DIFFERENCES BETWEEN FINGERS AND HANDS IN TAPPING ABILITY: DISSOCIATION BETWEEN SPEED AND REGULARITY

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INTRODUCTION

That the preferred hand performs more skillfully than the non-preferred hand is so obvious that the origins of its superior performance have been ignored until recently. Two separate types of questions arise.

(1) What is the *origin* of between hand differences? Are they the result of an inbuilt superiority of one hand, or do they develop as a result of differential practice and experience?

(2) What is the *mechanism* of between hand differences? That is, how do control processes differ between hands?

THE ORIGIN OF HAND DIFFERENCES

Plato (*Laws,* 794.d) argued that hand differences are entirely a result of differential usage, since "nature... makes the members on both sides broadly correspondent". Conversely Aristotle (*Magna Moralia,* 1194.b.32) argued that the preferred hand is innately superior to the non-preferred; "by nature... the right is... naturally superior to the left hand". Essentially these positions correspond to the extremes of modern theory. A variation upon them asks whether asymmetry is a function of innately superior *skill* or *preference,* allowing the possibility that one hand is preferred but is not more skillful, and then, as a result of preferential usage, it becomes more skillful as well (Morgan and McManus, 1986).

A critical question for distinguishing such theories is whether differential practise can reduce hand differences. In the following experiments we assess the role of experience in altering dominance.

As a measure of manual skill we have chosen the simple task of rapid tapping with a single finger. It has been used in other studies, being studied in its own right (Provins, 1956; 1958; Flowers, 1975; Peters, 1980,

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1981), and as a part of dual task experiments (e.g. Piazza, 1977; Kee et al., 1983), it shows clear asymmetries between hands (although the results of Flowers, 1975, are an exception), and is easy to explain to subjects. To our knowledge other studies have only examined differences between index fingers, whereas in the present study we consider all five fingers. In interpreting the results it should be remember that finger-tapping ability appears to be relatively isolated amongst tests of manual dexterity (Barnsley and Rabinovitch, 1970).

If differential experience is of importance in producing asymmetries in the finger-tapping task then we may predict that:

(1) Since most skilled tasks involve primarily the thumb and index fingers then these should show greatest asymmetries.

(2) Since left-handers live in a "right-handed world", then asymmetries should be less in left-handers than right-handers.

(3) Since piano playing and type-writing use all fingers of both hands (and typists do not show the conventional differences between hands on a typing task; Provins and Glencross, 1968), then individuals proficient at these tasks should show a reduced asymmetry in finger tapping ability. In so far as the skills differ (e.g. the non-preferred thumb is hardly used in typing: in piano-playing the left-hand is primarily used for chordal (parallel) rather than independent (serial) movements) this should be reflected in performance differences between the fingers. Differences between fingers in keystroke times have been investigated in typists (Salthouse, 1984); for the right hand the four fingers showed average times of 203.1, 203.1, 199.8, and 236.2 msecs (index to little, respectively), while fingers the times for left hand were 215.0, 212.8, 239.0 and 211.9 msecs for the same. These times are a function of the awkwardness of the position of the key, the difficulty of using the finger, and the frequency of the letter, in normal usage. Note however that although in general the fingers of the right hand are faster than those of the left, in the specific case of the little finger this situation is reversed, primarily due to its hitting the frequently used "A" key. A specific prediction must therefore be that tapping speed differentials between the hands in typists will be less or reversed in the little finger.

THE MECHANISM OF HAND DIFFERENCES

Peters (1980) has suggested that "the dominant hand performs both more quickly and more regularly (Peters and Durding, 1978, 1979)", a result also shown by Todor and Kyprie (1980) and Tobor et al. (1982); i.e. both the mean inter-tap interval (ITI) and the standard deviation of the ITI (ITISD) are less for the preferred hand. However the fact of a decreased standard deviation is not convincing evidence for improved regularity in the presence of an overall decreased mean. Regularity must measured relative to overall rate (i.e. as a *proportional* quantity, rather than as an absolute measure) and hence an appropriate measure is the coefficient of variation of the ITI (ITIVAR), calculated as ITIVAR = 100 × ITISD/ITI. A simple change of speed (i.e. a stretching of the time scale) will not modify ITIVAR (but will modify ITI and ITISD in parallel). Peters and Durding (1979) found no correlation between speed of tapping and regularity (measured as ITISD). Such a result seems unlikely, since to a first approximation one would predict from Weber's Law (Engen, 1972) that the relative deviations between intervals should be proportional to the interval size; a number of studies have found results broadly consistent with that position (Newell et al., 1984).

