Effect of Intensity of Dynamic Exercise on Pupil Diameter in Humans

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Abstract  To test the hypothesis that pupil diameter, which is innervated by the autonomic nervous system, increases with exercise intensity, we determined pupil diameter during incremental exercise in eight healthy subjects. The subjects performed an incremental ergometer exercise in a room illuminated at 90–100 lx. We continuously measured pupil diameter and heart rate before, during, and after the exercise. Pupil diameter increased significantly with exercise intensity (except at the lowest intensity), peaking at 113±3% (mean±SE) of the diameter during the resting baseline period. The diameter did not differ significantly between the resting baseline and recovery periods. These findings suggest that exercise enlarges pupil diameter and that the magnitude of dilation is related to exercise intensity.

Methods

Subjects

Eight subjects (four males and four females: age 25±5 yr, height 170±14 cm, weight 64±15 kg; mean±SD) volunteered for this study. The subjects were normotensive, did not take medication, and had no history of autonomic dysfunction or cardiovascular disease. Each subject refrained from eating and drinking for 2 hours before the experiment. The Institutional Review Board of the Institute of Health Science, Kyushu University, approved the experimental protocols, and all subjects provided written informed consent. All protocols conformed to the Declaration of Helsinki. The intensity of illumination was 90–100 lx near the subject’s head. Subjects looked at a target object illuminated at 30–50 lx throughout the protocol.

Procedures

After 3 min of resting, subjects performed incremental ergometer exercise on an electrically braked cycle ergometer (232c XL, Combi, Japan) until their heart rate (HR) exceeded 160 bpm. The initial work rate was 40 W for males and 30 W for females, and the intensity increased every 3 min by 40 and 30 W for males and females, respectively. After cessation of the exercise, subjects remained seated on the ergometer for recovery.

The subjects performed a mental arithmetic task 20 min before the exercise experiment. After 2 min of resting, subjects were told that they should sequentially subtract 7 or 13 from 100 or 1,000 for 2 min as rapidly as possible. These numbers
were randomly specified at the start of the arithmetic experiment. They answered orally, and an experimenter checked the accuracy of the answers.

**Measurements**

The pupil diameter of the right eye was continuously measured by an eye-movement tracking system (Talk-Eye II, Takei Science Instruments, Japan) at a sampling frequency of 30 Hz. This system measures the relative change in pupil diameter using infrared light. The pupil diameters on the X and Y axes were assessed. However, the pupil diameter on the X axis was used in subsequent analyses because the diameter on the Y axis was affected by the distance between the eyelids. In a pilot study, we observed that the test-retest error in the pupil diameter measurement at rest is within 3% in nine repetitions by three subjects.

The electrocardiogram (ECG) was continuously recorded by a monitor (OEC-6201, Nihon-Kohden, Japan) using standard bipolar leads (CMx). The blood pressure was monitored with an automatic sphygmomanometer on the right middle finger (Finometer, Finapres Medical Systems, Netherlands). These signals were sampled at 1 kHz using an A/D converter (PowerLab 8/30, ADInstruments).

Minute-by-minute HR and mean arterial pressure (MAP) values were calculated from ECG and blood pressure recordings. To obtain minute-by-minute pupil-diameter data, the 20 largest values of a 1-min continuous record were averaged to discard lower values, which are obtained during nictation. We did not use a thresholding protocol to discard lower values so as to avoid adopting data when the eyelids are at the starting-phase of closing and end-phase of opening. The data obtained during the last minute of each stage were used in the analysis since the HR and MAP reached their steady states during this period, while the diameter was similar within the individual stages. Each exercise stage was classified based on the HR as follows on an individual basis except for the first exercise stage: 80–100, 100–120, 120–140, and >140 bpm.

**Statistical analysis**

One-way repeated-measures ANOVA was used to examine the effects of stage and time on pupil diameter. When a significant F value was detected, this was further examined using Dunnett’s post hoc test to compare with the resting baseline value. To compare the effects of exercise intensity, the data sets obtained during exercise were compared with the intensity using Duncan’s post hoc test. Data are expressed henceforth as mean±SE values. Statistical significance was accepted at p<0.05. The statistical analyses were performed at the Computing and Communications Center at Kyushu University using SAS (ver. 8.2 SAS Institute, NC).

**Results**

Pupil diameter in most subjects increased with exercise stage; that is, according to exercise intensity. Actual HR and MAP values for each exercise category are listed in Table 1. The peak diameter, which was 113±3% of the resting baseline, was obtained for an HR of 148±3 bpm. The diameter increased significantly with exercise intensity. The pupil diameter during exercise is plotted against the HR in Fig. 1. At HRs greater than 94±2 bpm, the pupil diameter was significantly greater than the resting baseline. Exercise intensity significantly affected pupil diameter (Table 1). Pupil diameter during the recovery phase did not differ significantly from the baseline.

The performing of mental arithmetic significantly increased pupil diameter, to 106±2% of the resting value. During the recovery period from 0 min to 1 min after performing the arithmetic, it remained significantly larger than the resting baseline (103±2%). However, it did not differ significantly from the baseline at 1–2 min after performing the arithmetic (100±2%).

