NATIONAL INSTITUTE FOR PERSONNEL RESEARCH — NIPR PERS-427

Computer-controlled tests of manipulative dexterity

Nigel Connell

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Human Sciences Research Council
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Nigel Connell, B.Sc (Hons.), Senior Researcher

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ISBN 0 7969 0665 3

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ACKNOWLEDGEMENTS

Dr G K Nelson, Executive Director, NIPR

Dr T R Taylor, Head, Cognitive and Personality Research

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EKSERP

Die dringende behoefte aan geldige toetse van manipulerende handvaardigheid word aangetoon. Die struktuur van psigomotoriese vermoëns word beoordeel, en die uiters spesifieke aard van dié vermoëns word voorgestel as 'n belangrike faktor wat die onvoorspelbare prestasie van handvaardigheidtoetse veroorsaak. Navorsing met behulp van beweging- en tydstudie het basiese tekortkominge in die ontwerp van verskeie toetse aangetoon, en dui ook op maniere om die betroubaarheid en geldigheid van toetse te verbeter. Daar word aanbeveel dat 'n handvaardigheidstoetsbattery ontwikkel word wat van apparaat vir die meting van elementêre bewegingtydeenhede gebruik maak. Hierdie apparaat behoort modulêr te wees, en moet deur middel van 'n mikrorekenaar beheer word om maksimum buigsaamheid van gebruik te verseker.

ABSTRACT

The urgent need for valid tests of manipulative dexterity is noted. The structure of psychomotor abilities is reviewed, and the extreme specificity of these abilities is suggested as a major factor underlying the unpredictable performance of dexterity tests. Research using the methodology of motion and time study has revealed basic flaws in the design of many tests, and also indicates ways to improve test reliability and validity. It is recommended that a battery of dexterity tests be developed around apparatus for the measurement of elemental motion times. This apparatus should be modular and should be controlled by a microcomputer to ensure maximum flexibility of use.

1. INTRODUCTION

In countries which have mixed First- and Third-World economies such as South Africa, the influx of large numbers of people into cities in search of work has put heavy pressure on those entrusted with the task of training them in the skills which they need to become productive. Because of the magnitude of this problem, it is essential that workers are trained in those skills which they have the greatest potential of developing in as short a time as possible, and that deficiencies in various areas be diagnosed so that appropriate remedial action can be taken.

As Biesheuvel (1979) has pointed out, many black workers have been engaged in subsistence farming activities, manual labour, or operator tasks involving only simple skills. There is a general need to deal more effectively with the problems they may experience when being trained in the finer co-ordinative manual skills encountered in many industrial tasks. In this situation the use of tests of manipulative dexterity can be of considerable value, both from the point of view of vocational guidance and for the identification of those areas of an individual's psychomotor performance which need special attention during training.

Effective selection for manipulative dexterity is obviously a prerequisite for the efficient functioning of labour-intensive industries, which are still of considerable importance in South Africa. It may be argued that in many cases manipulative dexterity is no longer as important a factor as it was in the past, due to the rapid advancement of automation. However, as King (1964) has pointed out, it is often not realized that the manual tasks which remain in highly automated industries are usually the more difficult ones which make greater demands on the worker's abilities.

Before embarking on an extensive programme of manipulative dexterity test development and evaluation, the problems unique to these tests need to be examined in detail. In view of recent advances in the use of computerized psychological tests, it is important to establish whether computers can be incorporated into the design of dexterity tests. Of particular interest is the question of whether some of the weaknesses in existing dexterity tests can be overcome by such an approach.

The development and application of aptitude tests for the selection of industrial workers has been an important component of psychological endeavour since the first decade of this century. Although much progress has been made in the development of tests of cognitive ability, the same cannot be said of tests of manipulative dexterity, and as a consequence these tests have acquired a bad reputation in industry (Corlett, Salvendy & Seymour, 1971). Drewes (1961) has pointed out that numerous studies have revealed the existence of considerable difficulty in the choice of the appropriate dexterity tests for particular selection problems. Dexterity tests which appear to have reasonable face validity have often been bettered by tests which seem to have less in common with the job in question, and tests which have been shown to be valid for one job often fail to generalize to other similar jobs.