A purpose of the present study was to ask whether differences between fingers in speed or regularity of tapping are caused by the same mechanism as causes differences between hands.

An additional interest of the experiment was to search for sex differences in lateralised behaviours, which the extensive review of McGlone (1980) has suggested might exist. However Morgan (1980) has pointed out that it is feasible that a great number of results in the literature may not be truly significant, and type I errors may occur as a result of the "file-drawer problem" (Rosenthal, 1979).

MATERIALS AND METHOD

Subjects

All subject were students or employees of Bedford College. Typists had a speed of at least forty words per minute, and pianists had all achieved grade seven or above in the Royal School of Music's examination. Handedness was confirmed by a conventional 28-item handedness inventory (McManus, 1979), which produced scores in the range −1 (complete left-handedness) to +1 (complete right-handedness). The mean degree of lateralisation on the handedness inventory was 0.779 (SD .063) and −.307 (SD .125) for the right- and left-handers respectively in experiment I, and . 758 (SD .206) for the right-handed subjects of experiment II. The mean age of the subjects in experiment I was 22.9 (SD 5.9, range 19-35) and in experiment II was 21.3 (SD 3.5, range 19-34).

Tests and Procedure

Subjects were seated at a table of normal height and were asked to tap as quickly as possible with a single finger on a copper pad whose surface was approximately 5 mm above the surface of the table. They kept their hands flat upon the table, fingers moderately spread, and used only a single finger on each trial. Subjects were earthed via an electrode connected to their ankle. Contact of the finger with the pad was recorded electronically to an accuracy of 50 microseconds.

In each testing block a subject tapped with each of the five fingers of both hands. Within blocks the order of the 10 conditions was randomised, with a different order being used for each block for each subject. In each trial the subject tapped as quickly as possible for 10 seconds, starting at their own convenience. Each subject was given three consecutive blocks of trials, the entire experiment lasting approximately 30 to 45 minutes.

In experiment I,16 subjects were tested; 4 right-handed males, 4 left-handed males, 4 right-handed females, and 4 left-handed females, none of whom were pianists or typists. In experiment II, 12 subjects were tested, four right-handed female typists, four right-handed female pianists, and four right-handed female controls. No attempt was made to produce a single completely balanced experiment because of the problems of finding left-handed male typists.

RESULTS

The mean ITI for each finger in each condition was calculated by a three stage procedure, in order to avoid ITI and particularly ITISD and ITIVAR being distorted by occasional pauses (and hence very long intervals) or occasional "bounces" (and hence very short intervals). Firstly the median inter-tap interval was calculated for each trial. Intervals longer than 1.5 times the median were excluded, and all intervals less than half the median were merged with the subsequent interval. The mean ITI and the ITISD were then calculated from the remaining values. In most subjects very few values were eliminated by these corrections. It should be noted that this procedure is fairly conservative, only removing points which by any criterion would be regarded as outliers.

Experiment I

Analysis was by a conventional repeated measures analysis of variance, with handedness and sex as between subject measures, and hand used, finger and block as within-subject variables.

Rate of tapping (ITI)

Significant differences were found between fingers ($F=15.05$; d.f. $=4, 48$; $p<.001$), with the index finger being fastest and the ring finger slowest (Figure 1). The preferred hand was faster than the non-preferred hand ($F=49.34$; d.f. $=1, 12$; $p<.001$), and there was an interaction between hand used and finger ($F=4.74$; d.f. $=4, 48$; $p<.01$), the difference

