Human Hand Moves Proactively to the External Stimulus: An Evolutional Strategy for Minimizing Transient Error

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We investigated particularly the proactive nature of the visual-motor system by steady and transient experiments of a hand-tracking task, and confirmed that the hand motion precedes on the average the target motion in steady runs within a finite frequency range of the sinusoidal target motion. The question why and how much the hand motion should precede was answered by frequency-jump experiments. The results implied that the positive phase shift of the hand motion represents the proactive nature of the visual-motor control system which is adaptationally developed for each person to minimize the transient error of the hand motion when the target motion changes unexpectedly.

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How can humans as well as other animals respond to a constantly changing environment in spite of inevitable time delay [1,2] required for processing and transferring information in the sensory-motor system? It is widely believed that a predictive mechanism should exist in order to compensate this delay or to generate appropriate behavior [3]. In relation to the predictive function for compensating the delay in the visual-motor system, a number of psychophysical studies on hand-eye-tracking behavior have been carried out by using a variety of stimuli, including simple harmonic frequency [1,4], pseudorandom [5,6], square waves [7], and 2D complex [8].

The study of the phase relation in continuous hand-eye movements is important for understanding the strategy of catching moving objects such as preys [9] by the predictive mechanism of the sensory-motor system. However, systematic and consistent phase-lead in a finite frequency range has not been reported in single sinusoidal hand-eye tracking experiment , in which a phase shift between the hand motion and the target motion was clearly defined in comparison to the other experiments. This should be contrasted to the discrete synchronization tasks where it was reported that the subject's motion precedes the rhythmic pulsative stimuli not only in the visual-motor control system [10] but also in the auditory-motor control system [11,12]. Although their experimental results are important findings, they have not given a quantitative explanation as to what the amount of the precedence meant.

The purpose of the present Letter is not only to clarify the phase relation of the hand motion with respect to the continuous target motion in hand-tracking experiments, but also to answer in what case, to what extent, and why the phase of the hand motion is advanced with respect to that of the target motion. Here we report experimental results that the hand motion in steady motion runs does precede the target motion statistically over a finite frequency range, and furthermore, that the mean-value of precedence in steady runs corresponds to the optimal value for minimizing transient error of the hand when the target motion changes unexpectedly.

Eight male subjects (22–26 years old) participated in the present hand-tracking experiments. A subject was seated at 50 cm in front of a computer screen (1024 × 768 pixels resolution; 17-inch display), and was asked to trace a moving visual target (a red closed circle of 6 mm diameter) as accurately as possible by the motion of a cursor (a white open circle of 6 mm diameter) in the screen produced by hand motion through a mechanical computer mouse. Figure 1(a) shows an example of the sampled trace of the hand motion for the constant target frequency 0.8 Hz (sampling time = 20 ms). The hand motion fluctuates around the trajectory of the target; that is, the hand motion sometimes advances and sometimes delays with respect to the target motion.

Figure 1(b) shows an example of a histogram of a subject for the number of sampled events with various phase shifts sorted with bin size 0.03 rad for five target frequencies. The curves of the histogram were analyzed by a least-squares fitting for Gaussian curves with three parameters (mean-value, standard deviation, and amplitude). It was found that all the histograms observed for each target frequency and for each subject follow well-defined Gaussian distribution with determination coefficients $r^2 > 0.92$, and that the mean-value can be defined with statistical significance, even when the standard deviation is greater than the mean-value. Figures 1(c) and 1(d) show the frequency dependence of the mean-value of the phase shift and the standard deviation averaged over the calculated values of all the subjects. As shown in Fig. 1(c), the mean-value of the phase shift of the hand motion from the target motion is nearly zero in the frequency range ($0 < f < 0.5$ Hz). It is undoubtedly positive and increases with increasing frequency in the frequency range ($0.5 < f < 1.5$ Hz); that is, the hand motion

