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Influences of joystick spring resistance on the execution of simple and complex positioning movements [1]

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Abstract

To provide good proprioceptive feedback in a manual control device for a designation task, spring resistance of a joystick was optimized by adjustment of centering force and deflection nonlinearly with each other by using the psychophysical method of cross modality matching. Designation with zero and first order systems showed that the coarse adjustment was insensitive to stick and certain task parameters, although it was influenced by some biomechanical parameters and the anticipated demands of the final control positioning. Only the more difficult fine adjustment is sensitive to parameter alterations and therefore suitable for optimization attempts. The strong centering of the stick by a nonlinear degressive spring resistance facilitates fine adjustment. Through this, total adjustment time with the first order system is reduced by more than thirty percent, compared to a linear resistance. Tracking experiments affirm the usefulness and preference of nonlinear spring resistance.

To reduce the one-sided load through visual information transmission channels in modern, complex man-machine-systems, there are basically two possibilities :

1. Reducing the complexity of visual information by selecting and integrating only the necessary information (BERNOTAT, 1970).
2. Increasing the use of nonvisual information channels.

One possible nonvisual human information channel is the proprioceptive feedback. It is especially interesting, as it is implicit in every motor action of the human operator and therefore is present anyway in any control movement. The increasing use of servo-systems in manual control, for example in airplanes or even in motor cars, makes possible the introduction of any deflection-resistance characteristic into the control. This possibility may be advantageous to system performance, if the movement resistance of the control is designed according to the psychophysiological characteristics and anthropometrical limits of the human controller.

In order to investigate the proprioceptive feedback in control movements exclusively, visual feedback must be suppressed in the experimental mock-up. So that the relation between stimuli, such as visually presented deflections of light, and proprioceptively controlled motor responses may be measured :

$$R = f(S)$$

This relationship can be understood as a simple psychophysical function and according to STEVENS (1957) it is written as a power function

$$R = S^m$$

The method of "cross modality matching" provides the means to establish a relationship between two separate response modalities R_a and R_b via one independent stimulus S :

$$R_a = S^m$$

$$R_b = S^n$$

The resulting relationship between R_a and R_b :

$$R_b = R_a^{\frac{n}{m}}$$

In several experiments, the working group around STEVENS could prove empirically the adequacy of this theoretical relationship (see e.g. STEVENS, 1969).

If an event can be fed back to the operator in several sense modalities, it is appropriate, to match the intensities of stimuli to each other, according to the psychophysiological nature of the human. In cross modality experiments, this is implied through measurement of the subjects' behavior and one should expect good informational equivalency and redundancy in the matched sensory modalities.

Trying to determine the spring resistance of a control in respect to good proprioceptive feedback, one has to match perception of applied force with limb position according to the above mentioned procedure.

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[1] This article is based on a more extensive report by the author (see references).

D42

In psychophysical experiments with eleven subjects, matching of the motor response to the deflection of a light point on a TV-screen was investigated. One motor response was the deflection of the free-moving, the other, the applied force on the isometric joystick. A freely moving control offers no resistance to movement, an isometric stick offers no movement to applying force on it.

Position of the stick and applied force are matched nonlinearly to the independent signal, namely the visual perceivable jump of the light point. The subjects had no visual control of the motor activity and they were left solely to their proprioceptive feed-back.

The matching power function $R = S^n$ has an exponent n equal .7 for the free-moving stick. Remarkable is the pronounced nonlinearity with the isometric stick. The fitting power function has an exponent of .33. For comparison with data from the literature, one has to take the reciprocal value, which is 1.43, respectively 3.03.

Determining the spring resistance for the stick according to the method of cross modality matching, the resulting fraction is about .5. Taking values from the literature for the same sense modalities you come to an exponent of about .6.

If the spring resistance of a stick is determined according to the above defined rule for the dependancy of perceived force and position, it can be expected, that spring resistance is optimal in respect to proprioceptive feedback of the motor activity during activation of the stick.

To test the effect of different, and especially of nonlinear stick spring resistances on performance in a target acquisition task, several experiments were run with visual feedback on the display. The number of subjects ranged between four and eleven.

The acquisition task can be seperated into two parts; a coarse, fast part and one which is fine, and slow. One may expect, that manipulation of proprioceptive feedback should especially influence that part, which is too fast for effective visual control; this means, especially the coarse adjustment movement should be influenced by the spring characteristic of the stick.
The whole adjustment movement was divided into coarse and fine adjustment at the acceleration minimum (AMI) i.e. deceleration maximum, which is at least correlated with the beginning of fine control (see figure 1).

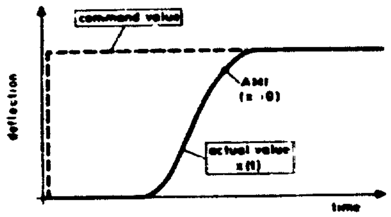

Figure 1. Step response with a zero order system
(AMI : acceleration minimum = deceleration maximum)

First experiments were done with a zero order system. Analysis of variance of the measured 880 movements in several directions with several amplitudes showed, that neither coarse, nor total adjustment time were significantly influenced by varying the spring resistance of the stick, which means the variation of the proprioceptive feedback provided to the operator (figure 2). Only in fine control are there small, but insignificant differences due to various spring characteristics.

