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A computational and experimental study to determine a temporal issue in voluntary movement

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Every movement takes some time, but there is not a clear answer of how does brain determine the movement duration. The fact that humans exhibit task-dependent laws of movement duration suggests that there should be a computational principle that determines a movement duration. There are hitherto two distinct principles proposed. One is finite-horizon optimal control, in which a movement duration is predetermined and then movement is optimized during that duration. The other is infinite-horizon optimal control, in which movement duration is not predetermined and movement is optimized over infinite movement period. Although whether movement is optimized over a finite or infinite period sounds a technical problem, it has an implication to a question of whether the brain predetermines a movement duration or not. Although both models can reproduce Fitts law and the main sequence equally well, their model predictions have not been systematically investigated in an experimentally testable way. We therefore compared predictions of these models in detail and tested those predictions in a behavioral experiment. A key difference between predictions of finite- and infinite-horizon control models lies in the difference in gains of Kalman filter and feedback control. Infinite-horizon models predict time-invariant gains whereas finite-horizon models predict time-variant gains. Consequently, movement corrections against unpredictable perturbations should be time-independent if infinite-horizon models are correct, and should be time-dependent if finite-horizon models are correct.

We designed a reaching experiment with visual or force perturbations at three different timings. Ten subjects participated in the reaching experiment, where they reached toward a target that was 20 cm away from a start. Their hands were hidden and the visual feedback was provided with a cursor on the screen. In some trials, there was no perturbation and the subjects made normal, control movements. In other trials, a visual perturbation (jump of cursor of 4 cm orthogonal to movement direction) or force perturbation (impulse of 10 N 50 ms orthogonal to movement direction) was imposed at early (100 ms), middle (200 ms) or late (300 ms) timing. Perturbation directions (i.e., left or right) were randomized on a trial basis to avoid any effect of adaptation or expectation. The movement pace of subjects are normalized in familiar blocks and are instruct to use the same pace in perturbation blocks. We measured the hand position and analyzed movement corrections against those perturbations.

Before conducting the experiment, we simulated this reaching experiment using the formulation of optimal feedback control proposed by Phillis, as Todorovs and Qians formulations differ considerably and are difficult for a direct comparison. We chose the model parameters so as to be consistent with previous studies. The Kalman and feedback gains were precomputed so as to minimize the quadratic cost function over a finite period (finite-horizon control) or over an infinite period (infinite-horizon control). We then defined the movement correction as velocity profile in a control trial subtracted from one in a perturbation trial. Against visual perturbations, the finite-horizon model predicted time-dependent movement corrections and the infinite-horizon model predicted the time-independent movement corrections. Similar results were obtained for the simulations of force perturbations. We therefore tested these predictions in a behavioral experiment. In visual condition, the correction against later perturbation is significantly different to the corrections of early and middle perturbations, but the early and middle are highly overlap. In force condition, these three corrections diverge after the sensory delay. Then we did statistical test at the peak value, in visual condition, $F(2, 2295) = 39.55, P < 0.01$; in force condition, $F(2, 2316) = 66.13, P < 0.01$, these result implies that the corrections against external perturbations of different timing are different. Then we separate the data into former trials and later trials to see whether there is any significant difference before and after learning. The results show that, neither the order of the three correction curves nor the p-value change too much each condition.

Experiment result is inconsistent with infinite-horizon control. To fit the experiment data by finite-horizon control, we tuned the parameters. We made a database which contains 1000 different parameters units, even through we can fit the order of the curves, the shape is quite strange in those certain values. The optimal feedback control has so many degrees of freedom, it is impossible to go over all the possible parameters. The movement duration problem is not settled yet, further research may consider finding more appropriate way to tune the parameters.