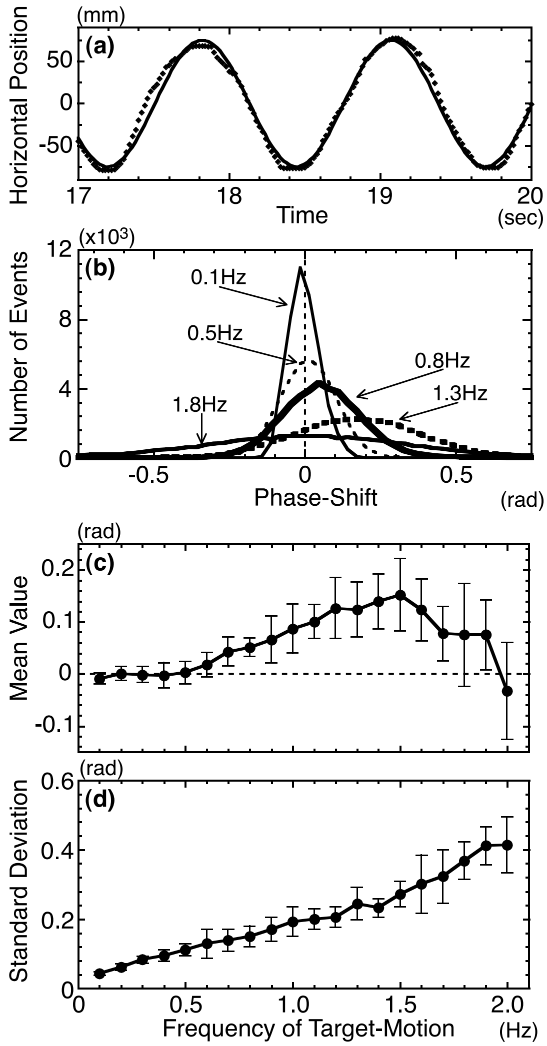

FIG. 1. Results of steady experiments. (a) An example of the sampled data (target frequency 0.8 Hz). The solid line shows the target motion and the dotted line shows the hand motion. (b) An example of histogram for the number of sampled events with various phase shifts observed between the hand motion and the target motion. Frequency dependence of the mean-value (c), and standard deviation (d) of the phase-shift histograms (b). The two graphs were calculated by averaging over the data of all the subjects. The error bars represent standard deviations.

on the average precedes the target motion with statistical significance, then it abruptly decreases in the frequency range ($f > 1.5$ Hz).

The standard deviation increases almost linearly with increasing frequency in all the frequency range investigated in Fig. 1(d), and when the value of the standard deviation is converted from the phase to the time scale, the standard deviation is close to 25 ms, almost independent of the target frequency, except for the low frequency range ($f < 0.5$ Hz) where the standard deviation increases with decreasing frequency [13].

The present experimental results of constant frequency task suggested that the hand motion is controlled with a phase preceding to the target motion consistently in a finite frequency range. If the predictive ability is necessary only to compensate the delay of signal processing in human sensory-motor system, the smaller the phase shift is in steady motion runs, the better the control would be functioning. However, what we observed was not limited to compensation of the delay. A question, therefore, would arise why the phase of the human hand motion statistically precedes that of the target motion as shown in the present experiments. We were led to think that the answer to this question may be obtained by asking what would be the best strategy of the human visual-motor control system for minimizing the error of the hand motion in tracking the unpredictably varying motion of the target in the real world, when the response of the control system is slow and at best comparable with the characteristic time of the target motion.

To clarify this point, we designed a transient experiment in which the frequency of target motion is suddenly changed to other values at an unknown time to the subject. The frequency shift was chosen randomly from six values (± 0.1 Hz, ± 0.2 Hz, ± 0.3 Hz). We have measured the average positional error of the hand with respect to the target in a first cycle after the sudden frequency change (FA cycle) for each run. Simultaneously, we have measured the phase shift in the last cycle before the change (LB cycle). The phase shift of the hand motion from the target motion fluctuates from a cycle to the next cycle, as can be seen from the distribution curve in Fig. 1(b), even when the frequency of the target motion is fixed. Utilizing this phase fluctuation positively, we could accumulate data of the transient error as a function of the phase shift just before the frequency jump, and we could obtain the optimum phase shift at which the transient error is the smallest.

In Fig. 2(a) is shown the transient error of the hand motion during FA cycle and the instantaneous phase shift in LB cycle for all the subjects when the initial frequency was 0.8 Hz. The dark circles are mean values for the data taken from all the subjects. Although the curve suggests some evidence for existence of minimum, the evaluation of the phase shift which corresponds to the minimum transient error is difficult, considering a large value of error bar.

We realized then that the large value of error bar and the rather flat mean-value curve may be originated by the different characteristics for different subjects. Therefore, the data are then analyzed for each subject separately. Figure 2(b) shows the same relation for a single subject as an example. We observe a parabolalike mean-value curve and the minimum may be determined more reasonably.