As a result of these difficulties, the predictive validity of dexterity tests is, on average, quite low and can vary greatly within a given job category. For example, Ghiselli and Brown (1955) reported that finger dexterity tests show an average validity of approximately 0,3 for assemblers and bench workers, and that validities ranging from -0,05 to +0,89 had been found in different studies. Given problems such as these, it is surprising that relatively little work has been done to refine existing dexterity tests. It appears to be the case that many tests are being used on the basis of faith alone, and with little regard to issues of test reliability or validity.

One of the most significant problems affecting the application of dexterity tests relates to the factorial structure of psychomotor abilities. Tests of different aspects of cognitive performance are all found to inter-correlate moderately, but this is not generally the case with tests of psychomotor ability. Ever since the introduction of psychomotor tests, it has been observed that these have low or zero inter-correlation, and consequently one cannot speak of "general motor ability". However, factor analytic studies have identified uncorrelated group factors, each of which is confined to a narrow range of behaviours.

As a consequence of this structure, it follows that a "minor" alteration to a dexterity test may result in an appreciable change to what the test measures. Similarly, "minor" differences between two jobs may have a significant effect on the psychomotor abilities which contribute towards proficiency in each job. The psychologist responsible for designing a dexterity test for a given job cannot, therefore, rely on any broadly applicable abilities to more or less ensure test validity, as can be done when designing a cognitive test. It has been stated by some (e.g., Drewes, 1961) that a detailed and accurate task analysis down to the "micro-motion" level is a prerequisite for the correct choice of a dexterity test.

Another reason for the low level of utilization of dexterity tests is that there is a general lack of knowledge of the psychomotor field by industrial and personnel psychologists. A perusal of journals which deal with personnel selection reveals the indiscriminate use of terms such as "motor ability", "eye-hand co-ordination" and the like, with little regard to the exact meaning of these terms. Fleishman and Hempel (1954a) report that the term "manual dexterity" is often used as though it were a unitary ability, despite the fairly well publicized differentiation between finger and hand dexterity.

Part of the problem possibly relates to the rather lack-lustre image of psychomotor research. The problem has undoubtedly been aggravated by unsubstantiated claims made by some test distributors (see Buros, 1949, pp. 684-685 and p. 700).

Most tests of manipulative dexterity have their origins in tests hastily developed to meet the manpower needs of the First World War. Although subsequent modifications have resulted in tests which are, to an extent, specialized, only a few of these approach the level of factorial purity desired of selection tests (Fleishman & Hempel, 1954a). It is generally found that dexterity tests have lower test-retest reliability than most other ability tests. This low reliability complicates the validation of dexterity tests and the study of their psychometric properties. Research which has examined the "microstructure" of performance on dexterity tests has revealed sources of random error variance which are a consequence of specific design defects common to a large number of these tests (Corlett <u>et al.,</u> 1971). Despite suggestions by Fleishman and others for the redesign of dexterity tests, remarkably few improvements have been effected.

The last decade or so has seen a tremendous surge in the development of computerized tests of intellectual abilities, but there has been almost no equivalent development in the assessment of manipulative dexterity. Apart from relatively few isolated cases where computerized tests of "motor ability", in the form of tapping and tracking tests, have been developed for the assessment of performance in hostile environments (Bittner <u>et al.,</u> 1986), or for the selection of military pilots (Hunter & Burke, 1987), virtually nothing has been done to automate any of the well-established dexterity tests.

An area of industrial research which has developed techniques applicable to the design of dexterity tests is that of motion and time study. Motion and time study analysts have developed various types of apparatus to measure the "elemental motions" which are believed to form the basis of manual performance. In spite of the rejection by psychologists of the theoretical assumptions of motion and time study, its observational techniques and attendant instrumentation have found their way into a few research programmes concerned with the design of dexterity tests, with largely beneficial results (e.g., Drewes, 1961; Salvendy, Corlett and Seymour, 1970; Corlett et al., 1971; Salvendy, 1975; Okada, 1985).

Although it is 35 years since suggestions were first made for the improvement of dexterity tests by automation and the incorporation of techniques akin to motion and time study (Harris and Smith, 1953), it appears that the only test commercially available which employs these principles is a test developed in one of the above-mentioned research programmes: the One-Hole Test (Salvendy, 1975). The lack of interest in this type of test has not been due to the unavailability of instrumentation, as fairly sophisticated apparatus for automated assessment of work performance has been in existence since the Second World War (e.g., the SETAR apparatus of Welford, 1951). However, a problem with many of the earlier instruments was their size, weight and cost. With the advent of the extremely versatile and inexpensive Personal Computer, this picture has completely changed.