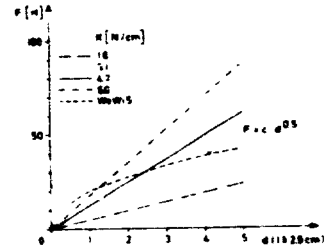

Figure 2 : Spring resistance of the control (zero order system)
d : stick deflection
F : centering force

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A tendency for an influence of mechanical parameters of the moving arm-control system on such movement parameters as maximum acceleration and speed was seen and can be explained in terms of movement time optimality.

In the next experiment, a first order system was used. With a single integration control system, the complexity of the control movement is increased and especially the fine control into the target area is more difficult, compared to a position control system. A small position error of the stick will be integrated and can by detected visually only with some time lag. This can result in an oscillation of the system output.

The experiment was run with four amplitudes and three directions of the command step, two different sizes of the target circle and several spring characteristics of the control : two linear and two nonlinear characteristics which are shown in figure 3. Ohne control was isometric. The experiment consisted of about 1500 trials.

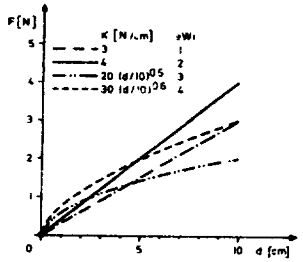

Figure 3 : Spring resistance of the control (first order system)
d : stick deflection
F : centering force

Analysis of variance results indicate, that the coarse adjustment time is almost perfectly invariant over all conditions and only fine adjustment time is sensitive to parameter alterations, and then only with the small target circle. This means, that with high demands on the precision of adjustment the difference between the various stick characteristics are quite pronounced. The following rank order resulted : the shortest adjustment times are achieved with the nonlinear spring characteristics ; the longest times result with the linear ones. The isometric performance times are in between these two. The differences are highly significant and are as high as thirty percent. The results show, that contrary to what might be expected, variation of the proprioceptive feedback, produced by variation of the spring resistance, has no effect on the coarse adjustment time, but rather a lot on the final, precise adjustment. From this result and an additional experiment to determine the effect of spring characteristic on the precision of movement repetition without visual feedback, one can draw the conclusion, that the variation of proprioceptive feedback has only negligible effects on the fast part of the acquisition task. It is supposed, that this part is executed according to the idea of preprogramming as SCHMIDT, R.A. and others advocate.

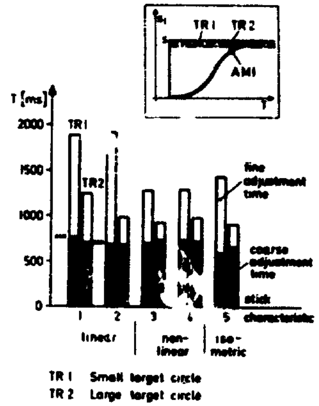

Figure 4 : Target acquisition time, separated into coarse and fine adjustment by the point of maximum deceleration

With these results, the influence of proprioceptive feedback on the execution of movements is not disproved, but only shifted to final adjustment movements which are usually unterstood to be mainly controlled visually. There is no problem, to understand fine adjustment control as a process, where command values are given by the visual sense, which are then executed in detail by the proprioceptive sense.

The experimental results show, that just fine control is significantly influenced by proprioceptive feedback.

The importance of final control time to total adjustment time is demonstrated in figure 5. It shows an almost negligible correlation between coarse and total

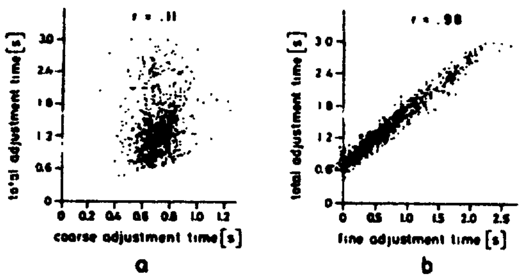

Figure 5 : Relationship (a) between total and coarse adjustment times and (b) between total and fine times (fine adjustment time is less than zero, if maximum deceleration point occurs in the target circle)

adjustment time, but a strong connection between fine and total adjustment time. With a correlation coefficient of .98, fine adjustment time accounts for about 96 percent of the variation of total adjustment time, whereas coarse adjustment time accounts for only about one to two percent. Conclusions of acquisition task experiments :

In target acquisition tasks, main concern should be directed towards facilitating fine control. Obviously, during coarse adjustment, parameter alterations are compensated by the operator in order to achieve a rather constant time and movement pattern, a finding, which is supported by some other authors (e.g. DIJKSTRA et.al. 1973). Strong centering of the stick by a nonlinear spring characteristic proved to facilitate final approach to the target without increasing the necessary force for wide deflections during the fast movement.

Continuous pursuit tracking runs with a two-dimensional forcing function with a .33 Hz cut-off frequency showed again the superiority of nonlinear spring characteristic. When subjects are able to adjust the spring characteristic by themselves, they all selected nearly the same nonlinear characteristic with an exponent of about .6 to the deflection term of the spring characteristic equation (see figure 6).

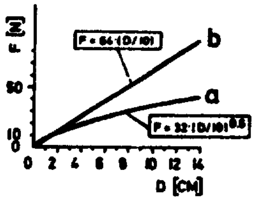

Figure 6 : Self adjusted nonlinear spring characteristic (a) For comparison a linear spring with similar force gradient near the neutral region (b)

Final conclusions :

1. Spring resistance of the control in higher order systems, as are most real systems, ought to be nonlinearly degressive to facilitate fine control adjustments without impeding coarse control movement.
2. For practical use, it is sufficient to take the self-adjusted values of a few well trained operators to determine the spring resistance of a control.

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