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Discontinuities in Tracking Strategies

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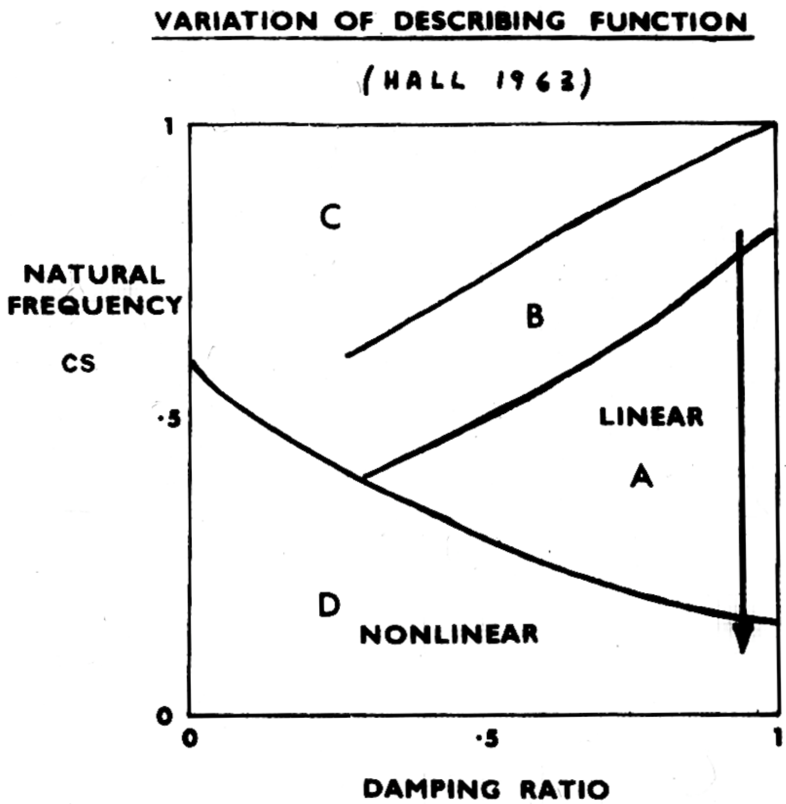
Twenty years ago Craik (1947) suggested that the output of the human operator performing a perceptual-motor control task consists of a sequence of discrete, "ballistic" movements. In a tracking task this discreteness would be apparent even thought the input to be tracked were smooth and continuous. After Craik there was a shift towards skills where the possible responses are necessarily discrete (as in key-pressing), and the nature and causes of the discrete output in a continuous tracking have been little investigated. The aim of the experiments reported here is to demonstrate that there are at least two distinct causes of discontinuity in the operator output, the first dependent on the availability of feedback information and the second upon the nature of the effector dynamics. In simple tracking tasks these are confounded, but they may be separated by appropriate choice of controlled system and control dynamics.

Discrete Movements and Their Relationship to Models of Control Strategy

Whilst research in British Laboratories has concentrated upon the interactions between successive discrete responses, in the USA more emphasis has been placed upon statistical evaluation of the stimulus-response (visual input/manual output) relationship in a small range of control tasks which are of practical importance. Much of the work on models of the control strategy of the human operator has been by aviation engineers who have adopted an entirely cybernetic approach, approximating his behaviour with that of systems which can be studied analytically and whose behaviour is already well-known. These models are based on linear differential operators and, if exact, would imply that a sinusoidal output and, more generally, that a smooth input will be tracked by a smooth output. Detailed, examination of tracking records shows that this is not so, but that, as Craik remarked, the output is made up of a sequence of discrete movements. Slide 1 shows the operator's output when tracking a sinusoidal input, together with the input itself (the error displayed to the operator is not shown—the task is compensatory tracking through a lag). It can be seen that the operator approximates the input by discrete steps, whereas the output of a linear servo would be of the same form as the input.