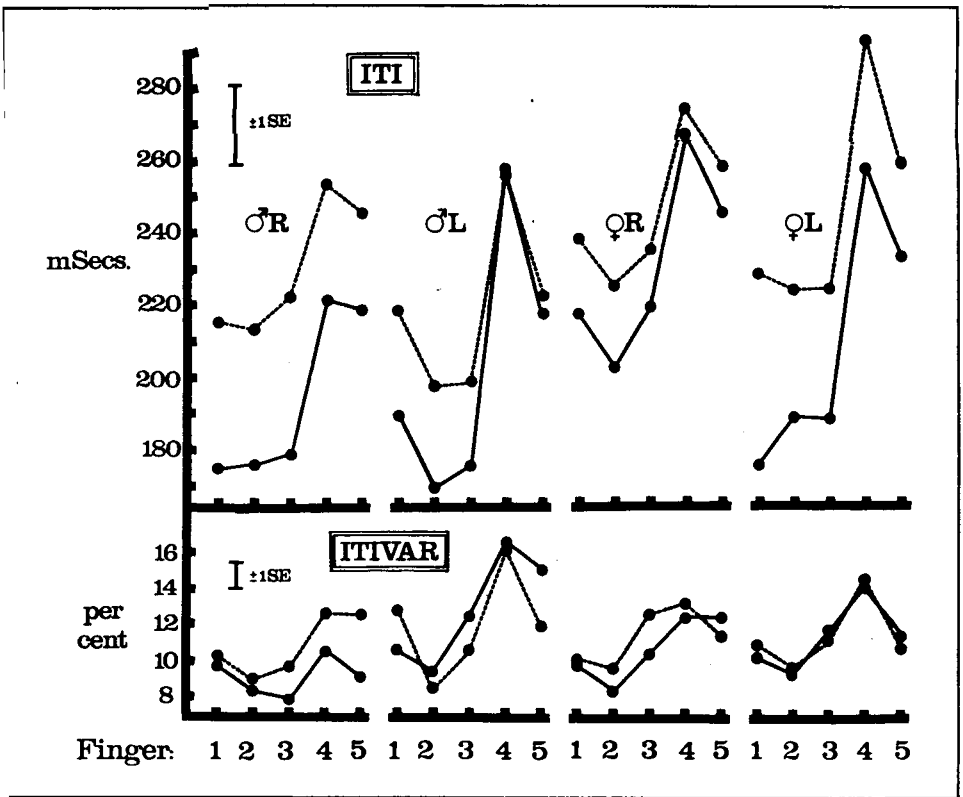


Fig. 1 — *Shows the mean ITI (top) and the mean ITIVAR (bottom) for the five fingers (1: 'humb; 2: index; 3: middle; 4: ring; 5: little) of the preferred hand (solid lines) and non-preferred hand (dashed line), of (from left to right) male right-handers, male left-handers, female right-handers, and male left-handers in experiment I.*

between the hands being greater for the index finger than for the ring or little finger. Block showed a highly significant linear trend (F=17.12; d.f. = 1, 24; p<.001), with later trials being faster than earlier trials. There was an interaction between finger and the linear block effect (F=6.33; d.f.=4, 96; p<.001), due to a greater improvement across blocks for the ring and little fingers than for the thumb and index finger. There was no interaction between finger, hand used and linear block (F=0.98; d.f.=4, 120; N.S.) or hand used and linear block (F=0.55; d.f.=1, 26; N.S.).

There were no main effects of sex or handedness and the only significant interaction involving sex or handedness was for sex × handedness × hand used (F=7.28; d.f.=1, 12; p<.025), the difference between preferred and non-preferred hands being greater in right-handed males (36.5 ms) and left-handed females (37.1 ms) than in left-handed males (16.9 ms) and right-handed females (15.9 ms). There was no evidence for interactions between finger and handedness (F=0.66; d.f.=4, 48; N.S.) or finger, handedness and hand used (F=0.66; d.f. =4, 48).

Regularity of tapping (ITIVAR)

There was a highly significant difference in ITIVAR between fingers (F=19.19; d.f.=4, 48; $p<.001$), with the ring finger being most variable and the index finger least variable (Figure 1). There was also a significant linear trend on block (F=7.4; d.f.=1, 24; $p<.025$), the coefficient of variation increasing from 10.92% on block 1 to 11.77% on block 3. There was no significant effect of hand used (F=1.09: d.f.=1, 12; N.S.), or of interactions between hand used, finger and block. No between subject effects were significant, nor were these significant interactions between sex and handedness and the within-subject factors.