Figure 3 shows the correlation of all the subjects between the mean phase shift in constant 0.8 Hz experiments and the phase-shift value in LB cycle corresponding to the minimum averaged error in FA cycle. We notice from Fig. 3 that the operating phase of the hand motion in steady tracking task in this target-frequency

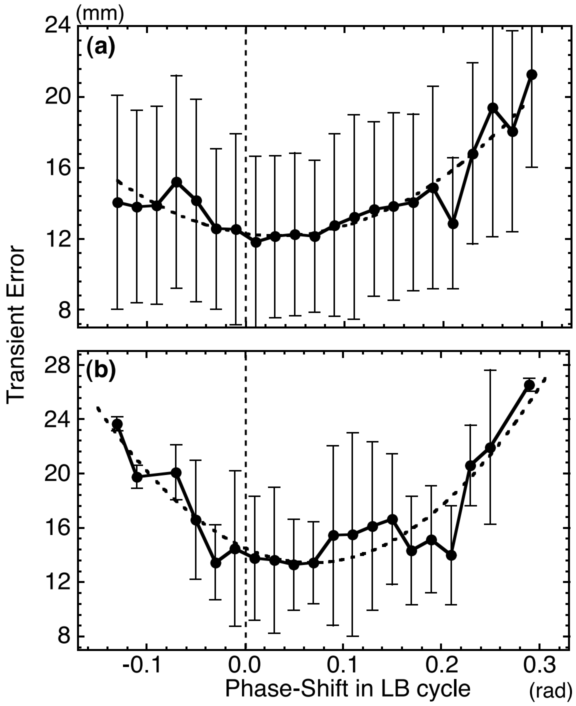

FIG. 2. Result of transient experiments. The dark circles show transient error in FA cycle as a function of the instantaneous phase shift in LB cycle (ψ^{LB}). The initial target frequency is 0.8 Hz. (a) Data taken from all the subjects. (b) Data for only one subject as an example. The dotted line illustrates the best fitted parabola curve [$r^2 = 0.83$ for (a), $240(\psi^{LB} - 0.068)^2 + 13.4$, $r^2 = 0.82$ for (b)].

range is set close to the optimum value for each subject ($F_{1,7} > 1.8 \times 10^{-3}$, $p > 0.96$), such that the transient error of the hand motion is the smallest when a sudden frequency change occurs in the target motion. The present experimental data clearly indicate that the visual-motor system in human beings may utilize "proactive [14] control," which minimizes future dynamic error by a phase-lead operation.

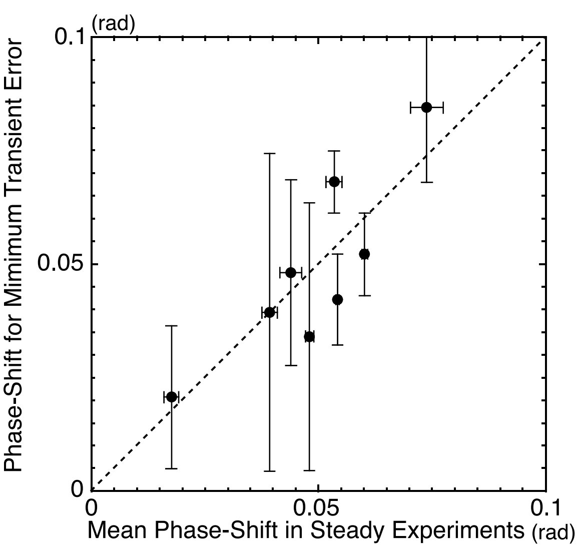

FIG. 3. Correlation between the steady phase shift at 0.8 Hz and the instantaneous phase shift in LB cycle corresponding to the minimum transient error at initial frequency 0.8 Hz for eight subjects.

