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Automaticity in Motor Learning: Evidence from Visuo-motor Tracking Performance and Pupil Dilation

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Abstract: Motor learning has traditionally been associated with the concept of automaticity. Automaticity refers to the reduction of the cognitive effort required to perform a motor task, as learning progresses. However, there is little detailed consensus in the literature on what the process of automatization actually involves. We measured tracking performance in two groups of participants while either the target or the manual cursor was suppressed for a brief period during each trial. Subjects learned to maintain accurate tracking through periods of target or cursor suppression. We have used this approach to investigate the internal models used during tracking, and their updating during motor learning. We have simultaneously measured tracking performance and pupil dilation as a measure of cognitive load. The results showed that pupil diameter decreases with learning process of tracking performance. Decrease of pupil diameter suggests that automatization is linked specifically to the learning of internal models.

Methods

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 sec. Each trial lasted 20 sec. Subjects held a modified joystick in their right hand, and moved it so that a visual cross hair cursor tracked the target as closely as possible.

Tracking trials were of 2 types, normal and suppressed tracking. In normal trials, the movements of the joystick produced congruent movements of the subject's cursor on the screen. In suppressed tracking, we blanked out either the target or the cursor during the trial. The disappearance occurred at an unpredictable time between 5 and 7 sec. Then, the target or cursor reappeared at a random time between 11 and 13 sec.

Pupillometry

Pupil diameter was measured at 60 Hz using an infra red 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.

Experimental design

All experimental blocks consisted of 5 trials. The experiment began with a pretest block of normal tracking trials. Next, subjects performed 6 learning blocks of target or cursor suppressed 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 when target or cursor disappeared.

20 subjects were recruited from among the students of Ryukoku University. Subjects' ages ranged between 19 and 24 years. 10 subjects were male, and 10 were female.

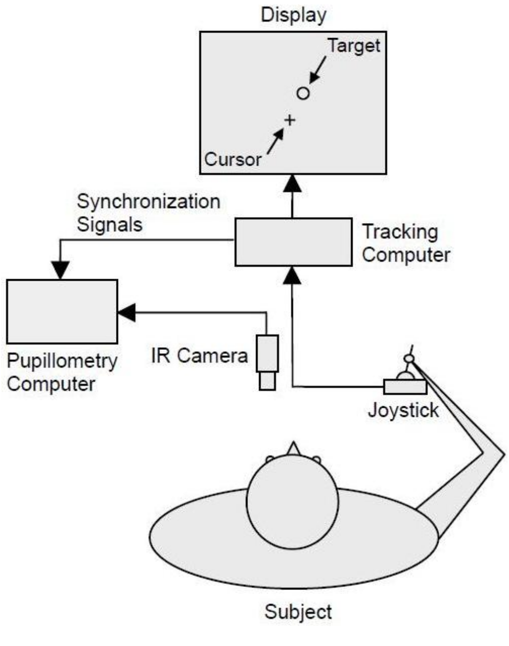

Figure 1: Experimental apparatus.

We divided the subjects into 2 groups. In learning blocks, the target suppression group performed target-suppressed trials and the cursor suppression group performed cursor-suppressed trials.

Results

Tracking data

The grand average traces of unsigned tracking error for each learning block are shown in Figure 2. This figure shows that the error during the suppression period varies across the learning blocks. In the target suppression

