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Slowed response to peripheral visual stimuli during strenuous exercise

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Abstract (238)

Recently, we proposed that strenuous exercise impairs peripheral visual perception because visual responses to peripheral visual stimuli were slowed during strenuous exercise. However, this proposal was challenged because strenuous exercise is also likely to affect the brain network underlying motor responses. The purpose of the current study was to resolve this issue. Fourteen participants performed a visual reaction-time (RT) task at rest and while exercising at 50% (moderate) and 75% (strenuous) peak oxygen uptake. Visual stimuli were randomly presented at different distances from fixation in two task conditions: the Central condition (2° or 5° from fixation) and the Peripheral condition (30° or 50° from fixation). We defined premotor time as the time between stimulus onset and the motor response, as determined using electromyographic recordings. In the Central condition, premotor time did not change during moderate (167 ± 19 ms) and strenuous (168 ± 24 ms) exercise from that at rest (164 ± 17 ms). In the Peripheral condition, premotor time significantly increased during moderate (181 ± 18 ms, $P < 0.05$) and strenuous exercise (189 ± 23 ms, $P < 0.001$) from that at rest (173 ± 17 ms). These results suggest that increases in Premotor Time to the peripheral visual stimuli did not result from an impaired motor-response network, but rather from impaired peripheral visual perception. We conclude that slowed response to peripheral visual stimuli during strenuous exercise primarily results from impaired visual perception of the periphery.

Key Words: brain, reaction time, premotor time, vision, central nervous system

1. Introduction

Many sports require visual perceptual skills under physiological stress. Recently, we found that strenuous exercise impaired the speed of responses to peripheral visual stimuli, and based on these findings we proposed that strenuous exercise impairs peripheral visual perception [1]. However, this proposal was challenged because of the inherent limitation in assessing visual perception with a reaction-time (RT) task in which a motor response is required [17]. Thus, as strenuous exercise is likely to affect the neuronal network required for motor responses, this could have been the source of the slower motor responses, rather than impaired perception [17].

In a series of studies that assessed peripheral visual perception during exercise, we calculated the premotor time as the amount of time needed by the central nervous system to process a visual stimulus, develop motor output, and conduct a motor command to the periphery [14]. Several cortical and subcortical brain areas are recruited for manual motor responses [18]. Furthermore, it has been shown that primary motor cortex (leg area) [9,12,19,20], supplementary motor area [9,12], cerebellum [9,12], and insular cortex [9,19,20] are involved in dynamic exercise. As suggested by Vaillancourt & Christou [17], given that metabolic resources are limited in the brain when multiple tasks are performed simultaneously, increased activation in brain areas involved in strenuous exercise might interfere with those that control the manual motor response used in reaction-time tasks similar to ours. However, to what extent this is the case remains to be clarified experimentally.

To address this issue, here we compare the effects of strenuous exercise on premotor time to centrally and peripherally presented visual stimuli. We hypothesized that if the slowed response to peripheral stimuli during strenuous exercise is caused by difficulties in peripheral perception, premotor time should only increase if stimuli are presented peripherally. Alternatively, if it is caused by a general impairment in motor output, premotor time during strenuous exercise should increase when stimuli are presented centrally as well as peripherally.

The purpose of this study was to examine whether the slowed response to peripheral visual stimuli during strenuous exercise results from impaired peripheral visual perception or from a general impairment in motor control. The present study will provide new insight into the effects of strenuous exercise on human visual perception.

2. Material and methods

2.1. Participants

Fourteen male participants (age = 23.4 ± 2.2 years; height = 1.70 ± 0.06 m; weight = 67.0 ± 6.5 kg; peak oxygen uptake [$\dot{V}O_2$]: 44.7 ± 5.0 ml/kg/min) gave written informed consent to participate in this study. Participants had normal or corrected-to-normal vision and no history of cardiovascular, cerebrovascular, or respiratory disease. All experimental procedures were approved by the local ethics committee of Fukuoka University and were in accordance with the Declaration of Helsinki.