Slide 1 Operator's output when tracking a sinusoidal input

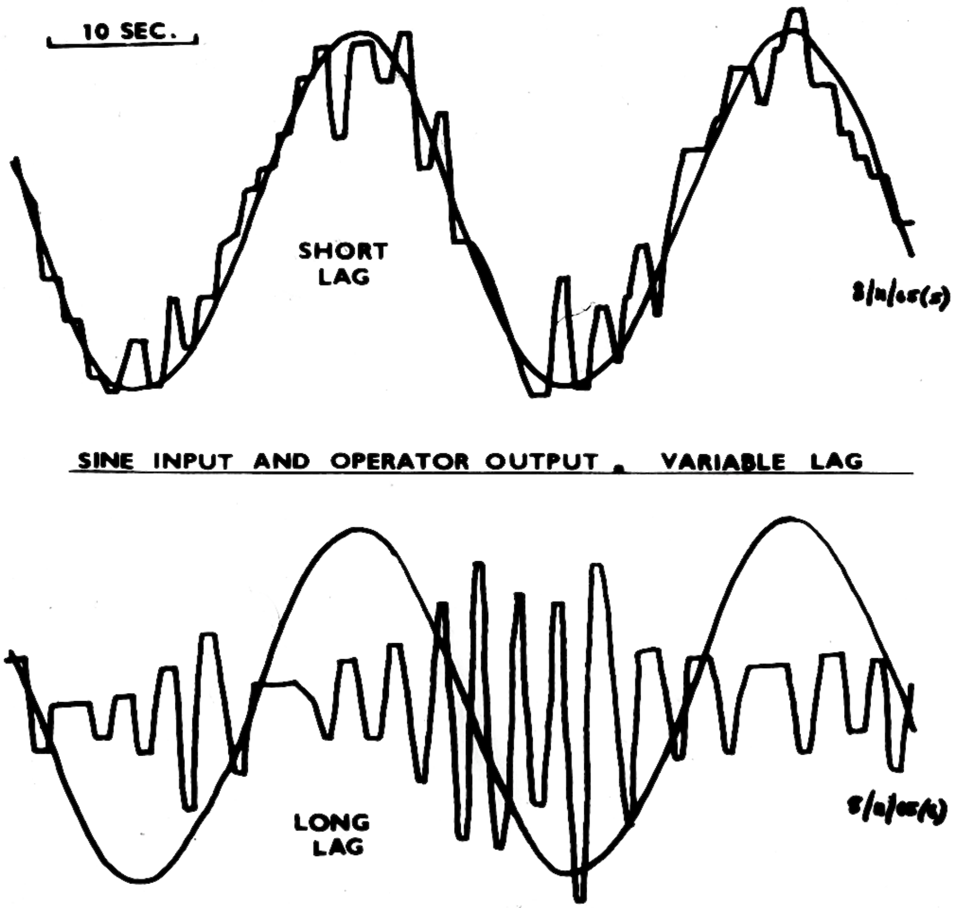
Despite the discrete nature of the operator's output, proponents of linear models have claimed a good fit to his behaviour in some tasks. Hall (1963) derived empirical models of the operator in a range of tasks simulating flying and a summary of his results is shown in slide 2. As the natural frequency and damping ratio of the simulated craft vary so does the fit; in region A the correlation between operator output and model output is above .9, whilst in region D it is below .5. It may be shown that the good fit is induced by the nature of the task, for the controller of a linear system has good linear representation in so far as it is able to maintain a small error (ie. perform the task!).



Slide 2 Goodness of fit of linear models of the human operator as a function of the natural frequency and damping ratio of the controlled system

In slide 3 the lower trace shows the effect of increasing the lag in the system, effectively taking it along the trajectory marked by the arrow, superimposed on Hall's diagram. The discrete steps in the operator's output become more and more prominent as the lag in the system increases until they dominate the output. This is the explanation of Hall's variation of linearity and reflects the degree to which the human operator is able to stabilize the system when feedback is delayed.

