Precision in Movements

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Under some circumstances the channel capacity of the human motor system has been shown to be constant. Relationships based on information theory have been developed between the time for movement and the amplitude and tolerance of the movement. In the present experiment movements were made in one plane only, and it was hoped to test the general applicability of the relationships. The apparatus consisted of a pointer, which was moved by the subject through a vertical plane between two separated targets.

The experimental results have shown a significant relationship between the time for one rotary movement and a binary logarithmic index which related amplitude with target width. The time taken was affected by the inertia of the rotary system. There was variation between the eight subjects in the time taken.

A comparison was made to see whether an index from the movement amplitude and target width was simply related to the values for the test determined from three Predetermined Motion Time Systems. Satisfactory times were not evolved from two of the three Predetermined Motion Time Systems, but one system, Methods-Time Measurement, gave reasonable data.

1. Introduction

Shannon and Weaver (1949) indicated that information theory could be applied to psychological problems, and Shannon developed equations for both discrete and continuous channels of information (the current concern is with continuous channels).

Shannon's Theorem 17 is

\[ \text{maximum channel capacity (C)} = W \log_2 \left( \frac{P + N}{N} \right) \text{bits/sec} \]

where

\[
W = \text{bandwidth}, \\
P = \text{average power of the transmitted signal}, \\
N = \text{power of the noise}.
\]

From this general statement Fitts (1954), making the assumption that initially all movements up to twice the required amplitude (A) of a movement in a precision task were equally probable, suggested for the human motor system an Index of Performance, \( (I_p) = C = -\frac{1}{t} \log_2 \left( \frac{W}{2A} \right) \) bits per second, where \( t \) is the average time in seconds per movement and \( W \) the width of the target; and an Index of Difficulty, \( I_d = t I_p \) bits per response.

Fitts proposed in effect that movement time equals

\[ a + b \log_2 \left( \frac{2A}{W} \right) \]

\[ \dagger \text{New lecturer, Department of Ergonomics and Cybernetics, University of Technology, Loughborough.} \]
The experimental evidence, however, did not support these proposed indices. In Fitts’ reciprocal tapping experiment the constant \( a \) became negative when movement time was plotted against his Index of Difficulty as it did for zero information per response: and further, the best line through the data was not straight but curved slightly upwards.

To deal with the first of these anomalies Crossman (1956) suggested that the movement time should be expressed as

\[ a + b \log_2 \left( \frac{A}{W} \right) \]

Applying this expression to experimental data Crossman found that \( a \) had a value 0.05 sec, which was the time he found that the subject spent lingering on the target.

The second variation between Fitts’ experimental data and his theoretical formulation could be reduced, it was suggested by Welford (1960), if movement time was taken to equal

\[ k \log_2 \left( \frac{A}{W + 0.5} \right) \]

with the movement time dependent upon a kind of Weber fraction in that the subject attempted to distinguish between distances to the near and far edges of the target. He contended that the subject chooses a distance \( W \) out of a total distance to the far edge of the target. Thus the ‘effective’ target width was less wide for targets close together because only the central region were noticed and this \( W \) reduction was reflected in a reduction of errors. Welford’s amendments to the originally proposed relationship seemed to improve it, providing a better fit between the experimental data and the theoretical formulation. Correcting the few errors which lay above or below a certain fixed percentage and assuming them to be normally distributed, he calculated the ‘effective’ \( W \) for the Fitts’ data and using his own index he showed that these data gave a straight line passing through the origin. The original plot was not straight but curved slightly up, with a distinct flattening at the lower values of \( I_d \).

In the experiment described in this paper, movements were made in a single plane and an attempt was made by statistical means to determine which of the three proposed Indices of Difficulty gave the best fit to the experimental data. Within limits, different weights of stylus had been shown previously (Fitts op. cit.) not to affect performance. Hence, it was suggested that the muscular activity did not affect performance and this supposition was tested by using two values of inertia in the experiment.

Concurrent with the experiment, predetermined motion time systems were used to derive estimates and make comparisons with experimental data.