**Discussion**

The present study demonstrates that exercise increases pupil diameter according to the intensity of dynamic exercise. Performing a mental task also dilates the pupil, as reported previously.

Both mental and physical activities could affect pupil diameter via modulation of the autonomic nervous system. Pupil diameter is controlled by the autonomic nervous system (Loewenfeld, 1993). The sympathetic branch enlarges the pupil by direct stimulation of the dilator muscles. The activation of the Edinger-Westphal complex, which is the motor center for the parasympathetic pathway, stimulates the sphincter muscles, resulting in a decreased diameter.

The dilation of the pupil by mental activity in the present study has also been reported previously (Loewenfeld, 1993; Steinhauer et al., 2004). Steinhauer et al. (2004) suggested that the dilation during a difficult mental task was induced mainly by cortical inhibition of the parasympathetic activity based on the responses to agents that block the autonomic

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Variables for each exercise category classified by the HR</th>
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</thead>
<tbody>
<tr>
<td><strong>Category</strong></td>
<td><strong>HR (bpm)</strong></td>
</tr>
<tr>
<td>Resting</td>
<td>68±5</td>
</tr>
<tr>
<td>First stage</td>
<td>82±2</td>
</tr>
<tr>
<td>80–100</td>
<td>94±2</td>
</tr>
<tr>
<td>100–120</td>
<td>114±1</td>
</tr>
<tr>
<td>120–140</td>
<td>129±2</td>
</tr>
<tr>
<td>&gt;140</td>
<td>148±3</td>
</tr>
<tr>
<td>Recovery 3 min</td>
<td>96±8</td>
</tr>
<tr>
<td>Recovery 6 min</td>
<td>89±6</td>
</tr>
</tbody>
</table>

Data are mean±SE values. ANOVA revealed significant effects of exercise intensity on the pupil diameter. *1st, *80, *100, *120, and *140 indicate significant differences relative to the exercise categories of the first stage, 80–100, 100–120, 120–140, and >140 bpm, respectively.
neurovascular system.

The neural pathway dilating the pupil during exercise is not established, though the involvement of autonomic nervous activities is implied, which generally and greatly change during exercise. Any proposal for the underlying mechanism must consider the findings for both the mental task and exercise, since the latter had a markedly larger effect on autonomic activity. We can only speculate on the pathway. There is evidence that oscillations of circulation and respiration are related to oscillation of the pupil diameter (Loewenfeld, 1993). Reticular activation enlarges the pupils by sympathetic discharges of the dilator muscles and by simultaneous inhibition of parasympathetic outflow from the midbrain. These pathways could therefore be related to the pupil dilation that occurs during exercise. Future studies should investigate whether sympathetic and parasympathetic pathways are related to this dilation, and where the neural signals enlarging the pupil during exercise come from, whether they be central commands or metabolically and mechanically activated afferent inputs (Kaufman and Forster, 1996; Mitchell, 1990).

The regulation of pupil diameter to change the amount of light entering the eye is important for correct eyesight (Loewenfeld, 1993). From the viewpoint of visual function, the changes in pupil diameter in the present study were not negligible. The relative amplitude to the light reflex from the baseline pupil diameter to the maximal constriction is reported to be 20–25% (Bar et al., 2005). The relative change in pupil diameter in response to mental tasks was previously reported to be roughly 10% (Steinhauer et al., 2004); the peak change in the present study was 13%. Thus, this change seems to be large enough to affect eyesight. The amount of light passing through the pupil is proportional to the square of the diameter, and hence a peak diameter change of 13% relative to the baseline corresponds to an increase in the light intensity of 127%, which should be sufficient to affect eyesight.

On the other hand, as for optical characteristics in the eyes themselves, it is unlikely that a change in pupil diameter during exercise would alter the visual function of the eyes. The depth of focus has been reported to be decreased by 0.12 diopters per 1-mm increase in pupil diameter (Ogle and Schwartz, 1959). The decrease in the depth of focus was less than 0.12 diopters in the present study since the normal pupil diameter range is less than 8 mm and the mean change in the present result was roughly 10%. This change is too small to have functional significance since the total reflective power of the eyeball is 60 diopters. In addition, the depth of field remains almost constant when the pupil diameter is larger than 5 mm (Charman and Whitefoot, 1977). The decrease in visual-field sensitivity with pupillary dilation is reportedly not clinically significant (Kudrna et al., 1995; Lindenmuth et al., 1990). Based on these previous studies, it is unlikely that pupil dilation associated with exercise alters the eyesight. Studies are needed to investigate the effect of increased pupil diameter on visual function.

Apart from eyesight, it is difficult to confirm the role of a pupil dilated during exercise and mental tasks. Certain implications have been indicated, such as for the amygdala, where memory of emotional reactions is found. It has a function associated with the detection of the pupil size of others (Demos et al., 2008). A pupil diameter dilated during exercise and mental task could play a role for signaling specific or nonspecific arousal to others. Future research could clarify the effects of pupil diameter on environmental monitoring, behavioral outcomes, and communicating with others.

In summary, pupil diameter increased significantly from the resting baseline with exercise intensity. This supports our hypothesis that the diameter increases with intensity of exercise, and implies that the change of autonomic nervous activity modulates the pupil diameter during exercise.

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