Thus the human operator is a switching-mode rather that a linear controller, and by increasing the lag in feedback his discrete corrections may be separated one from another. Examination of the corrective movements themselves reveals a second source of discontinuity which is discussed overleaf.



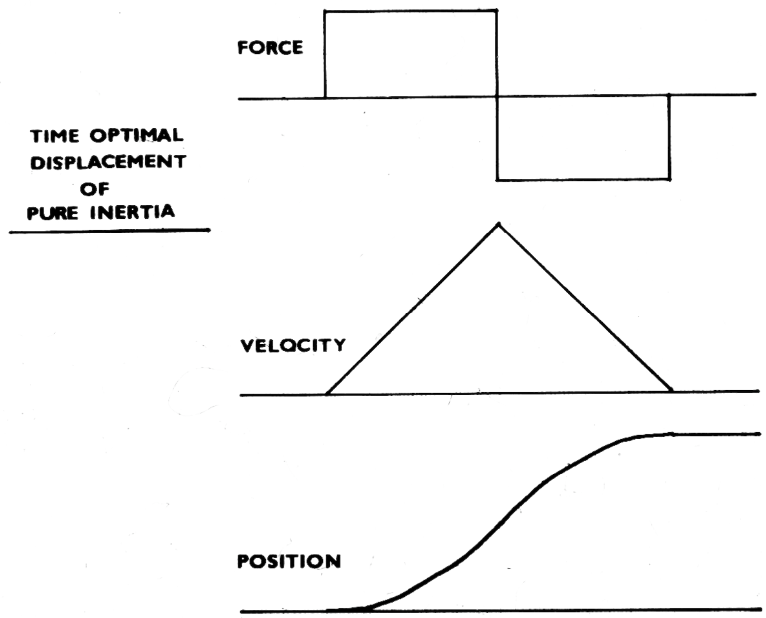
Slide 3 Operator's output when tracking a sinusoidal input with different lags

The Fine-Structure of Control Movements

To make the discrete movements which are components of the output of the human operator is itself a control task, for the arm has to move the joystick by a certain amount and must do so quickly and accurately. It can be shown that if either:

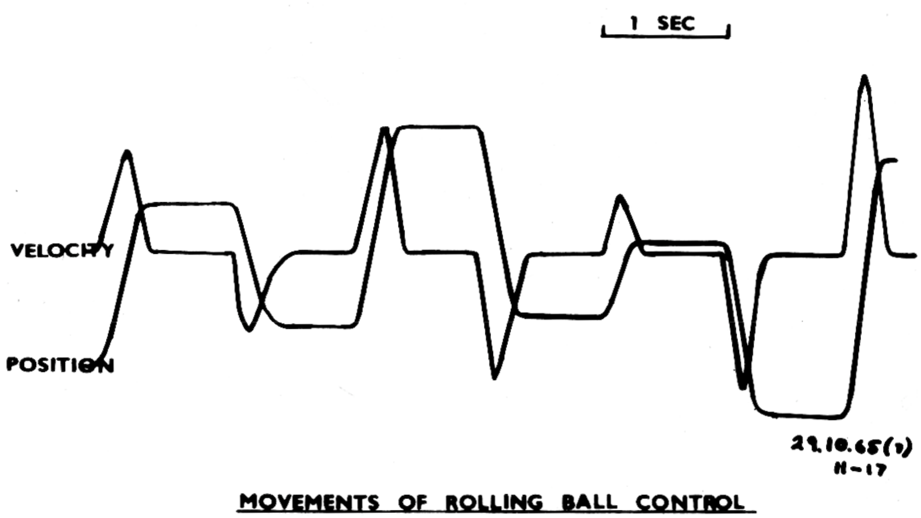
1. Command signals can be changed only at fixed intervals of time, or
2. Feedback signals can be sampled only at fixed intervals, or
3. The output force available is bounded in magnitude,

then the quickest way of moving a mass without overshoot is to apply to it a force with characteristics shown in slide 4, a constant acceleration for a given time and than an equal and opposite acceleration for the same time (a *bang-bang* command signal). The velocity of the mass then has a characteristic triangular shape and the position describes a double parabola. A model based on this type of motion has been used as an explanation of Fitt's law (Crossman & Goodeve 1963), and Lange (1965) has developed a more sophisticated model applicable to simple tracking situations.