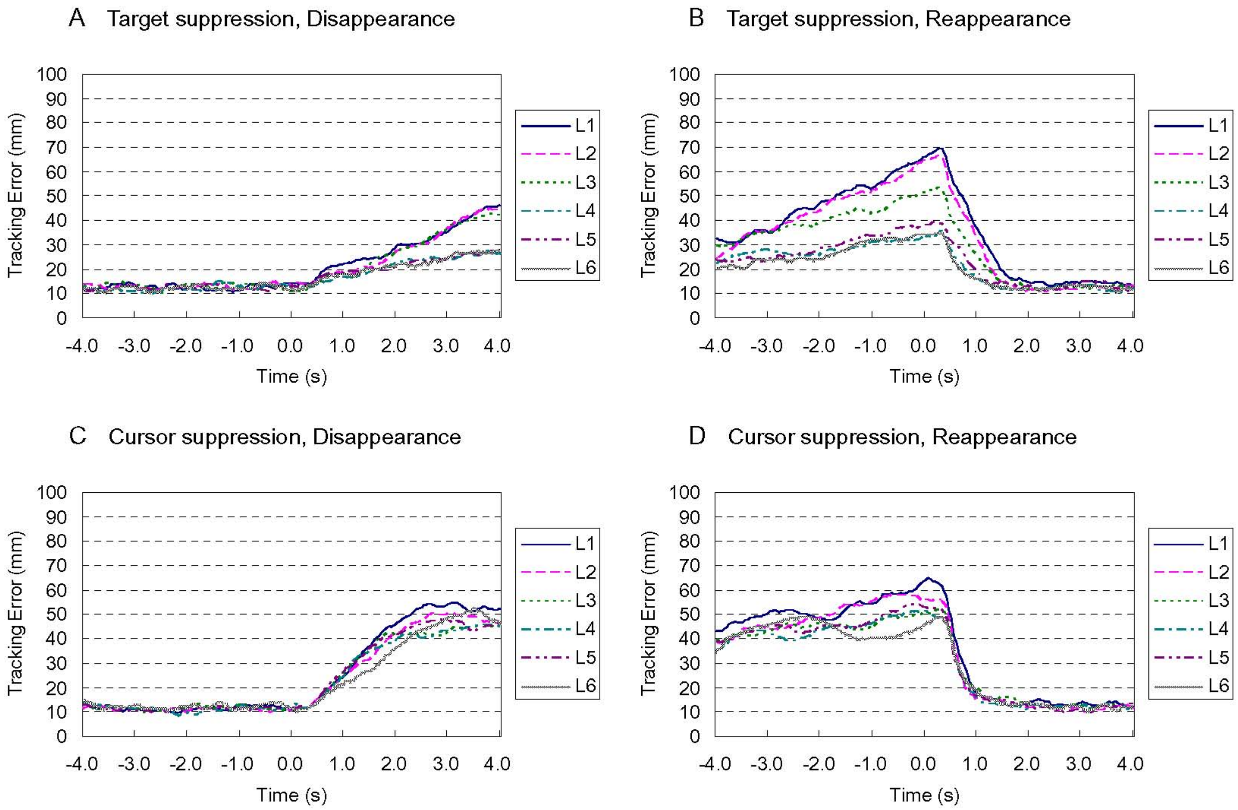

Figure 2: Grand average tracking error waveforms arranged by learning block.

group, tracking error is clearly higher for blocks 1-3 than blocks 4-6. The cursor suppression group also shows differences between blocks, but these are somewhat smaller than in the target suppression group.

We calculated mean tracking error on each trial during an epoch from the time of disappearance to 2 sec after reappearance. We compared the tracking error in the first and last learning blocks, using a mixed ANOVA with factors of group (between-subjects) and block (within-subjects). This showed a significant effect of block [$F(1,18) = 11.514$, $p = .003$] with lower tracking error in block 6 than in block 1, as predicted. There was no significant effect of group [$F(1,18) = 3.701$, $p = .070$] and no interaction [$F(1,18) = 1.859$, $p = .190$]. We also compared the tracking error in the first and last learning blocks in each group separately. The results showed significant effects of learning in target suppression group [$t(18) = 2.722$, $p = .0007$] and also in cursor suppression group [$t(18) = 1.923$, $p = .0035$]. Thus, subjects learned to track during the suppression period.

Pupil data

The grand average pupil diameter traces are shown in Figure 3. This figure shows that the amplitude of these dilations varies across learning blocks. In the target suppression group, the pupil dilation on disappearance is more marked for blocks 1 and 2 than for other blocks. In the cursor suppression group, the pupil dilation on disappearance is higher for blocks 1-3 than for 4-6. The pupil response to reappearance shows similar gradients but with less clear separation between blocks.

We extracted an epoch from 0.5 to 2 sec after disappearance for statistical analysis, and applied the same mixed ANOVA model as before. This showed a significant effect of learning, with smaller pupil dilations in block 6 than in block 1, [$F(1,18) = 12.929$, $p = .002$]. There was no main effect of group, and no interaction [both $F < 1$]. These data suggest that the disappearance event initiates a specific cognitive process associated with the internal model-based tracking, rather than conventional visual feedback-error-based tracking. Moreover, this cognitive process changes as a result of learning.