Proactive control is one class of predictive control [3], but the predictive control is not necessarily proactive. It sometimes works only for compensating the delay caused by transferring signals. As shown in Fig. 1(c), the mean-value of the phase shift stays nearly zero at the low frequency range and starts increasing at around the target frequency 0.5 Hz. This means that in the frequency range less than 0.5 Hz, the hand motion is only controlled by a predictive feedback mechanism because the hand motion under this control mode may easily catch up to the target without significant delay in this frequency range. For the target frequency greater than 0.5 Hz, the motion control mechanism in brain apparently switches the strategy to proactive control, which minimizes the transient error at the cost of the instantaneous positional accuracy. The critical frequency 0.5 Hz observed in the present continuous hand-tracking experiments coincides with that observed by Engström *et al.* [10] as the transition frequency from reactive to anticipatory motions in the synchronization task to the pulsative optical stimuli. This frequency observed in two different paradigms should reflect a fundamental frequency in the mechanism of the sensory-motor control system.

There has been a fair amount of experimental [15] and theoretical [16] literature that investigated the response of the systems with intrinsic and externally input delay and noise to understand human sensory-motor systems. However, fewer investigations [10,12,17] were carried out on the mechanism of phase shift of tracking or tapping motions. Here, we investigated phase-shift and transient characteristics in a delayed feedforward model [18], Eq. (1), which is a modification from previous work [1].

$$\begin{cases} \dot{Y}(t) = & \frac{1}{\tau_1}[T(t-\delta) - X(t-\delta)] + \gamma\dot{T}(t-\delta), \\ \dot{X}(t) = & \frac{1}{\tau_2}[Y(t-\xi) - X(t)]. \end{cases} \quad (1)$$

Here, T represents the coordinate of the target. X and Y represent, respectively, the cognitive coordinate and real space coordinate of the hand position. τ_1 and τ_2 are the time constants of the sensory-motor system, and δ and ξ are the delay time of the signal transport, which is typically 50 to 100 ms. γ represents relative contribution of the speed information to the positional error information of the target to recognition in the visual system. We found that most of the experimentally observed features were reproduced, including the good correlation of the steady phase shift and optimum phase for transient error shown in Fig. 4 with only one adjustable parameter γ. The discrepancy of the steady phase shift between the experimental values (Fig. 1) and the model (open diamond in Fig. 4) at low target frequency could be dissolved by introducing a nonlinear term [19] into Eq. (1).

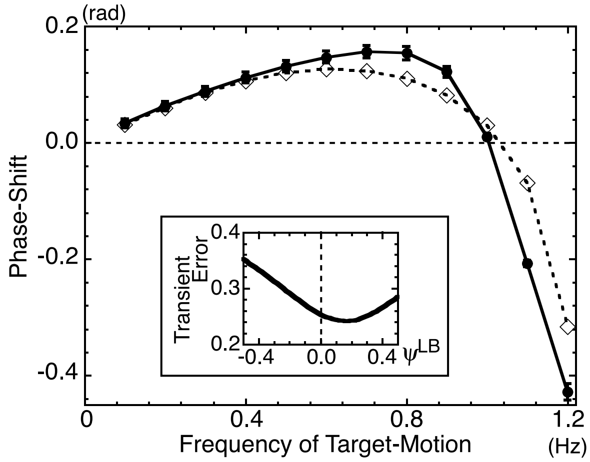

FIG. 4. Simulation results of steady and transient experiments in the present model [Eq. (1)]. The open diamond and the dotted line show the frequency dependence of the steady phase shift. The closed circle and the solid line show the estimated phase shift corresponding to the minimum transient error as a function of the initial frequency. The inset illustrates the transient error for the initial target frequency = 0.5 Hz as a function of ψ^{LB}. The values (1.5, 0.1, 0.1, 0.05, 0.05) were used for the parameters (γ, τ_1, τ_2, δ, ξ), respectively.

We have experimentally clarified the following three points in this Letter: (1) The human visual-motor system operates by phase-lead control, which should be called "proactive control" in a certain frequency range. (2) The value of the phase-lead is slightly different from a person to the other. (3) Nevertheless, the operation point of the phase-lead control of each person is set to the optimum value at which the transient error in the hand motion is minimum in case of a sudden change of the target motion (a minimization principle of dynamic error at a cost of phase shift in steady motion). The result implies that there is a universal design rule in visual-motor system to minimize this dynamic error, in spite of the fact that the visual-motor control system of each person has different characters and functions.

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[1] R. C. Miall, D. J. Weir, and J. F. Stein, Behavioural Brain Research **20**, 185 (1986).

[2] D. A. Robinson, J. L. Gordon, and S. E. Gordon, Biol. Cybern. **55**, 43 (1986); J. R. Carl, and R. S. Gellman, J. Neurophysiol. **57**, 1446 (1987); S. Lisberger, E. Morris, and L. Tyschen, Annual Review of Neuroscience **10**, 97 (1987).

