Pupillary Responses during Learning of Suppressed Tracking Tasks

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Abstract

We measured tracking performance in two groups while either the target or the manual cursor was suppressed for a brief period during each trial. 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.

INTRODUCTION

Pursuit tracking is well-established experimental paradigm for studying motor learning (Poulton, 1974). 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 (Brown & Carr, 1989).

We have used the target and cursor suppression approach to investigate the internal models (Imamizu et al., 2000) used during tracking, and their updating during motor learning. Moreover, by measuring pupil dilation (Beatty, 1982) as an indirect index of neural-cognitive activity during suppressed tracking, we show reliable learning-related changes in cognitive load consistent with acquisition of internal predictive models.

METHODS

Apparatus

The experimental apparatus consisted of a joystick and computer display for tracking measurement, and a pupillary measurement system.

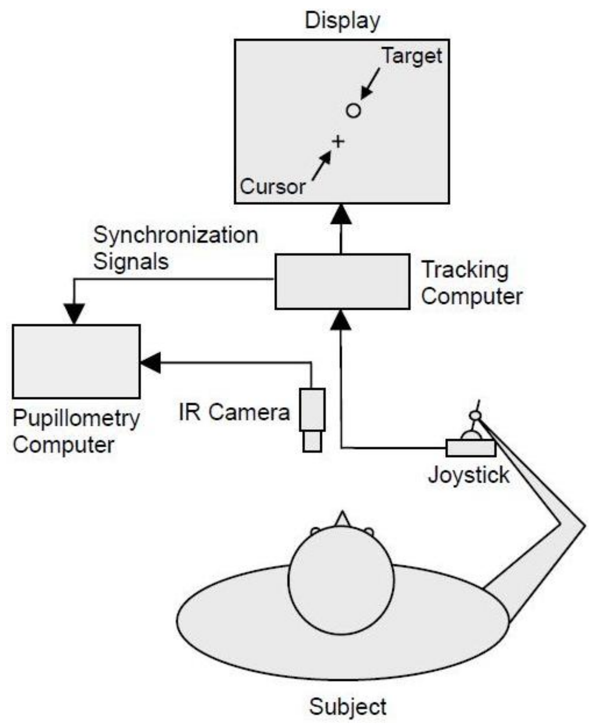

Figure 1: Experimental apparatus.

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. Target and cursor positions were digitized and stored on the computer at 30 Hz.

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.

Tracking error data from suppressed trials were aligned either to the time of disappearance, or reappearance of target/cursor as appropriate. An epoch from 4 sec before until 4 sec after was selected for display. Tracking error traces were then made for each subject in each block of the experiment.

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.

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 sec before disappearance or reappearance as appropriate.

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. Subjects' ages ranged between 19 and 24 years. We divided the subjects into 2 groups. Each group included 5 males and 5 females. The target suppression group performed target-suppressed trials in the learning blocks, and the cursor suppression group performed cursor-suppressed trials in learning blocks.

We measured tracking performance in two separate groups of participants while either the target or the manual cursor was suppressed for a brief period during each tracking trial (Beppu et al., 1987). Subjects learned to maintain accurate tracking through periods of target or cursor suppression. During the suppressed period, feedback-error-driven mechanisms cannot be used, and tracking performance therefore relies on prediction alone.

RESULTS

Tracking data

We have drawn the grand average traces of unsigned tracking error for each learning block (Kobori & Haggard, 2007), but are not shown here due to space limit. The traces show several features. First, tracking error is low prior to disappearance in both groups, and was comparable to pretest and posttest normal tracking trials. Second, tracking error increases gradually and monotonically after disappearance, and continues until just after the reappearance of the target or cursor. The initial increase in tracking error is more abrupt for the cursor suppression group than for the target suppression group. Error then decreases quickly and returns to the level before disappearance. Third, and most importantly for our purpose, the error during the suppression period varies across the learning blocks. In the target suppression 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.

