Pupillary Responses during Learning of Inverted Tracking Tasks

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Abstract— **We used visuomotor tracking as our motor task and studied how subjects learn to adjust for inversion of the relation between joystick movement and target movement. This task requires learning a novel sensorimotor transformation. We have measured tracking performance and pupil dilation simultaneously. We have used pupil dilation as a measure of cognitive load, since the diameter of the human pupil increases with task difficulty across a wide range of cognitive tasks. Subjects observed a target moving at constant velocity along a clockwise circular trajectory on a computer screen. Subjects held a joystick in their hand, and moved it so that a cursor tracked the target as closely as possible. 60 normal subjects participated in the experiment. During 6 blocks of learning, inversion-evoked tracking error and inversion-evoked pupil dilation both decreased significantly. This finding suggests increasing automatization of the to-be-learned sensorimotor transformation. Pupil measures were not correlated with tracking error on individual trials, suggesting that the inversion-evoked cognitive load reflects changes in motor task, and is not merely a response to high errors. Our results thus suggest a relatively direct physiological measure of the processes of motor-skill automatization.**

Keywords— **inverted tracking task, pupil dilation, sensorimotor transformation, cognitive load, automatization**

I. Introduction

Motor learning is a fundamental feature of all motor performance, and so it has been a central interest throughout the history of psychology. Motor learning has traditionally been associated with the concept of automaticity. Automaticity refers to the reduction of the cognitive effort required to perform a task, as learning progresses [1]. However, there is little consensus about how automaticity develops, about how to measure it, or about what neural processes are involved in automatization [2].

In order to discuss these points, we have used visuomotor tracking as our motor task and studied how subjects learn to adjust for inversion of the relation between joystick movement and cursor movement. This task requires learning a novel visuomotor transformation. We have measured tracking performance and pupil dilation simultaneously. We have used pupil dilation as a measure of cognitive load [3, 4], since the diameter of the human pupil increases with task difficulty across a wide range of cognitive tasks [5]. Though we used one-dimensional tracking task in our previous study [6], here we have adopted 3 types of two-dimensional tracking in order to study the relation between tracking performance and pupil dilation at different task difficulties.

II. Methods

A. Apparatus

The experimental apparatus consisted of a computer and joystick for tracking measurement, and a pupillary measurement system. Tracking and pupil data were synchronized by digital signals transmitted by the tracking computer at the start of each trial. The apparatus is shown in Fig. 1.

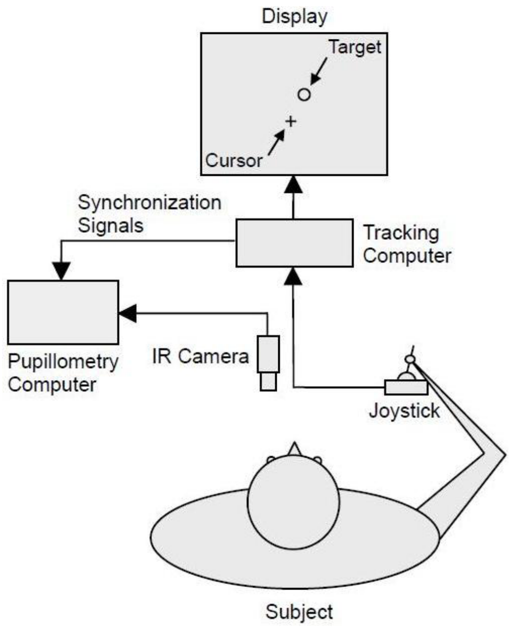

Fig. 1 Experimental apparatus.

B. Tracking

Subjects observed a circular target moving at constant tangential velocity along a clockwise circular trajectory on a computer screen. The target cycle was 5 s. Each trial lasted 20 s. Subjects held a modified joystick in their right hand,

O. Dössel and W.C. Schlegel (Eds.): WC 2009, IFMBE Proceedings 25/IX, pp. 211–214, 2009.
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and moved it so that a visual cross hair cursor tracked the target as closely as possible. Target and cursor positions were digitized and stored on the computer at 30 Hz.