Discussion

We found clear evidence for learning in both situations, based on a reduction in tracking error during the suppression period. Since feedback-error-driven correction cannot occur during either target or cursor suppression, improvements in suppressed tracking during the course of the experiment suggest that subjects must learn internal representations of the target movement, and also of their own movement. Many studies of tracking behavior agree that the motor learning underlying tracking performance is predictive in nature (Craik, 1947). Improvements in tracking performance may therefore occur because prediction improves with practice: subjects learn to predict.

Pupil dilation measures gave an independent measure of the cognitive effort associated with tracking during our task. We found large changes in pupil diameter associated with tracking error signals, particular at the time of reappearance after suppressed tracking. We found smaller, but still reliable, pupil diameter changes during the suppressed tracking period itself. These latter changes cannot be attributed to error-driven processes. Therefore, we were able to separate physiological

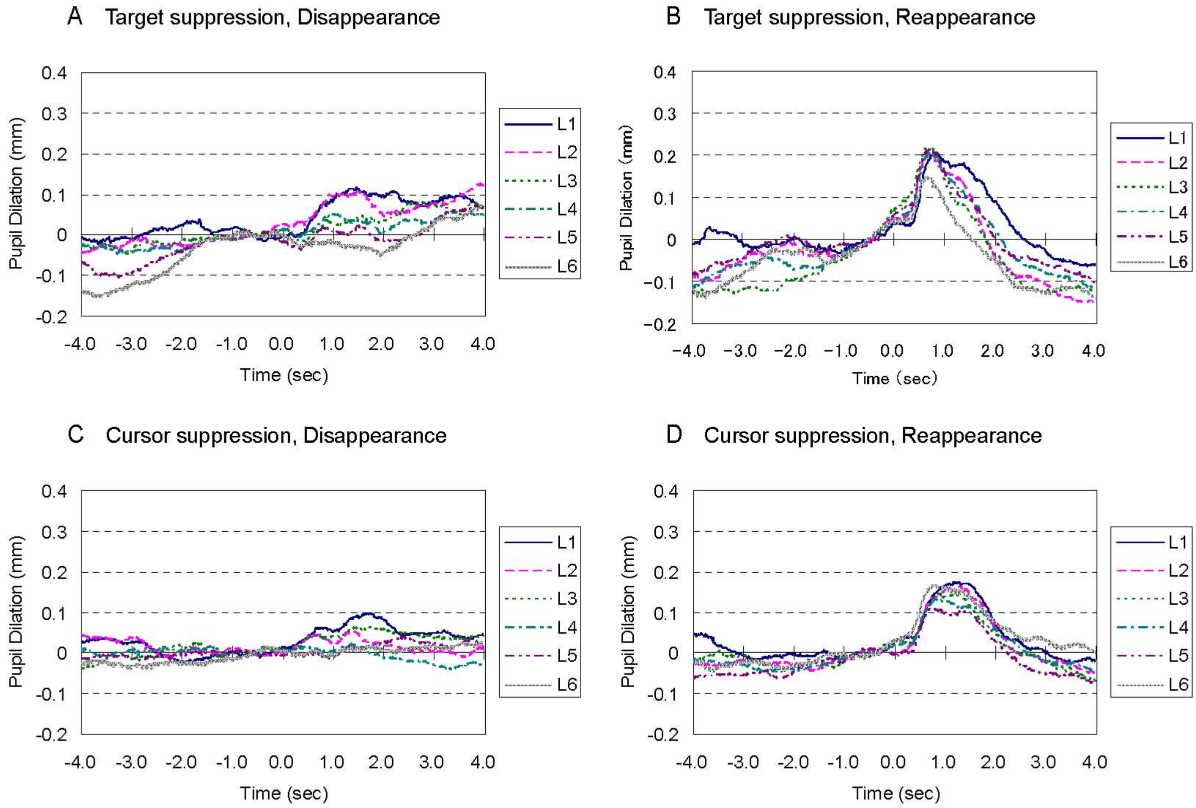

Figure 3: Grand average pupil diameter waveforms arranged by learning block.

correlates of the error-drive and model-driven components of tracking because they occurred during separate phases of the tracking task. In other studies, this separation was based on controlling for error-related activity in a separate control condition (Imamizu et al., 2000). Importantly, our pupillary measure showed clear learning-related change in both components. Our interest focused on the learning-related change in the model-based component of tracking. Motor learning is often described in terms of 'automatization', or decrease in cognitive effort required to perform a motor task (Brown & Carr, 1989). Our independent physiological measures of cognitive effort show that automatization is linked specifically to the learning of internal models, and not to other aspects of tracking such as visually-guided error correction.

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