This report will review the development and application of apparatus used in motion and time research, and will evaluate the possibility of utilizing similar apparatus in computer-controlled tests of manipulative dexterity. An attempt will also be made to determine the extent to which the theory and methods of motion and time study can be utilized in the specification of such tests. Theoretical work on the structure of psychomotor abilities will be reviewed, and the feasibility of developing a battery of tests for use in a wide variety of applications will be discussed.

2. THE STRUCTURE OF PSYCHOMOTOR ABILITIES

In the development of any psychological test, a knowledge of the factorial structure of the ability in question can be of assistance in item design; this knowledge also enables the test developer to make more accurate predictions about the criteria with which the test should correlate. In this chapter an outline of factor-analytic studies of psychomotor performance will be given. Emphasis will be placed on work done by E. A. Fleishman in view of the important contribution he has made to the understanding of the structure of psychomotor abilities. Fleishman's taxonomy of psychomotor abilities forms a reasonably sound basis for the design of tests for several reasons: (1) the samples upon which the factor analyses were based were often very large; (2) the invariance of factors was confirmed in different studies over a number of years; and (3) the "boundaries" of factors were investigated in studies which combined the techniques of factor analysis and experimental psychology.

2.1 Specificity of motor skills

Research on motor performance done in the first three decades of this century established as a general principle the distinction between the gross co-ordinations of athletics and certain outdoor vocations, and the fine co-ordinations involved in other manual skills (Seashore, 1951). The latter are distinguished by speed and/or precision rather than by strength, and the size of movements is smaller and usually involves the upper limbs - in particular the arms, hands and fingers. This report will put greater emphasis on these finer motor abilities, due to their overriding importance in a large number of industrial tasks.

When simple reaction time is measured with different muscle groups used in the response, high inter-correlations (>0,8) between various muscle groups are obtained, indicating that musculature itself is not a major factor underlying individual differences in motor skills. These high inter-correlations have led some researchers to postulate a general motor ability (Campbell, 1934, in Seashore, 1951); however the fallacy of this argument is revealed when patterns of movement are taken into account. In a visual simple reaction time experiment, for example, reaction times for responses involving a movement of 1 mm correlate only 0,45 with reaction times for responses in which a movement of 150 mm is made. Changing the pattern of the larger movement reduces the correlation further to 0,15 (Seashore, 1951). Another example of this high degree of specificity was shown by Seashore, Buxton and McCollom (1940) who found no correlation at all between visual simple reaction time and maximal tapping rate with the same hand and using the same key.

The absence of even moderate inter-correlations among different measures of motor performance rules out the existence of any general motor ability; however, group abilities have been identified within which individuals tend to rank consistently low or high over a (fairly narrow) range of related motor behaviours.

2.2 Fleishman's taxonomy of psychomotor abilities

In a series of studies done in the 1950s, Fleishman applied the technique of factor analysis to a wide variety of tests of motor performance, and with the help of a number of experimental studies developed a comprehensive taxonomy of human psychomotor abilities, both gross and fine (Fleishman, 1953, 1954, 1958a and 1958b, 1964; Fleishman & Hempel, 1954a, 1956;

Hempel & Fleishman, 1955). Eleven "perceptual-motor" factors and nine factors relating to physical proficiency appeared to account for the common variance in these studies.

Because each factor represents consistent individual differences over a range of related performances (albeit rather narrowly circumscribed), Fleishman maintains that each represents an ability, defined as a general trait or organismic factor that the individual brings with him/her when he/she begins to learn a new task. Ability must be distinguished from skill, which refers to the level of proficiency of an individual on a specific task such as flying an aircraft, or soldering an electric circuit. It is assumed that the skills involved in complex activities can be accounted for in terms of more basic abilities.

Fleishman (1972) has provided an overview of the methods and results of his research programme, and has summarized the perceptual-motor abilities as follows:

(1) Multilimb Co-ordination: the ability to to co-ordinate the movements of a number of limbs simultaneously in operating controls. This is general to tasks that require co-ordination of two feet, two hands, or hands and feet.

(2) Control Precision: highly controlled and precise muscular adjustments of controls where larger muscle groups are involved, extending to arm-hand as well as to leg movements.

(3) Response Orientation: rapid selection of controls to be moved, or directions to move them in.

(4) Reaction Time: speed with which the individual is able to respond to a stimulus when it appears, independent of the type of stimulus (visual or auditory), and independent of the type of response.

