slow brain potentials related to motor preparation and stimulus anticipation in a time estimation task. *Psychophysiology.* 1987;24(6):700–13.
19. Pollatos O, Schandry R. Accuracy of heartbeat perception is reflected in the amplitude of the heartbeat-evoked brain potential. *Psychophysiology.* 2004;41:476–82.
20. Kotani Y, Ohgami Y, Ishiwata T, Arai J, Kiryu S, Inoue Y. Source analysis of stimulus-preceding negativity constrained by functional magnetic resonance imaging. *Biol Psychol.* 2015;111:53–64.
21. Gu X, Hof PR, Friston KJ, Fan J. Anterior insular cortex and emotional awareness. *J Comp Neurol.* 2013;521(15):3371–88.
22. Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia.* 1971;9(1):97–113.
23. Hajcak G, Holroyd CB, Moser JS, Simons RF. Brain potentials associated with expected and unexpected good and bad outcomes. *Psychophysiology.* 2005;42(2):161–70.
24. Ring C, Brener J. Influence of beliefs about heart rate and actual heart rate on heartbeat counting. *Psychophysiology.* 1996;33:541–6.
25. Godefroid E, Pourtois G, Wiersema JR. Joint effects of sensory feedback and interoceptive awareness on conscious error detection: evidence from event related brain potentials. *Biol Psychol.* 2016;114:49–60.
26. Mehling WE, Price C, Daubenmier JJ, Acree M, Bartmess E, Stewart A. The Multidimensional Assessment of Interoceptive Awareness (MAIA). *PLoS One.* 2012;7(11):e48230.
27. Gratton G, Coles MG, Donchin E. A new method for off-line removal of ocular artifact. *Electroencephalogr Clin Neurophysiol.* 1983;55(4):468–84.
28. Graham FK. Constraints on measuring heart rate and period sequentially through real and cardiac time. *Psychophysiology.* 1978;15(5):492–5.
29. Dien J. The ERP PCA toolkit: an open source program for advanced statistical analysis of event-related potential data. *J Neurosci Methods.* 2010;187(1):138–45.
30. Masaki H, Takasawa N, Yamazaki K. Enhanced negative slope of the readiness potential preceding a target force production task. *Electroencephalogr Clin Neurophysiol.* 1998;108(4):390–7.
31. Craig AD. *How Do You Feel? An Interoceptive Moment with Your Neurobiological Self.* Princeton (NJ): Princeton University Press; 2014.
32. Sakurada T, Hirai M, Watanabe E. Optimization of a motor learning attention-directing strategy based on an individual's motor imagery ability. *Exp Brain Res.* 2016;234(1):301–11.
33. Nuri L, Shadmehr A, Ghotbi N, Attarbashi Moghadam B. Reaction time and anticipatory skill of athletes in open and closed skill-dominated sport. *Eur J Sport Sci.* 2013;13(5):431–6.
34. Späti J, Chumbley J, Brakowski J, et al. Functional lateralization of the anterior insula during feedback processing. *Hum Brain Mapp.* 2014;35(9):4428–39.
35. Ohgami Y, Kotani Y, Tsukamoto T, et al. Effects of monetary reward and punishment on stimulus-preceding negativity. *Psychophysiology.* 2006;43(3):227–36.
36. Paulus MP, Tapert SF, Schulteis G. The role of interoception and alliesthesia in addiction. *Pharmacol Biochem Behav.* 2009;94(1):1–7.
37. Nieuwenhuys R. The insular cortex. *Prog Brain Res.* 2012;195:123–63.
38. Luders E, Kurth F, Mayer EA, Toga AW, Narr KL, Gaser C. The unique brain anatomy of meditation practitioners: alterations in cortical gyrification. *Front Hum Neurosci.* 2012;6:1–9.
39. Hölzel BK, Lazar SW, Gard T, Schuman-Olivier Z, Vago DR, Ott U. How does mindfulness meditation work? Proposing mechanisms of action from a conceptual and neural perspective. *Perspect Psychol Sci.* 2011;6(6):537–59.
40. Foti D, Hajcak G. Depression and reduced sensitivity to non-rewards versus rewards: evidence from event-related potentials. *Biol Psychol.* 2009;81(1):1–8.
41. Nikulin VV, Brismar T. Long-range temporal correlations in alpha and beta oscillations: effect of arousal level and test–retest reliability. *Clin Neurophysiol.* 2004;115(8):1896–908.