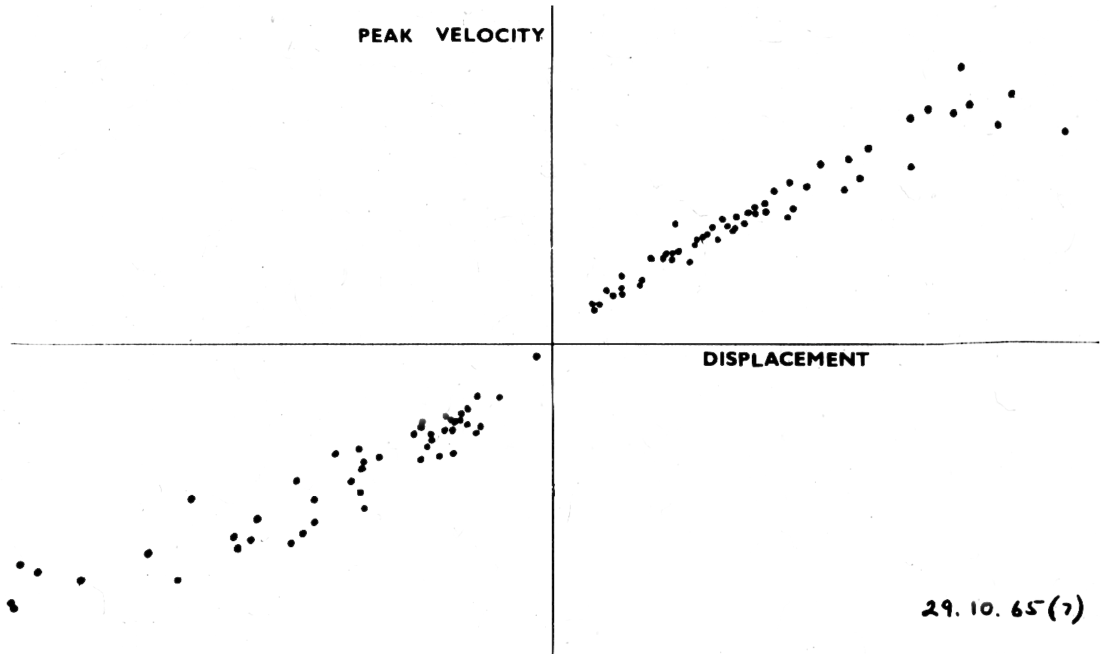


Slide 4 Optimal movement control, acceleration, velocity and position

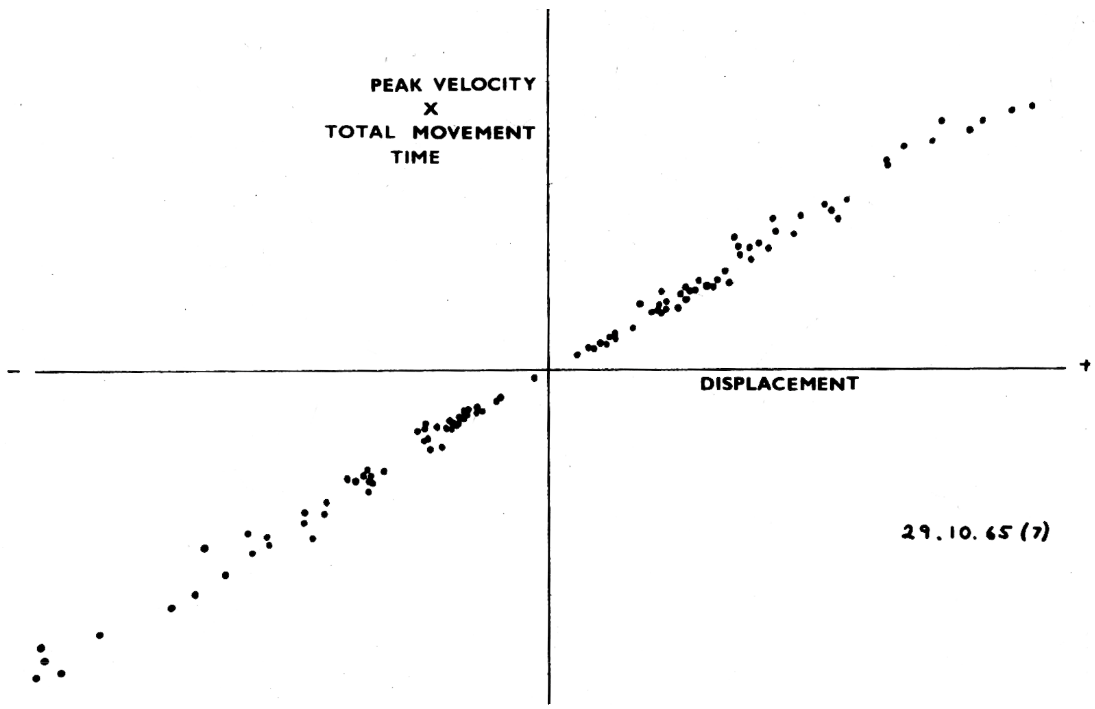
Slide 5 shows the position and velocity of the joystick being used in the tracking task above, and it will be seen that the velocity waveform has the characteristic triangles of bang-bang motion. To test that this is so the movement patterns have been analysed for total displacement, peak velocity and time of movement. If a linear controller were in use the displacement and velocity would vary proportionately with constant movement time. If a bang-bang controller were in use the peak velocity multiplied by movement time would be proportional to displacement. Scatter diagrams for these relationships are shown in slides 6 & 7 and it will be seen that the latter is a better fit.