2.2. Experimental procedure

The experiment was performed over three non-consecutive days. In the laboratory, the ambient temperature was between 21 and 23 °C, and the relative humidity was less than 50%. Before the main experiments, participants performed a maximal exercise test until exhaustion on a cycle ergometer (75XLII, COMBI Wellness, Tokyo, Japan). The maximal exercise test was terminated when participants were unable to maintain a pedaling rate of 50 rpm. Ventilatory parameters were measured using a gas analysis system (ARCO-2000, ARCO System, Chiba, Japan). Peak $\dot{V}O_2$ was determined as the highest oxygen uptake attained during the maximal exercise test. A few days before the main experiments, participants performed practice trials. They completed practice at least two blocks (120 trials) sitting on the cycle ergometer and while cycling until they were familiar with the task. We expect that these practice blocks minimize the possibility that learning affects the results.

On experimental days, participants performed RT tasks after they had adapted to a dark environment. We used two visual conditions (Central and Peripheral) that differed in how far away the visual stimuli were from fixation (central or peripheral visual fields). These visual conditions were blocked, and each one was tested on two different days, separated by at least 3 days. The condition order was counterbalanced across participants. Figure 1A shows the experimental protocol. At the beginning of the experiment, RT was measured for 3 min while participants rested on the cycle ergometer (baseline, or at-rest measurement). One minute following the at-rest measurement, participants gradually cycled the ergometer up to 50% (moderate: 114.2 ± 14.1 watts) and then 75% peak $\dot{V}O_2$ (strenuous: 178.5 ± 20.3 watts). Pedaling rate was freely chosen by each participant, and the duration of each workload was 6 min and 30 s. RT was measured 3 min after the increase in workload for each case.

Insert Figure 1 about here

2.3. RT measurement

We used light emitting diodes (LED) as visual stimuli. A green LED served as the fixation point (34 cd/m^2), and was located 58 cm in front of the participants and aligned to the midpoint between their eyes. The response stimuli were eight yellow LEDs (537 cd/m^2) that were positioned on a horizontal arc at 2°, 5°, 30°, and 50° to the right (+) and left (−) of the fixation LED, and equidistant (58 cm) from the midpoint between the eyes (Figure 1B). A microcontroller (PIC16F84, Microchip Technology Inc., USA) was used to light up the yellow LEDs, and participants were instructed to respond to this signal as quickly as possible by releasing a button on the right handlebar that was otherwise kept pressed with the right thumb. The RT was defined as the time between stimulus onset and the release of the button. In the Central condition, visual stimuli were randomly presented at the four positions closest to fixation (± 2° or ± 5°), and we can assume that participants oriented attention towards a narrow area of the visual field in this condition (Figure 1C). Likewise, in the Peripheral condition, visual stimuli were presented at the four peripheral locations (± 30° or ± 50°), and the participants presumably oriented visual attention towards a larger area of the visual field (Figure 1C). The heads of the participants were stabilized on a chin rest during the RT measurement to ensure that the eyes were directly in front of, and level with, the position of the fixation point. The chin rest was located between the handlebars. Participants were asked to focus on the fixation point binocularly throughout the RT measurement.

One RT-measurement block consisted of 60 trials. At the beginning of a block, all LEDs were lit up for 3 s, serving as a warning that the block was about to begin. After 3 s, the yellow LEDs were extinguished, while the fixation light remained illuminated throughout the remainder of the block. After a variable interval (2.5 to 3.5 s, with a step of 0.25 s), one of the yellow LEDs was illuminated. Each trial then consisted of a yellow LED for 100 ms followed by the variable interval. For analysis, RTs in each condition were combined because a previous study has indicated that differences in premotor time are small within the same visual field [3].

2.4. Electromyogram measurement

Surface electromyograms (EMGs) were recorded over the extensor pollicis longus muscle of the right forearm (Bagnoli, Delsys Inc., Boston, MA). This measurement allowed us to determine the onset of EMG activity without interference from muscle contraction needed for grasping of the handlebars. The analog output of the EMG was recorded at a sampling rate of 1 kHz using a PowerLab analog-to-digital converter (ML880/P PowerLab16/30, A/D instruments Japan, Tokyo, Japan). In the present study, RT was divided into premotor and motor components (premotor time and motor time) based on the EMG activity that reflected the motor response [7]. The onset of muscle contraction was determined by computer software combined with visual inspection. The details of the software used to determine contraction onset have been described elsewhere [5]. In the present study, we defined premotor time as the portion of the RT lasting from stimulus onset to onset of the motor response [3-5]. Motor time was the remaining portion of the RT, lasting from the onset of the motor response until the button was released, which mainly reflect the time required for muscle contraction [10, 11].