Inverted tracking trials were of 3 types, horizontal inversion, vertical inversion and bidirectional inversion. In inverted trials, the relation between joystick movement and cursor movement was inverted at an unpredictable time during the trial. For instance, in horizontal inversion, the subject had to move the joystick rightward to produce leftward movement of the cursor, and had to move the joystick leftward to produce rightward movement of the cursor. The inversion occurred at an unpredictable time between 11.5 and 12.5 s. The inverted relation remained for the rest of the tracking trial.

Tracking error data from inverted trials were aligned to the time of inversion, and epoch from 4 s before inversion until 6 s after was selected for display. Tracking error traces were then made for each subject in each block of the experiment.

C. Pupillometry

Pupil diameter was measured at 60 Hz using an infrared video eye-tracking system (NAC Image Technology Inc., EMR8B-NL). The subject sat comfortably with their head on a chin rest. The IR sensitive video camera was positioned to view the dominant eye for each subject. The pupil diameters were calculated from the pupil images and stored for later analysis.

Pupil diameter data were analyzed using the same way as tracking data. Traces were baseline-corrected by subtracting the mean pupil diameter on each trial during the 1 s before inversion.

D. Experimental design

All experimental blocks consisted of 5 trials. The experiment began with a pretest block of normal non-inverted tracking trials. Next, subjects performed 6 learning blocks of inverted trials each. Then, subjects performed a posttest block of normal trials similar to the pretest block. The subjects were instructed to continue tracking as accurately as possible even if the inversion happened.

60 subjects were recruited. Subjects' ages ranged between 18 and 24 years. We divided the subjects into 3 groups, horizontal inversion group, vertical inversion group, and bidirectional inversion group. Each group included 10 males and 10 females. The horizontal inversion group performed horizontal inverted trials, the vertical inversion group performed vertical inverted trials, and the bidirectional inversion group performed bidirectional inverted trials in the learning blocks.

III. Results

A. Tracking data

The grand average unsigned tracking error for each block is shown in Fig. 2. The inversion occurred at time 0. Several features of this figure deserve comment.

First, the error caused by inversion varies across the learning blocks. The tracking error is higher for block 1 than for the other blocks of the experiment. The learning effect between blocks is very clear in each group.

Second, regarding earlier blocks, the error in horizontal inversion group is higher than in vertical inversion group, but the error for block 6 is not differ among these groups.

Third, the tracking error in bidirectional inversion group decreases earlier than in the other groups, and the waveform is different from the others.

To draw learning curves, we measured mean tracking error during 4 s after inversion, and subtracted tracking error during the 1 s before inversion as a baseline.

Fig. 3 also shows the clear learning effect in each group and the difference among these groups. The differences between horizontal inversion group and vertical inversion group are significant ($p < 0.05$) for all blocks but block 6. On the other hand, the differences between vertical inversion group and bidirectional inversion group are not significant for all blocks.

B. Pupil data

The pupil data were analyzed as an indirect measure of the cognitive processes associated with skilled tracking. The grand average pupil diameter traces for each block is shown in Fig. 4. This figure shows several features.

First, the waveforms show a clear pupil dilation related to inversion. Pupil diameter begins to increase some 500 ms after inversion, and does not return to the level before inversion.

Second, the amplitude of pupil dilation evoked by the inversion varies across learning blocks. In general, inversion-evoked pupil dilation decreases during learning.

Third, the pupil dilation in horizontal inversion group is much higher than in vertical inversion group for all learning blocks.

Fourth, the pupil dilation in vertical inversion group is higher than in bidirectional inversion group for all blocks but block 1.

Fifth, the pupil dilation in bidirectional inversion group decreases earlier than in the other groups, and the waveform is different from the others.