[3] J. R. Flanagan and A. M. Wing, J. Neurosci. **17**, 1519 (1997); S. J. Blakemore, S. J. Goodbody, and D. M. Wolpert, J. Neurosci. **18**, 7511 (1998); J. Hore, S. Watts, and D. Tweed, J. Neurophysiol. **82**, 1187 (1999); P. Vetter and D. M. P. Wolpert, J. Neurophysiol. **84**, 1026 (2000); J. R. Flanagan and S. Lolley, J. Neurosci. **21**, 136 (2001); Y. Ohki, B. B. Edin, and R. S. Johansson, J. Neurosci. **22**, 600 (2002).

[4] O. Bock, Behavioural Brain Research **24**, 93 (1987); R. S. Turner, S. T. Grafton, J. R. Votaw, M. R. Delong, and J. M. Hoffman, J. Neurophysiol. **80**, 2162 (1998).

[5] L. R. Young and L. Stark, IEEE Trans. Hum. Factors Electron. **4**, 28 (1963);N. H. Drewell, Institute of Aerospace Studies, University of Toronto UTIAS Technical Report No. 176 (1972); G. R. Barnes, S. F. Donnelly, and R. D. Eason, J. Physiol. **389**, 111 (1987); A. V. van den Berg, Experimental Brain Research **72**, 95 (1988).

[6] S. Yasui and L. R. Young, J. Physiol. **347**, 17 (1984).

[7] G. R. Barnes and P. T. Asselman, J. Physiol. **439**, 439 (1991); S. G. Wells and G. R. Barnes, Vision Research **39**, 2767 (1999); M. Churchland and S. G. Lisberger, J. Neurophysiol. **84**, 216 (2000); J. L. Gardner and S. G. Lisberger, J. Neurosci. **21**, 2075 (2001).

[8] R. E. Kettner *et al.*, J. Neurophysiol. **77**, 2115 (1997); M. Suh, H.-C. Leung, and R. E. Kettner, J. Neurophysiol. **84**, 1835 (2000).

[9] G. J. P. Savelsbergh, H. T. A. Whiting, A. M. Burden, and R. M. Bartlett, Experimental Brain Research **89**, 223 (1992).

[10] D. A. Engström, J. A. S. Kelso, and T. Holroyd, Human Movement Science **15**, 809 (1996).

[11] M. Franek, T. Radil, M. Indra, and P. Lansky, International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology **5**, 187 (1987); J. Mates and G. Aschersleben, Acta Psychologica **104**, 29 (2000).

[12] Y. Chen, M. Ding, and J. A. S. Kelso, Phys. Rev. Lett. **79**, 4501 (1997).

[13] F. Ishida and Y. Sawada, in *Proceedings of the 2001 International Symposium on Nonlinear Theory and Its Applications, Miyagi, Japan* (to be published), Vol. 2, pp. 379–382.

[14] A. Berthoz, in *The Brain's Sense of Movement*, translated by G. Weiss (Harvard University Press, London, 2000).

[15] M. Lauk, C. C. Chow, A. E. Pavlik, and J. J. Collins, Phys. Rev. Lett. **80**, 413 (1998); J. L. Cabrera and J. G. Milton, Phys. Rev. Lett. **89**, 158702 (2002); A. Priplata *et al.*, Phys. Rev. Lett. **89**, 238101 (2002).

[16] P. Tass, J. Kurths, M. G. Rosenblum, G. Guasti, and H. Hefter, Phys. Rev. E **54**, R2224 (1996); T. D. Frank and P. J. Beek, Phys. Rev. E **64**, 021917 (2001); L. S. Tsimring and A. Pikovsky, Phys. Rev. Lett. **87**, 250602 (2001).

[17] H. Haken, J. A. S. Kelso, and H. Bunz, Biol. Cybern. **51**, 347 (1985); G. Schöner, H. Haken, and J. A. S. Kelso, Biol. Cybern. **53**, 247 (1986).

[18] F. Ishida and Y. Sawada, Trans. Soc. Instrum. & Control Eng. Japan **39**, 59 (2003).

[19] F. Ishida, Y. Kuramoto, and Y. Sawada, in *Proceedings of International Joint Conference on Neural Network 2003* (IEEE, Piscataway, NJ, 2003).