2.5. Other measurements

Before and immediately after exercise, capillary blood was collected from the right earlobe to determine blood lactate concentration (Lactate Pro, Arkray, Kyoto, Japan). During the experiment, we measured minute ventilation ($\dot{V}_E$) and $\dot{V}O_2$, and heart rate (HR) using a heart-rate monitor (RS800CX, Polar, Finland). Ratings of perceived exertion (RPE; 6−20 Borg scale) [6] were recorded immediately after each RT measurement. An electro-oculogram (EOG) was recorded at a sampling rate of 1 kHz to monitor overt eye movements and eye blinking during the RT measurement.

2.6. Data and statistical analysis

We excluded some trials from analysis. First, we excluded error trials, defined as those in which no response was made to the visual stimulus, a response was made during the variable interval before stimulus onset, or the RT was less than 100 ms (anticipation). Second, we excluded trials in which overt eye movements or eye blinking was detected. After these trials were excluded, premotor and motor times were averaged for each participant. $\dot{V}_E$, $\dot{V}O_2$, and HR during the RT measurement were also averaged. For the premotor time, motor time, error trials, $\dot{V}_E$, $\dot{V}O_2$, HR, and RPE, we performed a repeated-measures ANOVA with Condition (central or peripheral) and Exercise (rest, moderate, or strenuous) as within-participant variables. For blood lactate concentration, we performed an ANOVA with Condition and Time (pre or post) as within-variables. The degree of freedom was corrected using the Huynh Feldt Epsilon when the assumption of sphericity was violated. We conducted Tukey's multiple comparisons or t-tests, where appropriate. All data are expressed as the mean ± SD. The level of significance was set at $P < 0.05$.

3. Results

3.1. Physiological parameters and RPE

Analysis of the physiological measurements and RPE are shown in Table 1. We observed significant main effects of Exercise on $\dot{V}E$ [F(1.15,14.95) = 330.25, $P < 0.001$, $\eta_p^2 = 0.96$], $\dot{V}O_2$ [F(1.43,18.63) = 1930.98., $P < 0.001$, $\eta_p^2 = 0.99$], HR [F(2,26) = 1849.55, $P < 0.001$, $\eta_p^2 = 0.99$], and RPE [F(2,26) = 1304.65, $P < 0.001$, $\eta_p^2 = 0.99$]. We also observed a significant main effect of Time on blood lactate concentration [F(1,13) = 207.31, $P < 0.001$, $\eta_p^2 = 0.94$]. We did not observe main effects of Condition on $\dot{V}E$ [F(1,13) = 1.32, $P = 0.27$, $\eta_p^2 = 0.09$], $\dot{V}O_2$ [F(1,13) = 0.24, $P = 0.64$, $\eta_p^2 = 0.02$], HR [F(1,13) = 1.02, $P = 0.33$, $\eta_p^2 = 0.07$], RPE [F(1,13) = 0.10, $P = 0.76$, $\eta_p^2 = 0.01$], and blood lactate concentration [F(1,13) =

0.49, $P = 0.50$, $\eta_p^2 = 0.04$]. No interactions were found between Exercise and Condition on $\dot{V}E$ [F(1.21,15.73) = 1.41, $P = 0.26$, $\eta_p^2 = 0.10$], $\dot{V}O_2$ [F(1.23,15.99) = 0.84, $P = 0.40$, $\eta_p^2 = 0.06$], HR [F(2,26) = 0.89, $P = 0.42$, $\eta_p^2 = 0.06$], and RPE [F(2,26) = 1.29, $P = 0.29$, $\eta_p^2 = 0.09$], and between Time and Condition on blood lactate concentration [F(1,13) = 0.12, $P = 0.73$, $\eta_p^2 = 0.01$]. Hence, we combined data from both conditions for further analysis. Post hoc multiple comparisons indicated that $\dot{V}_E$, $\dot{V}O_2$, HR, and RPE increased during exercise with the workload (all *Ps* < 0.001). Collectively, physiological parameters and RPE increased progressively with exercise, regardless of where the visual stimuli were presented (centrally or peripherally).