The improvement across blocks in tracking during the suppression period arises from learning an internal model of either the target movement (target suppression group) or the subject's own movement (cursor suppression group). We therefore 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

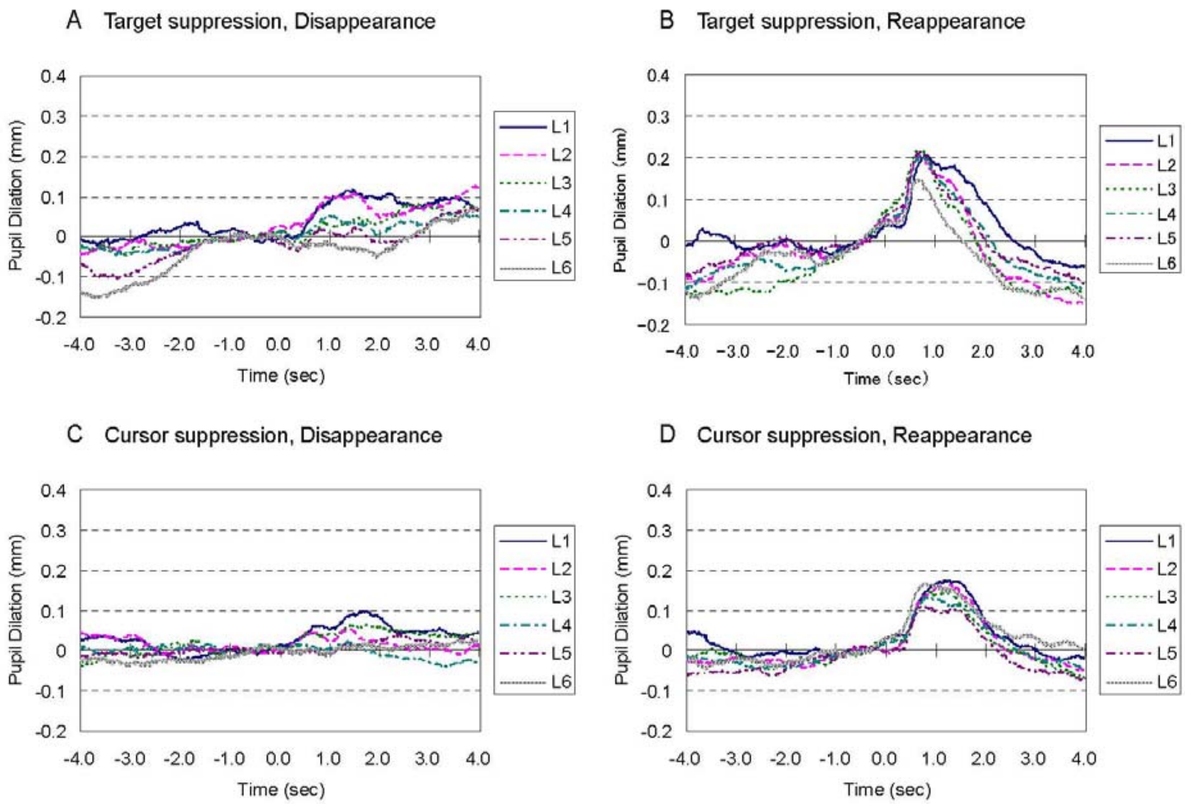

Figure 2: Grand average pupil diameter waveforms arranged by learning block.

suppression group [t(18) = 1.923, p = .0035]. Thus, subjects learned to track during the suppression period.

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 are shown in Figure 2. Data from suppressed trials are aligned either to the time of disappearance, or the time of reappearance as appropriate. The upper row shows the performance of the target suppression group at the point of target disappearance (panel A), and reappearance (panel B). The data for the cursor suppression group is shown in the lower row (C, D). L1 refers to learning block 1.

Several features are found in Figure 2. First, the disappearance of the target or the cursor produces a clear dilation, or increase in pupil diameter. This begins around 0.5 sec after the disappearance, and reaches a clear peak at 1.5 sec. Reappearance produces a second, rather larger dilation, with a somewhat longer duration. Second, and more importantly, the amplitude of these dilations varies across learning blocks. In the target suppression group, the pupil dilation on disappearance (Figure 2A) 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.

In normal tracking in pretest and posttest blocks, the pupil diameter remained constant and showed no dilation during the course of the trial in either group (not shown).

Because we were primarily interested in the learning of internal models for tracking, we focused our analysis on the pupillary response to disappearance of the target or cursor. We therefore 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 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.

Acknowledgments

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