(5) Speed of Arm Movement: the speed with which an individual can make a gross, discrete arm movement when accuracy of movement is not a requirement.

(6) Rate Control: the precise timing of continuous responses relative to changes in speed and direction of a continuously moving target or object.

(7) Manual Dexterity: skilful, well directed arm-hand movements in manipulating fairly large objects under speeded conditions.

(8) Finger Dexterity: the ability to make skilful, controlled manipulations of tiny objects, involving primarily the fingers.

(9) Arm-Hand Steadiness: the ability to make precise arm-hand positioning movements where strength and speed are minimized. This is general to tasks requiring steady limb position or movement of the limb steadily in a lateral or to and from plane, and best measured by tasks recording arm tremor.

Finally, there are two very specific factors measured best by printed tests:

(1) Wrist-Finger Speed: rapid tapping of a pencil in relatively large areas.

(2) Aiming: dotting in a series of circles less than 6,3 mm diameter in highly speeded printed tests

2.3 Limitations of the taxonomy

Despite the thoroughness of Fleishman's work, there is no guarantee that this list of perceptual-motor abilities is exhaustive. In more recent studies of performance on very complex multidimensional tracking tasks, Parker and Fleishman (1960) have shown that the amount of variance accounted for by the above abilities is as low as 25% (compared with 60% found in earlier studies with simpler criterion tasks). While this magnitude of prediction may be significant from the point of view of conventional testing, it does suggest that more comprehensive theories of motor control and learning need to be developed. These should facilitate the design of more powerful tests of psychomotor ability.

The small amount of variance overlap found in the study of Parker and Fleishman (1960) can be attributed to two factors: (1) the use of different "control laws" on the criterion task compared with those of the tests (these relate control stick movement and movement of stimuli); and (2) the criterion appeared to require the ability to time-share different tasks. Parker and Fleishman noted that the abilities contributing towards performance on tasks such as this appear not to fall within the sphere of "psychomotor" abilities - "observing" and "prediction" seem to be more important. These abilities appear to involve a greater degree of central information processing, and their relationship to other cognitive processes has not yet been fully determined.

While factor analysis has confirmed the absence of a general factor of motor ability, it is not really clear to what extent this has helped the development of a general theory of psychomotor performance. Smith and Smith (1962) are fairly critical of factor-analytic work, and note that:

> "the factors identified ... are characteristics of motion which might be identified from direct observation of the performances involved. In other words, the statistical procedures do not extract much more than one might get from superficial observation ... Such [taxonomic] systems may have some practical value in describing tasks or devising tests, but they have little scientific significance. The specificity of movements is such that they resist classification in the most general of terms."

Some psychologists have also denied the psychometric meaningfulness of Fleishman's factors, and prefer to give them the status of "bloated specifics", or "pseudo-factors". These can result from the inclusion in a factor analysis of tests or test items which show high inter-correlation simply because the differences between them are, in essence, trivial (Kline, 1979).

In defence of Fleishman, it must be pointed out that the use of the experimental paradigm in several of his studies has added both empirical and theoretical support for the meaningfulness of these factors (e.g., Fleishman, 1957). The application of a task taxonomy based on Fleishman's system has on several occasions helped to unify apparently disparate experimental results (e.g., Levine, Romashko & Fleishman, 1973). It is the utility of the taxonomic system <u>outside</u> a factor-analytic context which confers theoretical respectability.

Recent research on motor control and learning has taken place within the information processing paradigm, and it is not yet clear whether this approach will be able to throw much light on the factors underlying the psychomotor abilities identified by Fleishman (but see Sections 3.1 and 4). Much of this research has been oriented towards the description of the mechanisms of motor control, and variance due to individual differences is simply regarded as error. A problem with the more recent research is that the term "psychomotor" has taken on a new meaning. On the one hand classically designated "sensory" and "cognitive" processes have been labelled "motor" (Weimer, 1977, in Whiting, 1980), while on the other hand theories of motor control have taken on a distinctively cognitive flavour, with terms such as "schema", "motor program", "module", etc., abounding (Whiting, 1980).

There is no doubt that the elucidation of "bridging" principles, which determine the nature of the interaction between lower-order psychomotor processes and higher cognitive structures, is to be welcomed. Cognitive psychologists such as Bruner (1973) and Piaget (1953) have shown how important the development of sensorimotor schemas in the first few years of the infant's life are to the later formation of symbolic systems of representation. Bruner goes as far as saying:

> "For it is my conviction ... that the manner in which the hands are mastered by skill, how they achieve their full adaptive application, can tell us much about the nature of human problem solving and thought."