Insert Table1 about here

3.2. Premotor time and motor time

Figure 2A shows the average premotor time at rest and during moderate and strenuous exercise. ANOVA revealed a significant main effect of Condition [F(1,13) = 31.19, $P < 0.001$, $\eta_p^2 = 0.71$], indicating that when visual stimuli were in the periphery, motor onset began later than when they were located centrally. We also found a significant interaction between Condition and Exercise [F(2,26) = 4.19, $P = 0.03$, $\eta_p^2 = 0.24$], indicating that changes in premotor time in response to exercise differed between the Central and Peripheral conditions. While premotor time did not change depending on the level of exercise during the Central condition, it increased with exercise in the Peripheral condition. Specifically, post-hoc multiple comparisons showed that premotor time was significantly longer during moderate exercise ($P = 0.03$) and strenuous exercise (P < 0.001) than at rest, and longer during strenuous exercise than during moderate exercise ($P = 0.03$). Figure 2B shows the average motor time at rest and during exercise. ANOVA revealed that motor time was not affected by Condition [F(1,13) = 0.22, *P* = 0.65, η_p^2 = 0.02] or Exercise [F(1.31,16.99) = 1.11, *P* = 0.33, η_p^2 = 0.08]. Error trials accounted for 3.6% of all trials. Exercise [F(1,13) = 0.47, *P* = 0.50, η_p^2 = 0.04] or Condition [F(2,26) = 1.90, *P* = 0.17, η_p^2 = 0.13] did not affect the number of error trials.

Insert Figure 2 about here

4. Discussion

The present study tested the hypothesis that slowed response to peripheral visual stimuli during strenuous exercise can be attributed to impaired visual perception. We observed that while premotor time for peripheral visual stimuli increased during moderate and strenuous exercise, premotor time for central visual stimuli did not. These results demonstrate that extended premotor time for peripheral visual stimuli was not the result of an impaired neural network for motor responses, but was rather related to impaired peripheral visual perception. Therefore, the conflict appears to be resolved, with impaired visual perception being the major contributor to the effect. In the present study, participants responded to visual stimuli by releasing the button with the right thumb. The motor response was a simple movement, and we do not assume that complex neural network was recruited. Accordingly, it is no wonder that neural network for motor responses was not affected by strenuous exercise.

In the present study, we did not find differences between the Central and Peripheral conditions in the physiological parameters or RPE values during exercise. This means that the physical demands on the participants were practically identical between the two conditions. We can therefore exclude the possibility that the difference in premotor time between conditions was the result of differing physical demands. Furthermore, motor time did not change during exercise in either the Central or Peripheral condition. These results demonstrate that exercise did not affect the muscle contractions that were required for responding to the visual stimuli.

In a previous study, we separately examined the effects of moderate exercise on premotor time using either central or peripheral visual stimuli [2]. The results indicated that premotor time to peripheral visual stimuli increased during moderate exercise, while premotor time to central visual stimuli did not change. These findings were corroborated by the present results showing that premotor time to peripheral visual stimuli increased during moderate exercise. In a follow-up study, we investigated the effects of strenuous exercise on premotor time under the condition that visual stimuli were randomly presented in a large area of the central and peripheral visual fields with equal probability [3]. Then, we observed that premotor time increased for both central and peripheral visual stimuli. However, because the visual stimuli in that study were presented in a large area of the central and peripheral visual fields, we could not be sure that the increased premotor time to peripheral visual stimuli during strenuous exercise was exclusively because of impairments in peripheral visual perception. To clarify this, here we used a block design to separately test how centrally and peripherally presented visual stimuli affect premotor time during exercise.

We observed that premotor time for peripheral visual stimuli significantly increased during strenuous exercise. Because the manual response was the same for both conditions, we reasoned that if strenuous exercise only impairs peripheral visual perception, premotor time for central visual stimuli would not increase during strenuous exercise. Indeed, premotor time for central visual stimuli was not affected during strenuous exercise. Therefore, the present results suggest that increases in premotor time to peripheral visual stimuli were not likely the result of an impaired motor response. Rather, they likely resulted from impaired peripheral visual perception. At the current stage, there is no theory to account for the present findings sufficiently. However, in the Peripheral condition, participants probably oriented visual attention to a large area of the visual field. Because higher cortical areas, including the prefrontal and parietal cortex, are involved in the control of visual attention [8, 15], the present results support the notion that strenuous exercise may impair the ability to orient visual attention to a large area of the visual field [1]. Nevertheless, further investigation is necessary to understand how strenuous exercise impairs peripheral visual perception. In particular, the effects of acute exercise on early visual processing stages (e.g. retina) should be investigated.