Experiment II

Analysis was by a conventional repeated measures analysis of var- iance, similar to that in experiment I, except that sex and handedness wer replaced by a "skill" factor.

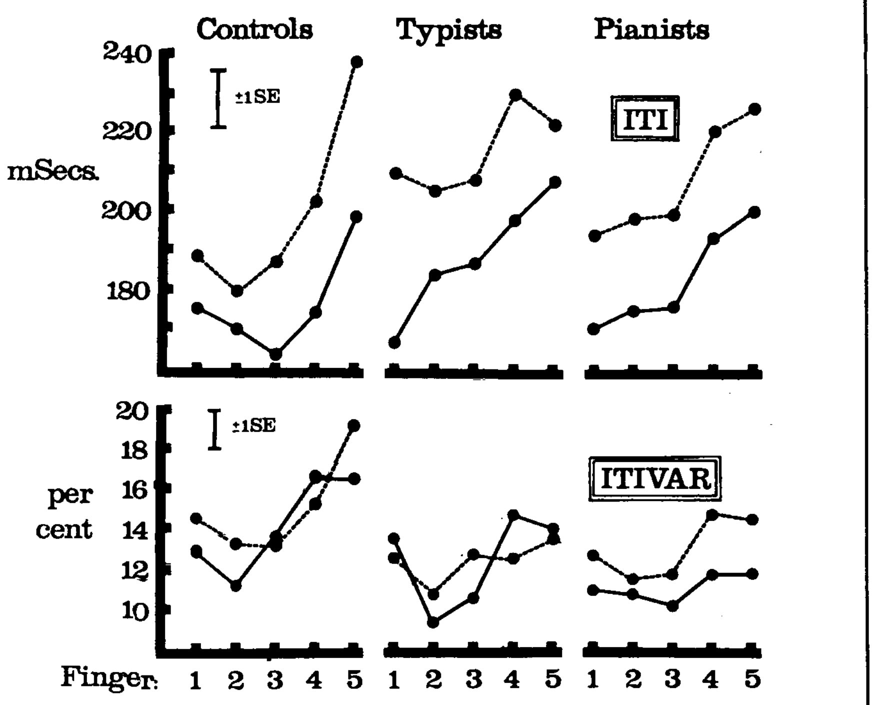
Rate of tapping (ITI)

Significant differences were found between fingers (F=13.96; d.f.=4 36; $p<.001$), with the little finger being slowest and the thumb bein fastest (Figure 2). The preferred hand was faster than the non-preferre hand (F=28.71; d.f.=1, 9; $p<.001$). There was no interaction betwee fingers and the hand used (F=0.37; d.f.=4, 36; N.S.). The linear effect c block was not significant. There were no significant interactions betwee block, finger and hand used.

There were no main effects of skill group, and neither were the interactions between skill and finger (F=1.06; d.f.= 8, 36; N.S.), skill an hand used (F=.063; d.f.=2, 9), or finger, hand used and skill (F=0.7 d.f.=8, 36; N.S.). There were no significant interactions between skill an block, or between skill, block, hand used and finger.

Regularity of tapping (ITIVAR)

ITIVAR showed highly significant differences between finge (F=10.65; d.f.=4, 36; $p<.001$), the index finger showing least variabilit and the little finger the most (Figure 2). There was a significant linea trend on block (F=12.59; d.f.=1, 18; $p<.01$), with the third showin more variability than the first (13.91% vs. 12.23%). There was n



ʼig. 2 — *As for Figure 1 except that results are (from left to right), for controls, typists and ianists, in experiment II.*

lifference in variability between the hands (F = 1.21; d.f. = 1, 9; N.S.), and here were no interactions between hand used and finger (F = 0.65; l.f. = 4, 36; N.S.) or between hand used and block.