The formation of control processes which can regulate action patterns according to some internal representation of a desired state embedded within the spatio-temporal characteristics of the external environment is the first step towards the formation of higher-order cognitive structures. This pattern of organisation persists within the mature individual, as revealed by Verster (1982) who found that performance on a selection of tests could be characterized in terms of a hierarchical structure of processes: psychomotor processes were found to be at the lowest level of the hierarchy, with sensory encoding, perceptual transformations and conceptual strategy formation forming successively higher levels.

2.4 Implications for psychomotor test development

The extreme specificity of perceptual-motor skills dictates that the particular abilities required in a given job <u>must</u> be identified before appropriate selection tests can be determined. Failure to do this may lead to the choice of tests measuring inappropriate abilities, and will result in a battery with low validity. Ideally, every psychomotor selection test should be linked to a procedure designed specifically to help the personnel psychologist determine whether the abilities measured by the test match the job for which a selection test is required. Various systematic techniques for the determination of the "ability profile" of jobs have been developed for this purpose (e.g., Mallamad, Levine & Fleishman, 1980). However, much research still needs to be done, and the possibility remains that a particular job may involve some abilities not included in a task analysis based on Fleishman's taxonomic system.

Unfortunately, this virtually rules out the concept of a fixed battery of tests applicable to most industrial jobs, and implies that work-sample tests may have to be devised in some cases. However, Robertson and Kandola (1982) have shown that this may well be worth the effort, as work-sample psychomotor tests have been found to possess the highest predictive validity of all tests. In addition, they reduce the adverse impact of selection procedures on minority groups and are more readily accepted by job applicants.

As an alternative to the job sample approach, dexterity tests could possibly be designed to be modifiable to suit specific applications. This is where computerized testing excels, but the requirement for modifiable hardware is a problem. Such a test would have to be validated on the specific job concerned, and would not necessarily be of use in related jobs. In any event, the separate validation of dexterity tests for each application has been recommended by a number of researchers as

The "one best way" of performing the job is then determined by rearranging and deleting therbligs, and time standards of performance for the job are set by adding the times of all therbligs in the improved method. Although the validity of this approach is supposed to be ensured by the use of "scientific analysis" (Mundel, 1970), in practice the determination of time standards involves inadequate sampling and the application of arbitrary "normalization" procedures.

Depending on which work study system is used, up to 17 different therbligs may be defined. In studies where performance on simple assembly jobs or dexterity tests has been investigated, less complex systems limited to the therbligs Reach, Grasp, Move, Position, and Release have been employed. Turn and Disengage may also be included, but occur with considerably lower frequency in this type of task (Drewes, 1961; Corlett _et al.,_ 1971). In the case of simple assembly work, the instrumentation required to measure the time of onset and duration of Reach, Grasp, Move and Position is fairly straightforward and does not require the use of cinematography. Instrumentation for the measurement of therblig times will be discussed in detail in Section 6.

It must be stressed that the adoption of the observational techniques of motion and time study does not imply the endorsement of its theoretical assumptions. The attitude of psychology towards the theoretical basis of motion and time study can best be summed up by quoting Smith and Smith (1962):

> "The duration of a single movement depends on the configuration of physical conditions in which it occurs, as well as on its position within a motion sequence. Many configurational effects are significant, with travel-distance and movement-timing interactions especially so. The experimental results confirm ... that a movement cannot be specified or standardized independently of its integrative relationships with other movements and other variables. Work factor and methods factor systems of work specification have fundamental defects which cannot be adjusted out by any number of correction tables."

The fact that therbligs cannot be manipulated according to the assumptions of a linear, additive model has serious implications for test construction: if a dexterity test is to correlate with a job, it is important to ensure commonality of therblig pattern as well as therblig frequency distribution. Consequently, it is probable that valid tests of manipulative dexterity are likely to be similar to work-samples of the jobs for which they are being used.