Kahneman [13] claimed that increased arousal causes narrowing of attentional focus, with a progressive elimination of input from the more peripheral aspects of the environment. In his proposal, the term “peripheral” does not mean peripheral vision *per se*, but refers to events that are relatively improbable because most events are likely to occur in the central visual field [16]. In the present study, participants were aware that visual stimuli would be flashed in the periphery. However, premotor time increased during strenuous exercise only to the peripheral visual stimuli. Our results are in line with Kahneman’s proposal; the increase in arousal level induced by strenuous exercise led attentional focus to become narrow, which impaired the ability to detect peripheral visual stimuli. Thus, apart from physiological mechanisms, it is noteworthy that the present findings are compatible with this psychological concept.

Until now, little has been known about how acute exercise affects peripheral visual perception. Different findings may arise when different experimental conditions are employed (e.g. physical fitness of participants, type of perceptual task, and exercise intensity and duration). Therefore, it may be premature to draw a general conclusion that peripheral visual perception is impaired during strenuous exercise. However, at this stage, our behavioral data suggest that this is the case. In future studies, neuroimaging may provide evidence that clarifies the effects of strenuous exercise on central and peripheral visual perception. Finally, in the present study, we assessed peripheral visual perception exclusively from the same horizontal plane. To further understand the effects of acute exercise on human peripheral visual perception, peripheral visual perception needs to be assessed from a broader range of the visual field including upper and lower visual fields.

Conclusion

The present study investigated whether slowed response to peripheral visual stimuli during strenuous exercise results from impaired visual perception. The results demonstrated that increases in premotor time for peripheral visual stimuli could not be explained by an impaired neural network for motor responses, but could be explained by impaired peripheral visual perception. Hence, we conclude that slowed response to peripheral visual stimuli during strenuous exercise is primarily due to impaired peripheral visual perception.

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dynamic exercise in humans. J Physiol 1997;503 (Pt 2):277–83.

Figure Legends

Figure 1 (A) Illustration of the experimental protocol. Dashed lines show the duration of the RT measurements (3 min). Downward arrows indicate the timing of each measurement. (B) Location of the fixation point and visual stimuli (top view). Visual stimuli were positioned horizontally at 2°, 5°, 30°, and 50° either to the right or left of the midpoint between the eyes with an equidistance of 58 cm. (C) Simplified horizontal views from the participants. Dashed ovals indicate areas of visual attention to which the participants were presumably oriented in each condition. Note that shape, size, and angle of the stimuli were different from the actual ones for clarification.

Figure 2 (A) Premotor time at rest and during moderate and strenuous exercise. (B) Motor time at rest and during moderate and strenuous exercise. White bars represent the Central condition. Black bars represent the Peripheral condition. #$P < 0.05$, ###$P < 0.001$, vs. Rest in the Peripheral condition, §$P < 0.05$, vs. Moderate in the Peripheral condition.

Table 1

Table 1. Results of physiological data and RPE.

Variable	Condition	Exercise workload			
		Rest	Moderate	Strenuous	After
$\dot{V}_E$, L/min	Central	9.5 ± 1.6	47.5 ± 6.8 *	84.8 ± 13.3 * †	
	Peripheral	8.9 ± 2.0	47.2 ± 8.4 *	81.7 ± 18.0 * †	
$\dot{V}O_2$, ml/min/kg	Central	4.6 ± 0.9	26.9 ± 3.1 *	40.1 ± 4.2 * †	
	Peripheral	4.6 ± 0.9	26.9 ± 2.1 *	39.1 ± 3.2 * †	
HR	Central	67 ± 11	135 ± 11 *	174 ± 12 * †	
	Peripheral	69 ± 10	137 ± 8 *	174 ± 9 * †	
RPE	Central	6.6 ± 0.9	12.3 ± 1.1 *	16.5 ± 1.5 * †	
	Peripheral	6.3 ± 0.5	12.6 ± 1.2 *	16.8 ± 0.9 * †	
Blood lactate concentration, mmol/l	Central	1.0 ± 0.2			6.6 ± 1.5 *
	Peripheral	1.1 ± 0.3			6.8 ± 1.7 *

Values are mean ± SD; * $p < 0.001$, vs. Rest; † $p < 0.001$ vs. Moderate.
RPE, Ratings of Perceived Exertion; V_E, minute ventilation; VO_2, oxygen uptake; HR, heart rate.