No significant differences were found between the skill groups, and

TABLE I

ʼhe correlations between ITI and either ITISD or ITIVAR, for each of the finger/hand ·ombinations, as well as the mean of these correlations (using Fisher's Z transformation)

ʼinger	ITI with ITISD			ITI with ITIVAR		
	Preferred	Non-preferred	Overall	Preferred	Non-preferred	Overall
1	.149	.261	.307	−.284	−.301	−.209
2	.214	−.068	.225	−.177	−.511	−.255
3	.469	.358	.478	.075	−.143	.024
4	.818	.789	.806	.165	.237	.205
5	.688	.388	.592	−.134	−.053	.061
ʼlean	.518	.389	.517	−.093	−.164	−.178

neither were there significant interactions between skill and hand used, finger or block.

Correlation between measures

The overall correlation between ITI and ITISD across trials was 0.671 ($N = 840$; $p << .001$). Analysis of covariance showed that this regression was not simply a result of between subject differences, but was present at all strata of the within-subjects design (e.g. $z = 10.63$, $p << .001$ at the subiect $\times$ finger $\times$ hand $\times$block stratum). The correlation between ITI and ITIVAR was 0.136, which in view of the large sample size is statistically significant, but implies a shared variance of only 1.8%. Table I shows the correlations of ITI with ITSD and ITIVAR for the fingers considered individually, for the preferred and non-preferred hands. Correlations of ITI with ITISD were positive in most cases, although the correlations were smallest for the index finger. Correlations of ITI with ITIVAR were scattered around zero, and showed less range than those for ITI with ITISD.

Discussion

Although ITI differs both between fingers and between hands, ITIVAR differs only between fingers and not between hands. By implication, functional differences between hands and between fingers arise from separate mechanisms. Considering just ITI, we may follow Sternberg (1969) and argue that the presence of additivity between hand and finger implies that the independent variables are acting at different stages (although it should be noted that Taylor, 1976, has argued that strictly one may only derive the somewhat weaker implication that interactions between independent variables imply action at the same stage). If hand and finger have actions at different stages then it is possible, though not necessary, that they could have different effects upon other dependent variables. Since ITIVAR is effectively uncorrelated wich ITI it may be regarded as a second dependent variable, and its significant relation to finger but not to hand, supports the suggestion of hand and finger acting at different processing stages. It might be argued in following the Sternberg paradigm that strictly we have not found pure additivity for hand and finger in experiment I. However Figure 1 shows this interaction applying only to the differences between the first three and the last two fingers, the latter being the least practiced, an interpretation supported by the lack of interaction in experiment II. In summary, the best interpreation of the results of the two experiments is that differences between ıand and between fingers in ITI are occurring at separate loci. Similarly, he additivity of finger and block in determining ITIVAR, found in both xperiments, suggests that finger and block are acting at separate loci.

Differences between fingers within hands might arise either from tructural variations within a cerebral hemisphere, or within any of the notor system at a more peripheral level. An obvious candidate is in the lifferent musculature used for moving the separate fingers. Across the wo experiments the 4th (ring) finger is the worst at the task (this is shown articularly clearly in experiment I) and the first (thumb) and second index) fingers are the best at the task. The fifth finger is generally slightly etter at the task than the fourth finger, particularly in those subjects in xperiment II who are generally skilled users of all fingers. To a large xtent these differences can be explained by differences in musculature. eters (1980) has suggested that the most important component of differences between the hands in tapping speed of the index fingers is the rate f the down/up transition, i.e., the movement from flexion to extension. his is primarily dependent upon the extensor musculature of the fingers. Most of the fingers are extended by *extensor digitorum*, which has four endons, inserting into the 2nd, 3rd, 4th and 5th fingers. These tendons are ıot however independent, but show inter-tendinous connections (Davies nd Coupland, 1967), which inhibit individual finger movements; these onnections are greatest between fingers 4 and 5, moderate between 3 and 4, and least between 2 and 3. In addition the second finger has its own ndependent extensor, *extensor indicis*, as does the fifth finger, *extensor ligiti minimi*. On the basis of *extensor digitorum* alone we would predict an order of tapping of 2>3>4>5. However the existence of *extensor digiti ninimi* means that an order 2>3>5>4 is possible. Clearly individual lifferences in tendinous interconnections and in the relative bulk of the various muscles, could result in variations around this order, hints of which can be found in the results of experiments I and II. Indeed, 26.5% of he total variance in the combined experiments, after removal of differences in means between subjects and between fingers, is accounted for by he residual subject × finger term. The musculature of the thumb is ompletely independent of that of the fingers, and hence we would expect erformance as good as that of the index finger.