2. Design of Experiment

2.1. Apparatus

Figure 1 shows the general arrangement of the apparatus. It was a matte black circular disc of 10 in. radius on which brass targets could be fixed radially with various degrees of separation. A knob at the centre of the disc could be turned to position a white pointer along any radius. The targets had 6 in.
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ems were data.

a matt radially could be ad 6 in.

Figure 1. The general arrangement of the apparatus.

The average time taken to move between two targets alternately by swivelling the point could be determined for each of the 16 combinations of target width and amplitudes. This was done by electronically and automatically recording for each movement throughout a 15 sec period the time spent by each subject on each of the two targets, and also the time spent between those targets. Electric contact was made between the extreme tip of the metal pointer and
brush contacts set at the top of the targets. Both targets were assigned channel identification numbers and, by scrutiny of the results from a teleprinter, it was possible to check that the correct movement pattern had been adhered to—that meant no errors. If other combinations were present, they indicated an undershoot or overshoot of the targets. When errors occurred within a cycle, that cycle was not included in the analysis.

The 15 sec period was timed by stop-watch, but a complete time record to one-hundredth of a second was kept using S.E.T.A.R. Mark VX and this accounted for the whole of every period of experimentation.

The two values of inertia were obtained by screwing a cylindrical steel weight of approximately 4 lb on to the back of the spindle which held the pointer. This gave the values of inertia as 0.01 lb/in. sec² (low) and 0.06 lb/in. sec² (high).

Extraneous visual cues were virtually eliminated by the use of a matt-black surface on the apparatus free from scratches or other marks. Contact between the pointer and the electrically conducting fibre brushes was not perceivable by subjects. Fluorescent lights in the laboratory were supplemented by a localized tungsten filament lamp illumination to obviate stroboscopic effects.

2.2. Procedure

The eight subjects were male, right handed, with ages ranging from 18 to 36 years.

The experiments took place on three consecutive days for each subject. The first day was a trial day and allowed the subject to become accustomed to the tasks.

Written instructions explained to the subject what to do.

‘Using a forearm swivel, turn the knob so as to position the white line on the pointer within the two targets, alternately.

‘Score as many positionings as you can. If you under-shoot or over-shoot the target, an error will be recorded. You will be given a two-second warning before a trial. Position your hand on the knob and start moving as soon as you are told. Emphasize accuracy rather than speed.

‘Each trial will last 15 seconds and will be followed by a two-minute rest period.’

Each subject was tested for the 32 conditions given by the 16 possible combinations of target width and amplitude presented randomly at the low inertial value and by the same 16 combinations presented in a different random series at the high inertial value.

3. Results

3.1. Indices of Difficulty

For each of the three Indices of Difficulty the regression of \( \log_{10} \text{of each index} \) on \( \log_{10} \text{of the average movement time} \) was computed and plotted against the appropriate index (a horizontal line should have resulted for the best index indicating a zero regression coefficient). Confidence limits were placed on the values of the regression coefficients to indicate the best Index of Difficulty. This was taken as that for which at 95 per cent (or beyond) confidence limits, the plot of movement time against the index gave a straight line inclined to the x-axis and passing through the origin.
### Precision in Movements

#### Table 1. Fitts' Index

<table>
<thead>
<tr>
<th>Subject</th>
<th>Inertia condition</th>
<th>Regression coefficient (b)</th>
<th>Standard error of (b)</th>
<th>Where appropriate regression equation for line through origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>-0.003261*</td>
<td>0.009996</td>
<td>$Y = -0.1133 \times x_1$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.01810</td>
<td>0.005309</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>-0.01476*</td>
<td>0.004162</td>
<td>$Y = -0.1608 \times x_1$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.006547*</td>
<td>0.008963</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>-0.04980</td>
<td>0.01494</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.006273</td>
<td>0.01508</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>-0.08365</td>
<td>0.01608</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.09303</td>
<td>0.01781</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>-0.001297*</td>
<td>0.01075</td>
<td>$Y = -0.1159 \times x_1$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.02210</td>
<td>0.008564</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>-0.02227*</td>
<td>0.009896</td>
<td>$Y = -0.1368 \times x_1$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.03030</td>
<td>0.008742</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Low</td>
<td>-0.02729</td>
<td>0.008280</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.03300</td>
<td>0.009284</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Low</td>
<td>-0.02841</td>
<td>0.005238</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>-0.01388</td>
<td>0.005771</td>
<td></td>
</tr>
</tbody>
</table>