Slide 5 Position and velocity of the joystick in the tracking task

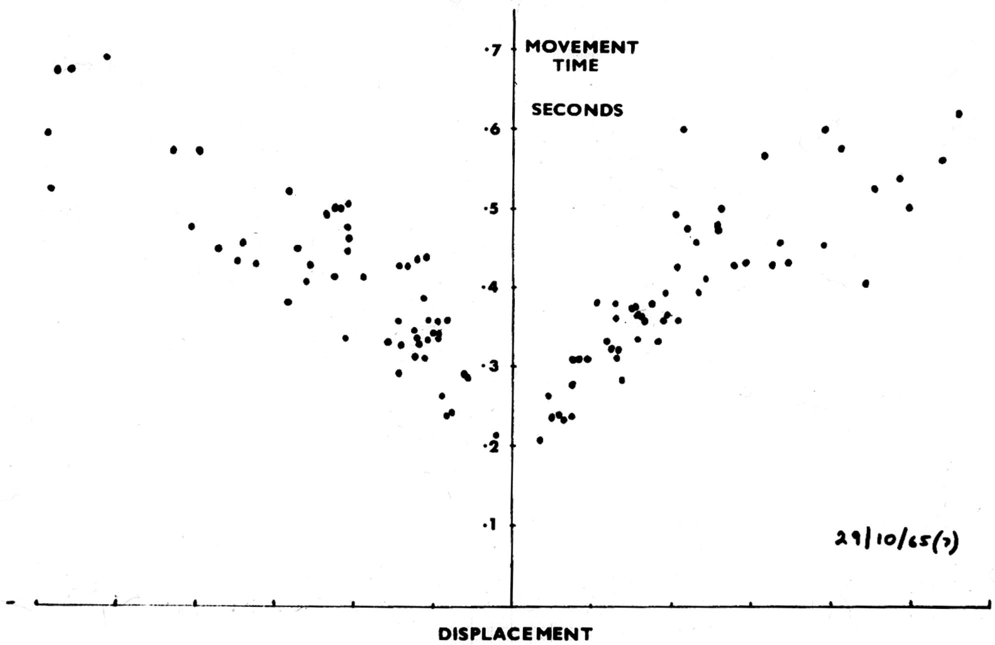


Slide 6 Velocity against displacement



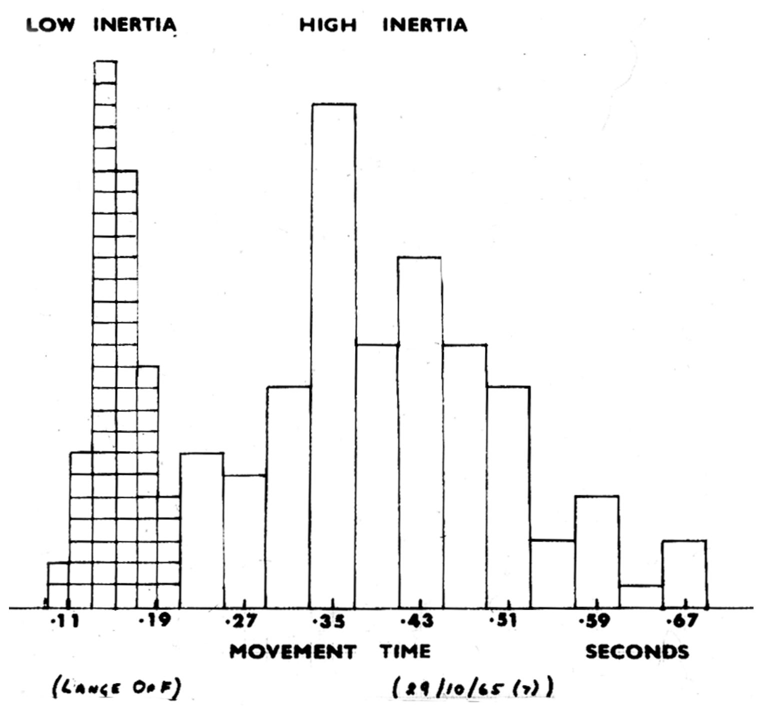
Slide 7 Peak velocity times movement time against displacement

Bang-bang motion has been previously ascribed to reasons 1 or 2 above, assuming that in the human visual or motor output there is a discontinuity of about 100 cs recurrence. If this were the sole cause of this type of motion them the time taken for any displacement would be constant and independent of the inertia of the control. A scatter diagram of movement-time against displacement is shown in slide 8, and it will be seen that the time rises with displacement but tends to 200 msec rather than zero as the displacement tends to zero.



Slide 8 Movement time against displacement

A heavy rolling ball rather than the light joysticks of previous workers was used in this experiment, and in slide 9 the distribution of movement times is compared with that obtained by Lange for one of his subjects. It can be seen that with greater inertia there is more spread and the times are very much increased. This suggests that bang-bang control is used for a complex combination of reasons rather than simply data-sampling or bounds on force, and in future experiments it is hoped to elucidate this.



Slide 9 Comparison of movement times for low inertia and high inertia joysticks

Conclusions

In a simple tracking task where the controlled element is pure gain immediate feedback is available to the operator and he is limited in speed of response only by his internal delays and his movement time. These are of the same order and are therefore confounded. If external delays are suitably imposed discrete movements may be separated out, and on examination these are themselves found to exhibit a discontinuity in their form of control.

References

Craik 1947 "Theory of the Human Operator in control Systems" Brit.J.Psychol. 38 56-61

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Crossman & Goodeve 1963 Private Circulation to EPS

Lange 1965 PhD Thesis, Imperial College, London.