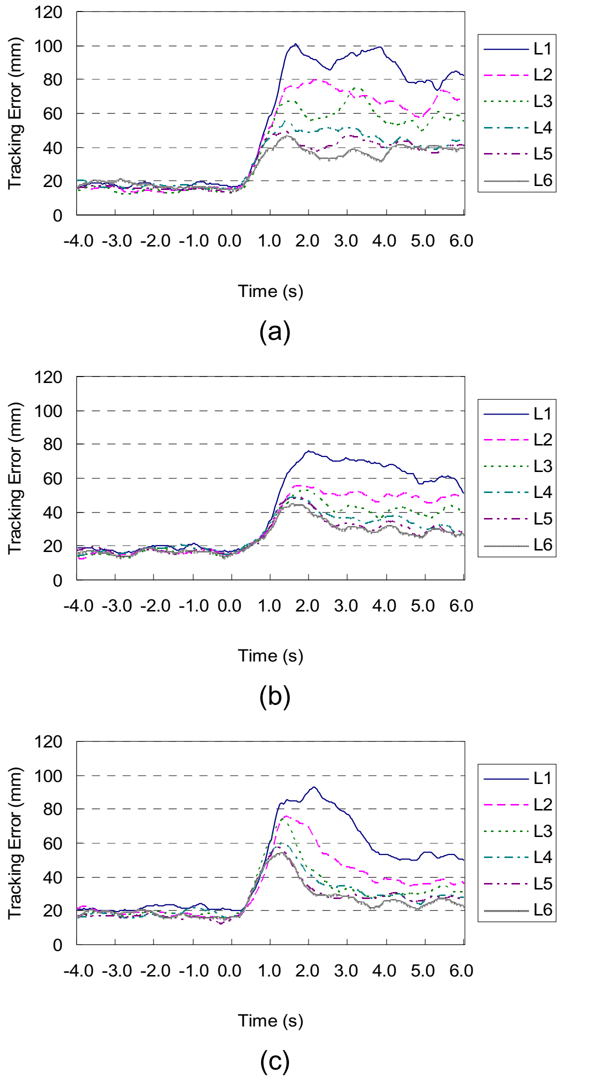

Fig. 2 The waveform of grand average tracking error arranged by learning block. (a) Horizontal inversion group, (b) Vertical inversion group, (c) Bidirectional inversion group. Ln refers to nth learning block.

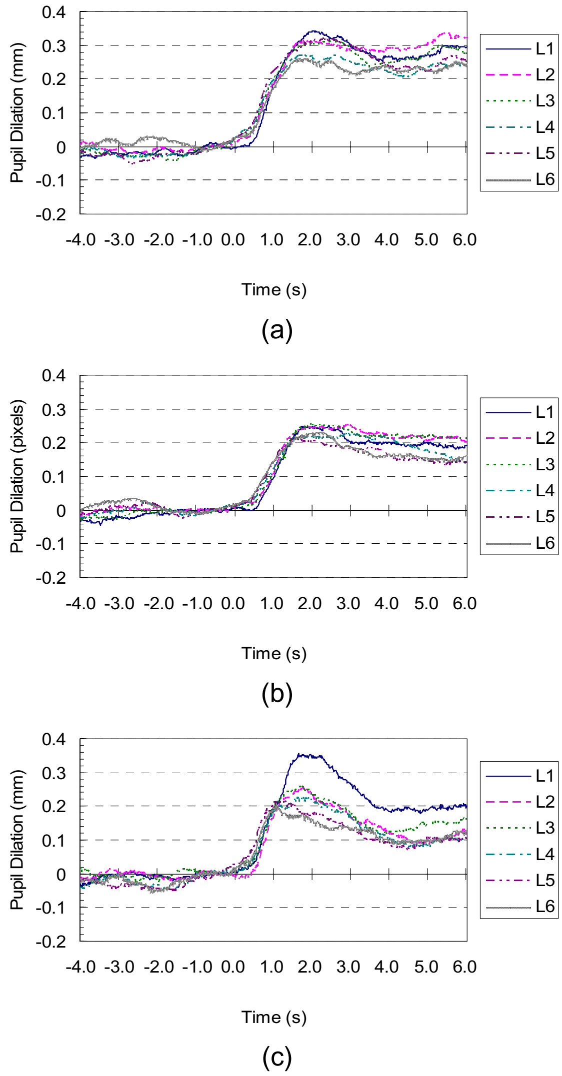

Fig. 4 The waveform of grand average pupil dilation arranged by learning block. (a) Horizontal inversion group, (b) Vertical inversion group, (c) Bidirectional inversion group. Ln refers to nth learning block.