*Not significantly different from zero at 95 per cent confidence level

#### Table 2. Crossman's Index

<table>
<thead>
<tr>
<th>Subject</th>
<th>Inertia condition</th>
<th>Regression coefficient (b)</th>
<th>Standard error of (b)</th>
<th>Where appropriate regression equation for line through origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>+0.0660</td>
<td>0.02146</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.06922</td>
<td>0.01760</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>+0.05348</td>
<td>0.01514</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.05335</td>
<td>0.01514</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>+0.04393*</td>
<td>0.02186</td>
<td>$Y = -0.1531 \times x_1$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.008393*</td>
<td>0.01819</td>
<td>$Y = -0.1759 \times x_2$</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>+0.01566*</td>
<td>0.02062</td>
<td>$Y = -0.1855 \times x_3$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.02406*</td>
<td>0.02464</td>
<td>$Y = -0.1823 \times x_4$</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>+0.03300*</td>
<td>0.01731</td>
<td>$Y = -0.1728 \times x_5$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.04393</td>
<td>0.01893</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>+0.02441*</td>
<td>0.01857</td>
<td>$Y = -0.201 \times x_6$</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.03725</td>
<td>0.01475</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Low</td>
<td>+0.03086</td>
<td>0.01378</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.03544*</td>
<td>0.01760</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Low</td>
<td>+0.03982</td>
<td>0.01355</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>+0.0644</td>
<td>0.01428</td>
<td></td>
</tr>
</tbody>
</table>

*Not significantly different from zero at 95 per cent confidence limits

Tables 1, 2 and 3 show the result with separate calculations for the two inertia values used with each subject.

For Fitts' index (Table 1) in only 5 cases out of 16 could the regression coefficient be expected to be zero when 95 per cent or less confidence limits were set. All regression coefficients were negative.

For Crossman's index (Table 2) all regression coefficients were positive except for Subject 4. It is opportune to comment here that Subject 4 was not a satisfactory subject because he (disclosed at a later stage) was ambidextrous. He should not have been used in the experiment even though he used his right hand. Use of Crossman's index showed there was some improvement; that the line passed through the origin. Seven out of 16 conditions produced lines passing through the origin.
Table 3. Welford's Index

<table>
<thead>
<tr>
<th>Subject</th>
<th>Inertia condition</th>
<th>Regression coefficient (b)</th>
<th>Standard error of (b)</th>
<th>Where appropriate regression equation for line through origin</th>
<th>Index of performance (l_p), based on reciprocal of slope of line through origin (bits per sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>+0-001885*</td>
<td>-0-01236</td>
<td>(Y = -0-1476x_2)</td>
<td>6-78</td>
</tr>
<tr>
<td>2</td>
<td>High</td>
<td>+0-0009068*</td>
<td>-0-005953</td>
<td>(Y = -0-1445x_2)</td>
<td>4-92</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
<td>+0-001566*</td>
<td>-0-009449</td>
<td>(Y = -0-2932x_2)</td>
<td>4-84</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>+0-002901*</td>
<td>-0-01871</td>
<td>(Y = -0-1369x_2)</td>
<td>5-35</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>+0-006668</td>
<td>-0-01927</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>+0-0002303*</td>
<td>-0-01998</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>+0-002138*</td>
<td>-0-067965</td>
<td>(Y = -0-1530x_2)</td>
<td>6-53</td>
</tr>
<tr>
<td>8</td>
<td>Low</td>
<td>+0-000816*</td>
<td>-0-003895</td>
<td>(Y = -0-1619x_2)</td>
<td>6-17</td>
</tr>
<tr>
<td>9</td>
<td>Low</td>
<td>+0-002303</td>
<td>-0-01291</td>
<td>(Y = -0-1780x_2)</td>
<td>5-62</td>
</tr>
<tr>
<td>10</td>
<td>High</td>
<td>+0-000556*</td>
<td>-0-0167</td>
<td>(Y = -0-1850x_2)</td>
<td>5-35</td>
</tr>
<tr>
<td>11</td>
<td>Low</td>
<td>+0-0006250*</td>
<td>-0-01028</td>
<td>(Y = -0-1931x_2)</td>
<td>5-18</td>
</tr>
<tr>
<td>12</td>
<td>Low</td>
<td>+0-0009484*</td>
<td>-0-01227</td>
<td>(Y = -0-2182x_2)</td>
<td>4-58</td>
</tr>
<tr>
<td>13</td>
<td>High</td>
<td>+0-001194*</td>
<td>-0-008493</td>
<td>(Y = -0-2229x_2)</td>
<td>4-48</td>
</tr>
<tr>
<td>14</td>
<td>High</td>
<td>+0-005054*</td>
<td>-0-03386</td>
<td>(Y = -0-2046x_2)</td>
<td>4-05</td>
</tr>
</tbody>
</table>