The different variabilities of the fingers suggests separate control athways; the absence of such differences between the hands implies a ossible single control centre. The differences in means between the hands which are to a large extent independent of differences between fingers, articularly in experiment II), are best accounted for by a cerebral dominance mechanism, the dominant hemisphere by *preference* also being pecialised for skill preference. This hypothesis is consistent with neu-

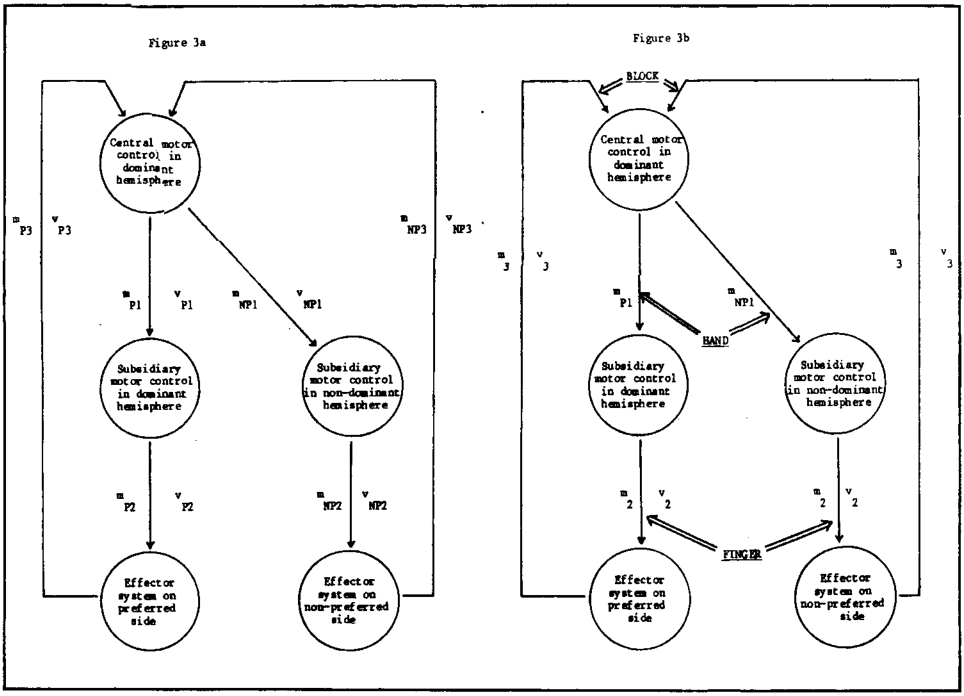


Fig. 3 — *a) Possible structural model to account for experimental results, showing all free parameters (m = mean; v = variance). b) Constrained structural model, showing loci of influence of Hand, Finger and Block (see text).*

ropsychological evidence on apraxia, which suggests that lesions of the left hemisphere in right-handers can cause specific cognitive problems with motor control, in the absence of any specific movement disorder (Hécaen, 1981) and that the left hemisphere may contain a specific motor control centre which can become disconnected from the right hemisphere (e.g. Watson and Heilman, 1983). Annett et al. (1979) have suggested that "differences between hands in the control of aiming movements are unlikely to be due to differential efficiency in processing feedback information, but rather to greater variability in the mechanism for initiating these movements" (p. 651). Such a model is consistent with our present results. If there is a single control centre for both hands, then it would be expected to be more noisy when tapping control occurs across hemispheres, rather than within, and hence the mean interval between taps would be longer, as a result of cumulative errors.

A further differentiation of the effects of ITI and ITIVAR is shown between blocks. Overall the two experiments showed a significant decrease of ITI across blocks, whereas in both cases ITIVAR *increased* significantly across blocks. Probabily the best interpretation of this is that increasing ITIVAR is associated with fatigue (and hence general noise in the system), although further experiments would be required to confirm this.