In spite of the differences between the approaches of psychologists and motion and time study practitioners, researchers in the fields of cognitive development and motor skill acquisition are using concepts which bear a resemblance to the notion of elemental motions. Thus Bruner (1973) sees skilled activity as the formation of a program specifying an objective or terminal state to be achieved, and requiring the serial ordering of a set of constituent, modular action subroutines. In the infant these develop from two sources: the innate repertoire of action patterns, initially awkward, but gradually shaped into longer sequences, and also (more importantly) through the adaptation of initially gross acts to the spatio-temporal pattern of new tasks by segmentation or differentiation into component elements or modules. Once these action modules are refined to the extent that they become semi-autonomous, they acquire a generic quality, in that they can be incorporated into different motor programs in which the serial order of components can be re-arranged at will.

3.2 Work study methods in the measurement of dexterity

At least one test of manipulative dexterity (the One-Hole Test) owes its existence to the application of work study methods to the investigation of skill acquisition on assembly tasks. Seymour (1954, 1959) investigated the change in individual therblig times as a function of practice. The importance of looking at separate components of action had earlier been stressed by Bartlett (1947, 1948; in Welford, 1952), who pointed out that it is the form, order and timing of these, rather than overall achievement, which will enable researchers to gain an understanding of skilled performance.

Seymour observed that the decrease of cycle times followed the pattern typical of learning curves, but of particular interest was the fact that individual therbligs were not equally affected - stationary therbligs (Grasp and Position) improved more than movement therbligs (Reach and Move). Although some of this difference was due to a decrease in the frequency of fumbles, the principal improvement arose from a shift in the distribution of therblig times so that the proportion of shorter times increased relative to the proportion of longer times, while the minimum therblig time remained constant.

Seymour also noted that subjects differed in their ability to select shorter responses, and that the number of cycles required to achieve a given degree of proficiency varied appreciably from one subject to another. He suggested that the rate of change in therblig time distribution might provide a measure of individual suitability for assembly jobs of the type under investigation. Furthermore, the average rate of change in therblig distributions could provide a measure of the difficulty of different tasks.

Corlett, Salvendy and Seymour (1971) noted that the capacity to improve in performance on a task is often more important than capacity to perform at a given level. This is especially true in the context of modern industrial development where frequent technological change requires operatives to quickly attain an acceptable level of performance on new tasks. They also noted that a measure of the improvement in therblig times would provide a more sensitive measure than total cycle time, as these manifest clear systematic changes sooner than do total cycle times. In order to investigate the change in therblig times with practice on tests of "manual dexterity for fine work" (i.e., Finger Dexterity), the O'Connor Finger Dexterity Test and the Purdue Pegboard were adapted to enable the measurement of therblig times.

In the exploratory phase of this study, Corlett et al. (1971) found that repetition of these two tests was accompanied by only slight improvement in times for the therbligs Reach, Grasp, Move and Position. At first it seemed as if this might have been due to the subjects being prevented from developing consistent response patterns, due to the change in angles and distances of movement from bins to holes as they proceeded through the tests. A modified Purdue Pegboard was then developed, in which pegs had to be inserted into a single "bottomless" hole, making the physical limits of the therbligs Move and Reach nearly constant. Therblig times were then recorded for from 300 to 500 cycles on each test.

These modifications resulted in subjects taking 18% less time to complete each cycle. Reach, which had the least variability, improved more than any other therblig or the cycle as a whole. The mean and standard deviation times of the therbligs Grasp and Position seemed to be governed by the number of fumbles.

Since it was evident that the performances being investigated were more complex than realized at first, high speed motion picture films were made of one subject working at the three tests. The mean time per cycle, the standard deviation, and the number of fumbles were found to be heavily dependent on the subject's method of using her fingers and thumbs, and on whether or not the subject looked closely at what she was doing at critical moments in the cycle. It was evident that the random distributions of pegs in the bins and the varying angle and distance of movement in the tests prevented the subject from adopting a systematic pattern of performance.

Corlett et al. (1971) concluded that the Purdue Pegboard and the O'Connor Finger Dexterity Tests are inherently too variable and insufficiently well controlled to be used as tests of speed-skill acquisition. The variability of the modified Purdue Pegboard, although reduced, was still unacceptably high. These poor design features were probably one of the main reasons why dexterity tests had developed a bad reputation in industry.

The modified Purdue Pegboard was again redesigned to reduce the error variance resulting from random positioning of pegs in the bin. In the new version (the One-Hole Test), pegs are grasped from a single point. Analysis of high speed films showed that the chance effects which were much in evidence in the original tests had been eliminated, and this significantly reduced intra-subject variance in times for therbligs Reach and Grasp (Salvendy et al., 1970; Salvendy, 1975).