* Not significantly different from zero at 95 per cent confidence level

Contrasting the negative and positive values for the regression coefficients, using Fitts' index and Crossman's index respectively, it was apparent that to obtain values of the regression coefficients closer to zero, a value of expression for the Index of Difficulty somewhere between Fitts' and Crossman's ideas was needed. Welford's suggestion of \(\log_2([A/W] + 0.5)\) fitted that specification and, additionally, gave the best fit to the experimental time data.

![Figure 2](image-url)  
Typical result of experiments showing average movement time plotted against Welford's index of difficulty.

Graphicated it is evident that data past to cut the Welford's index and be distributed.

3.2. Inference
Tests between inertia a 1 and 5 times rat

4.1. Induction
The good fit lines have the regression equation

Table the equation of 95 per cent could be ascertainment

Accept through performance and as a bits per second.

* 'absolute
The \(I_p\) which is the reciprocal transfer \(I_p\) value
While exhibiting errors w near a
One is the 4 days.
Graphs plotted of average movement time against Welford's index as illustrated in Figure 2 demonstrate that the slight curvature upwards, as may be graphically shown to exist when similar plots based on Fitts' index or Crossman's index are drawn, has disappeared. The regression lines for the experimental data pass through the axis close to the origin. There is, however, a tendency for the time axis below the origin. Eleven out of 16 lines do this. However, Welford's method for correcting for errors was not used in the present experiment because the experimenter could not assume that errors were normally distributed.

12. Inertia Values

\( t \)-tests were used to ascertain whether there was a significant difference between mean times from actual experimental data of movements with low inertia and those with high inertia. A significant difference at a level between 1 and 5 per cent was found between the two inertia values when performance rates were analysed for five subjects out of the eight.

4. Discussion

11. Indices of Difficulty

The most illuminating evidence that Welford's Index of Difficulty gives a good fit to the experimental data comes from Table 3. Thirteen out of 16 lines have quite high probabilities of containing zero regression coefficients in the regression of the logarithmic function against Welford's index.

Table 3 has a column headed Index of Performance \( I_p \) and this is based upon the equations of the lines which pass through the origin, when confidence limits of 95 per cent or less are set. For the six subjects who produced lines that could reasonably pass through the origin, the \( I_p \) values were tested by \( t \)-tests to ascertain whether or not the mean difference for low and high inertia conditions was zero. A significant difference of between 1 and 5 was found.

Accepting that lines plotting movement times against Welford's index pass through the origin, and using Table 3 as a guide, there is some variation in performance (in bits per second) between subjects. This ignores Subjects 3 and 4. The range is from 4.05 to 6.92 bits per second. This range of 2.87 bits per second is small in relation to the total spread of human activity in information terms, which has been shown to be from about 2 to 35 bits per second. Differences in the present experiment should be related to this 'absolute' scale of performance.

The \( I_p \) values obtained are about half those found by Fitts in his experiments, who found values of about 9 or 10 for most of his experimental conditions in the reciprocal lapping task. Similar values were obtained for the 'dis- transfer' task. Fitts' 'pin-transfer' experiment gave results with average \( I_p \) values of about 11 bits per second.

While discussing performance, it is worth mentioning that all subjects exhibited occasionally the tendency to produce errors within a run. The errors were randomly distributed; this indicating that the subject was working near maximum channel capacity.