A possible model is shown in Figure 3a. A single lateralised central motor control centre in the dominant hemispheres drives subsidiary motor control centres in the two hemispheres (perhaps located in sensorimotor cortex, basal ganglia, or cerebella). These subsidiary centres drive the effectors (the muscles, tendons, and associated neural apparatus), and the effectors return feedback to the central controller. Each stage in the process takes time (a mean of m sec) and is noisy or variable (adding in variance, v, to the output). A complete model would therefore have a total of twelve parameters (m and v at each of three stages on the two sides). However such a model may be constrained. The subsidiary motor centres and the effectors are not known to be morphologically asymmetric and are probably functionally symmetric, and thus we may set $m_{P2}, = m_{NP2}$; $m_{P3} = m_{NP3}$; $v_{P2} = v_{NP2}$; and $v_{P3} = v_{NP3}$. Given that the first stage is manifestly asymmetric, being located in only one cerebral hemisphere, then $m_{P1} \neq m_{NP1}$. And since the first stage is entirely intra-cortical, we may argue that its variability will probabily be much less than that of stages 2 and 3, being a function of neuronal rather than mechanical processes, so that $v_{P1} = v_{NP1} \simeq 0$. Finally we may note that the second stage, from subsidiary motor centres to the end-stage of the effector process clearly differs between fingers (see above). Given these constraints, an interpretation is that differences between hands are at stage 1, and produce differences in ITI. Differences between fingers act at stage 2, and produce differences in both ITI and ITIVAR, and differences in block are forced, by exclusion, to act at the third, feedback, stage, where they influence both ITI and ITIVAR and are presumably a reflection of fatigue effects.

Peters and Durding (1979) found no correlation between ITI and ITISD, whereas we found a large correlation (0.671) between these variables. Our experiment used all five fingers, whereas Peters and Durding considered only the index fingers, for which our results suggest that the correlation of ITI with ITISD is relatively small, although still positive. Nevertheless considering all of the fingers it is clear that there is a correlation between ITI and ITISD, as Weber's Law predicts, and that this correlation is not present for ITI with ITIVAR. Overall ITIVAR is therefore a better measure of variability than ITISD, although it is conceivable that some other transformation of the data would produce a yet improved measure, and we note that Newell et al. (1984) report a number of studies for which the relation between force and variability of force is better expressed as a square-root function, rather that as the linear function that Weber's Law would predict.

The absence of any consistent pattern of differences between groups of subjects in these experiments suggests that performance differences between the hands cannot be explained in terms of differential practise between hands, since within both experiments the degree of improvement was similar in both preferred and non-preferred hands, and the differences between the hands were comparable in right- and left-handers, and in typists and pianists, groups who might be expected to have differential previous experience of making fine movements with their non-preferred hands. The only way of avoiding this conclusion is by suggesting that finger-tapping and typing/piano-playing show no overlap in task-requirements although in view of the elemental nature of finger-tapping, this seems unlikely. It would also raise doubts about the whole testability of the experience hypothesis.

Substantial differences were found between the five fingers in overall tapping speed, while the difference between the preferred and non-preferred hands was approximately the same for all fingers. These results suggest that functional differences between the hands are unlikely to be a result of previous practise. That conclusion is consistent with Peters (1981) who tested thirteen subjects on from 350 to 1150 trials of a tapping task; whilst in general there was a small overall increase in speed across the experiment, the relative difference between the hands remained constant (in distinction to the result of Peters, 1976, on a sigle subject).

ABSTRACT

The mean inter-tap interval (ITI) and the coefficient of variation of the ITI (ITIVAR) were measured in all five fingers of the preferred and non-preferred hand in two experiments. Subjects were right- or left-handed, males or females in experiments I and right-handed female typists, pianists, or controls in experiment II. Lack of consistent difference between right- and left-handers, and between those with and without special manual skills, suggested that hand differences in tapping are not a consequence of differential practise between hands.

ITI showed differences both between fingers and between hands, whereas ITIVAR only showed differences between fingers. Separate mechanisms are inferred, and it is suggested that differences between fingers are a function of differential peripheral motor control, whereas differences between hands are a consequence of cerebral dominance of control mechanisms, and a model is presented.

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