Figure 1
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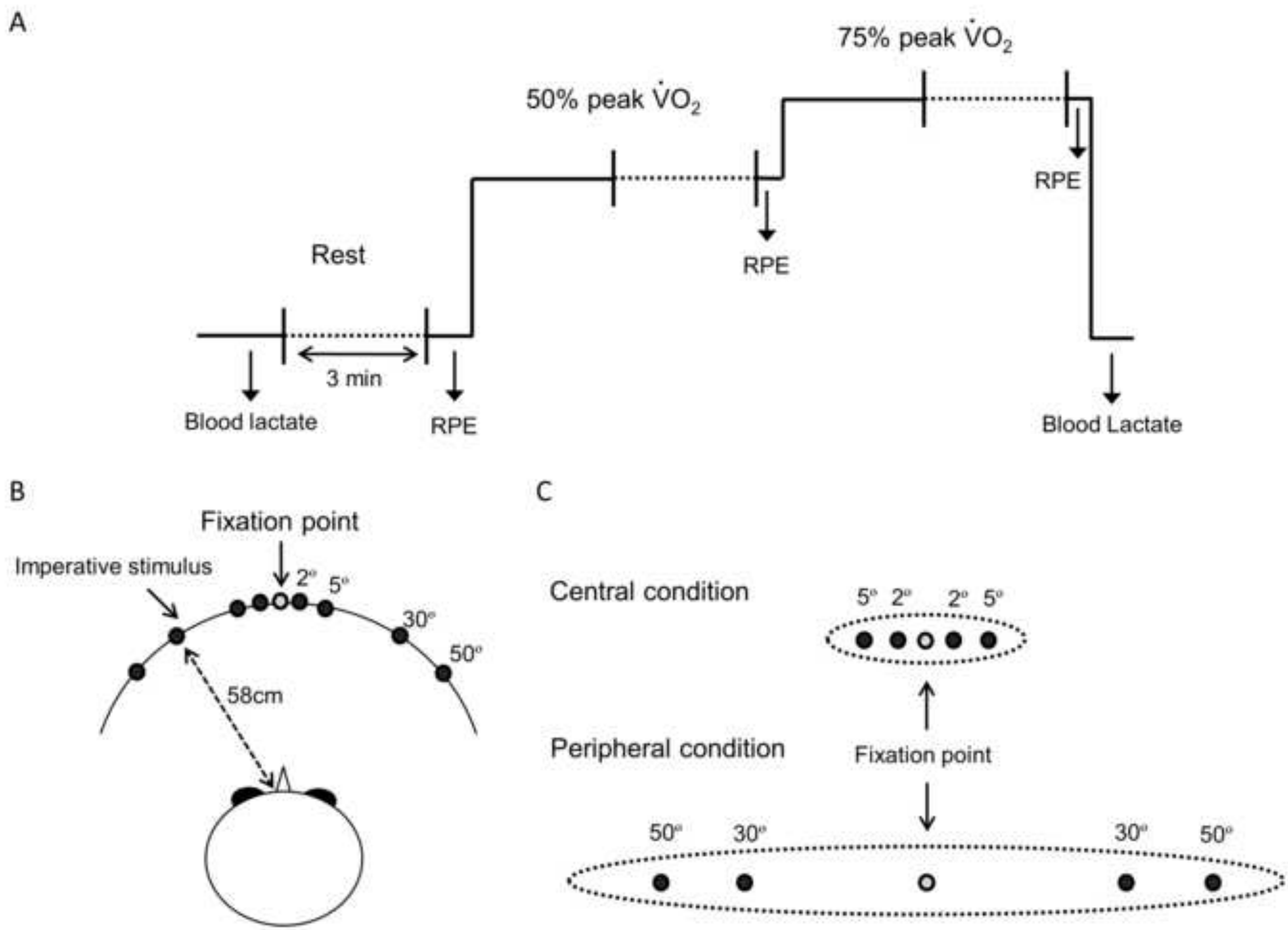

Figure 2
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