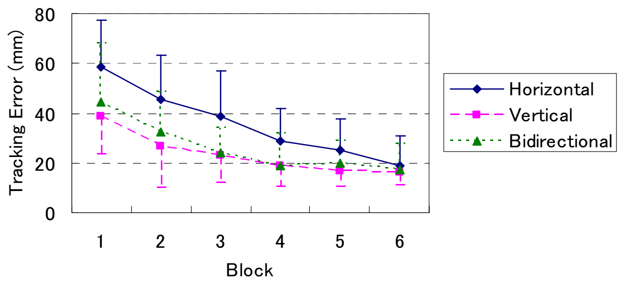

Fig. 3 Learning curve of tracking error for each learning block.

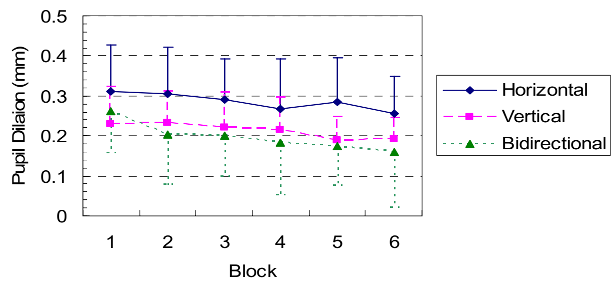

Fig. 5 Learning curve of pupil dilation for each learning block.

To draw learning curves, we calculated the mean pupil diameter from 0.5 to 4.5 s after inversion, and subtracted the pupil diameter during the 1 s before inversion as a baseline.

Fig. 5 also shows the learning effect in each group and the difference among these groups.

We compared the pupil dilation in block 1 and in block 6 in each group, the learning effects are all significant ($p < 0.05$ for horizontal inversion group and vertical inversion group, $p < 0.01$ for bidirectional group).

The differences between horizontal inversion group and vertical inversion group are significant ($p < 0.05$) for all blocks but block 2 and block 4. On the other hand, the differences between vertical inversion group and bidirectional inversion group are not significant for all blocks.

C. Relation between tracking error and pupil dilation

We also calculated the correlation coefficients between tracking error and pupil dilation on a trial-by-trial basis in each group. These are 0.16, 0.22 and 0.23 in horizontal inversion group, vertical inversion group and bidirectional inversion group. Tracking error and pupil dilation correlate very lowly across trials in all groups.

The relation between tracking error and pupil dilation is shown in Fig. 6. This figure shows the clear learning effects in tracking error and pupil dilation. It also shows the difference among the experimental groups. The pupil dilations in these groups are quite different in each block, though the tracking errors in the groups are similar in block 6.

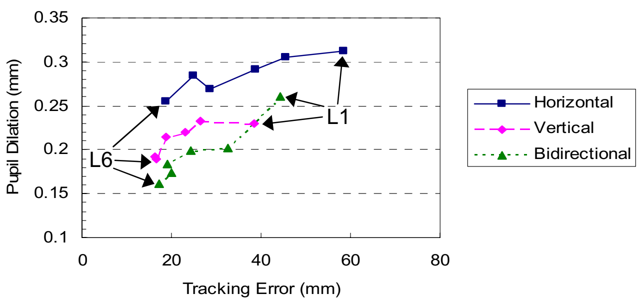

Fig. 6 Relation between tracking error and pupil dilation.

IV. Discussion

The findings are summarized below. First, subjects can learn a novel sensorimotor mapping when tracking unpredictably inverts. Second, tracking inversion evokes pupil dilation, suggesting that engaging the new sensorimotor transformation involves a cognitive load. Third, inversion-evoked pupil dilations decrease with learning, implying a gradual reduction in this cognitive load, or an automatization of inverting tracking. Fourth, this cognitive load is not merely driven by tracking performance, since tracking error and pupil dilation do not correlate across trials.

Our data extend previous studies of automatization of motor learning in many ways. We have developed pupil dilation as a new and relatively direct physiological measure of cognitive effort during learning. Although pupil dilation is known to correlate with task difficulty, and thus presumably with cognitive effort, in many different tasks [5], we are not aware of any previous use of pupil data to describe processing changes during learning. Our pupil measures provide psychophysiological evidence for a reduction in cognitive effort during learning inverted tracking, directly supporting an automatization theory of motor learning.

Acknowledgment

This work was supported in part by a grant from High-tech Research Center of Ryukoku University. This paper was partially written at Institute of Cognitive Neuroscience, University College London, thanks to Professor Patrick Haggard and the Research Abroad Program of Ryukoku University.

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