The effect of all improvements was evident in the values of test-retest reliability measured on six groups of subjects in a validation study: this ranged from 0,21 to 0,80 for the Purdue Pegboard, and from 0,54 to 0,92 for the One-Hole Test. The correlation between the One-Hole Test and the Purdue Pegboard was 0,34. A significant observation was the lack of any correlation between the therblig times for Reach, Grasp, Move and

Position. This is yet another demonstration of the specificity inherent in motor skill, and verifies that the analysis of performance into therbligs adds potentially useful uncorrelated variables for the prediction of criterion performance.

An interesting finding was that only performance on later trials of the One-Hole Test (after 30 seconds) was significantly correlated with the criterion. The mean times of later performances in the therblig Reach, in particular, contributed markedly towards prediction of performance in two of the groups. Additionally, the change in performance over trials on the One-Hole Test had greater predictive power than the total score on the test. Salvendy (1975) reported that the weighted average concurrent and predictive validities (calculated from multiple regressions using the best predictors) were 0,66 and 0,75 respectively. This is markedly higher than the corresponding average validities of 0,2 and 0,4 quoted by Ghiselli (1966), and demonstrates the value of the application of motion and time study techniques.

An important point stressed by Salvendy et al. (1970) is that none of the 110 items of the full battery of tests was able to predict performance in all groups. This, together with the significant variation of test-retest reliability from one group to another, demonstrates the need to determine reliability and validity for each individual application.

Another of the very few examples of the application of motion and time study techniques to dexterity test development is that of Drewes (1961). Drewes maintained that many dexterity tests measure the performance of only single elementary motions, or limited combinations of them. He hypothesized that the predictive validity of a test which accurately duplicates the sequence of motion elements on a job would be greater than that of a test that does not intentionally do so. Although not specifically stated, Drewes was in fact maintaining that the high degree of specificity of motor skills is a consequence of a lack of common movement elements, or patterns of elements, from one skill to another.

A pegboard-type dexterity test was chosen for investigation because the therbligs Reach, Grasp, Move, Position and Release are present in almost every assembly job, and are essentially the same as those involved in placing pegs in a board. Although these therbligs are common to the two situations, additional variables, known as methods factors or work factors, had to be taken into account, as these can effect therblig times appreciably. Examples of work factors are: distance of movement, force exerted, perceptual complexity, and precision of movement. The Methods-Time Measurement (MTM) system of motion and time study was adopted for the purposes of job analysis and test design because it takes cognisance of these factors.

In order to simulate the MTM element Position, three methods factors were taken into account: (1) class of fit (determined by the clearance between peg and hole); (2) symmetry (infinite - circular peg, constrained - square peg, and single assembly position - pentagonal peg with unequal sides); and (3) ease of handling (using pegs of two lengths which could by MTM standards be classified as easy and difficult to handle). Bi-manual operations were also built into the test by designing boards as bins filled with small blocks so that the blocks could be removed from bins with both hands during the test. The experimental test model consisted of 14 boards and 18 sets of pegs, and was named the Purdue Elemental Motions Tests (PEMT).

Validation was carried out on a sample of 72 subjects working on nine "bench" jobs involving manual operations in which a high degree of dexterity appeared to be essential. The performance criterion was an efficiency index indicating a worker's productivity in relation to standards established by the company. Each subject was given four tests: the Minnesota Rate of Manipulation (MRM) Test (Turning subtest), two variations of the PEMT (those which best simulated the motions of the jobs in question), and a third variation of the PEMT whose motion patterns were intentionally mismatched with those of the job (the "Least Appropriate PEMT"). Both variations of the Most Appropriate PEMT were found to exhibit significant validity computed over all nine jobs. The Least Appropriate PEMT and the MRM did not show any validity. No test showed validity for five non-assembly jobs included in the study as a control.

Drewes' study is of significance as it verifies the need for commonality of therbligs and work factors between test and job. This can be ensured by undertaking a micro-analysis of job performance before embarking on test design. If this analysis is based on the formal procedures of a motion and time study method, the amount of guesswork involved can be substantially reduced. Dexterity test publishers should ideally provide a detailed specification of the therblig structure of a test, expressed in the terms of a standardized system such as MTM.

To summarize, the principal benefits to be gained from the application of motion and time study techniques are:

(1) Micro-motion analysis provides a systematic procedure for the analysis of manual tasks. The detailed specification of the therbligs and work factors pertaining to a given job take the guesswork out of the choice or design of appropriate dexterity tests.