One factor in connection with the experiment must be emphasized; this is the effect of practice. The experiment was limited to three consecutive days. Performance times would have become shorter with further practice.
and hence the index of difficulty would have been reduced. This point is further discussed in connection with its theoretical implication by Kay (1962).

4.2. Inertia Values

As statistical differences in five cases out of eight were found with tests which compared the differences between movement time for the two values of inertia, it does appear that muscular considerations might account for the differences in performance rate.

5. Comparison of Experimental Results with Predetermined Motion Time System Predictions

Standard performance is 60 on a 60/80 time study rating scale. Because the subjects were instructed to work at the fastest rate consistent with minimum errors, it was considered that they had 'high incentive', and the maximum rate normally maintained is 15 per cent above incentive level, or 92 on a 60/80 scale.

Figure 3. Showing time values for work factor P.M.T.S. against Welford's index of difficulty.

Figures 3–5 depict for each P.M.T.S. the time values at the 'high incentive level' of working for both values of inertia, against Welford's Index of Difficulty. Figure 3, for Work Factors, shows a straight line, but the slope is small compared with the 'estimated best lines' for low inertia and high inertia, obtained from the average of the experimental data derived from all eight subjects. Apart from lack of differentiation between inertia values, the Work Factor lines are 0-2 sec too small for $I_d$ values of about 6, and 0-4 sec too high for $I_d$ values of about 0-8.
This point is by Kay (1962).

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92 on a 60/80

Figure 4. Showing time values for Methods-Time Measurement against Welford's index of difficulty.

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high incentive of Difficulty.
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right inertia,
all eight
s, the Work

Figure 5. Showing time values for basic motion time study against Welford's index of difficulty.
Methods—Time Measurement gave the best fit to the experimental data for $I_a$ values of less than 3; there is some widening differentiation between the lines for the two inertias. Generally, $M.T.M.$, has a steeper slope than the experimental one, and for $I_a$ values of 6 the $M.T.M.$ lines are over 0.3 sec too high.

Basic Motion Time Study derivations did not bear much resemblance to the experimental ones. The $B.M.T.$ system differentiated between inertia values but, for $I_a$ values of less than 2, the $B.M.T.$ curves did not provide enough time for any movements.

Il a été possible de montrer que, dans certaines circonstances, la capacité du canal relatif à la motricité était constante. Un ensemble de relations inspirées de la théorie de l'information et reliant le temps de mouvement à l'amplitude et à la précision du mouvement, ont été élaborées. Dans la présente recherche, où les mouvements avaient lieu dans un seul plan, l'intention des auteurs était de vérifier l'application générale des indices proposés.

Le dispositif expérimental consistait en une grange indiquant que le sujet devait faire priser alternativement, dans un plan vertical, entre deux cibles.

Les résultats obtenus ont montré qu'il existe une relation significative entre le temps mis pour un mouvement de rotation et un indice logarithmique (en base binaire) reliant l'amplitude à la largeur de la cible. Le temps mis était également influencé par l'écrit du système de rotation de même que par la variabilité interindividuelle existant entre les 8 sujets.

Les données obtenues ont été exprimées au moyen de trois autres indices fournis par le Système des Temps et Mouvements préétablis, et les résultats ainsi obtenus ont été comparés à l'indice reliant l'amplitude du mouvement à la largeur de la cible. L'accord concernant les temps mis n'était pas satisfaisant pour deux des trois indices pris en considération; par contre, le système $M.T.M.$ a permis un ajustement satisfaisant des données.


Die experimentellen Ergebnisse lassen eine statistische Beziehung zwischen der Zeit für eine Drehbewegung und einem binären logarithmischen Index aus Amplitude und Zielpunkt ergeben. Die Zeit für die Drehbewegung wurde durch die Trägheit des rotierenden Systems beinflußt.

Die Bewegungszeit varierte zwischen den 8 Versuchspersonen.

Es wurde ein Vergleich angestellt, um zu sehen, ob ein Index aus Bewegungsdauer und Zielpunkt in einfacher Beziehung zu den Testwerten steht, die mit 3 verschiedenen Systemen in Vorbestimmung der Bewegungsdauer ermittelt wurden. Zufriedenstellende Zeiten ergaben sich nur bei einem der Systeme: "Methods—Time Measurement".

References