(2) Work study techniques have been able to identify the causes of the low reliability of dexterity tests.

(3) It has been shown that the times for some therbligs (and the change in these times) are more predictive of criterion performance than are scores for the test taken as a whole.

(4) Instrumentation developed for motion and time study may be adapted for use in tests of manipulative dexterity. Individual therblig times can be measured very conveniently by interfacing the test apparatus with a Personal Computer.

4. THE FITTS TAPPING TASK

Fitts (1954) proposed an information-theoretic index of difficulty for motor responses which has turned out to be very useful for the prediction of movement times in many tasks, and which also has potential for the assessment of individual movement capacity. The index accounts for the close relationship which has been observed between the speed, amplitude and accuracy of movements. Fitts hypothesized that if the amplitude and tolerance limits of a task are controlled by the experimenter, and the subject is instructed to work at his maximum rate, then the average time per response will be proportional to the minimum average amount of information per response demanded by the particular conditions of amplitude and tolerance.

The most commonly used test of Fitts' "Law" has been a reciprocal tapping task in which the subject has to alternately tap with a stylus two rectangular metal plates as rapidly as possible, and with minimal errors. Movement tolerance and amplitude are controlled by varying the width of the plates and the distance between their centres respectively.

The index of difficulty proposed by Fitts is:

$$I_d = -\log_2(W_s/2A) \quad \text{bits per response} \quad . . . . (i)$$

while the index of performance is given by:

$$I_p = -(1/t)\log_2(W_s/2A) \quad \text{bits per second} . . . (ii)$$

where W_s is the tolerance range (target width), A is the average amplitude of movement (distance between the centres of the targets), and t is the average time per movement.

In Fitts' (1954) study, the index of performance for the best eight out of 16 combinations of W_s and A varied between 10,3 and 11,5 bits per second - a range of only 1,2 bits - but performance at the extremes of difficulty tended to fall off. Although the latter variation rules out the possibility of a fixed channel capacity for all movements, the law does seem to describe human movement performance over a remarkably wide range of tasks, from the reciprocal tapping task described above to the peg cr washer transfer tasks encountered in many tests of manipulative dexterity. Fitts and Peterson (1964) found that the law could also be applied to discrete movement times in a two-choice reaction time task.

Fitts (1954) predicted that different muscle groups would have different rates of information generation. Langolf, Chaffin and Foulke (1975), in an experiment with movement amplitudes ranging from 0,25 cm to 30,5 cm, found that this is indeed the case. The small amplitude task involved the transfer of a miniature peg which subjects manipulated by means of a special handle while observing the "pegboard" through a microscope. For the smallest movements (involving the fingers only) the rate of information generation was 38 bits per second, while for movements involving the wrist the rate dropped to 23 bits per second. Longer distance arm movements showed a much lower rate of 10 bits per second - a replication of Fitts' (1954) results.

The finding that different muscle groups have differing rates of information generation throws some light on the mechanisms which may underlie the psychomotor abilities identified by Fleishman. It seems probable that muscle groups having similar rates of information generation would be more able to form co-ordinated groups in the execution of a particular movement than muscles with differing information rates. The formation of such "synergies" (Bernstein, 1967) could well be the basis for some of these abilities, in particular those requiring a high degree of inter-muscle co-ordination such as Control Precision, Multilimb Co-ordination, Hand Dexterity and Finger Dexterity.

Rearranging equations (i) and (ii) we get:

$$MT = a + bI_d . . . .(iii)$$

where MT is the mean movement time, and a and b are empirically fitted regression constants, with the slope parameter b being the inverse of the motor information generation rate.

When I_d is used as a predictor of movement times the result is frequently highly successful, with more than 90% of the variance being accounted for (Langolf et al., 1975). The relationship between I_d and MT seems to be more or less constant, irrespective of the amount of practice, and therefore the value of the slope parameter b, calculated for an individual, could be used as an index of the individual's capacity to make accurate and rapid positioning movements. It may even be possible to calculate the information rate attributable to the Grasp and Position components of a pegboard task by finding the difference between MT for tapping from hole to hole (without pegs) and MT for movements over the same distances, but including the insertion and extraction of pegs.

Of somewhat academic interest is the assertion by Kvalseth (1979, 1981) that Fitts' formula for I_d is based on an incorrect analogy with Shannon's (1948) theorem 17. Using a measure that has a rigorous information-theoretic foundation, Kvalseth has shown that the maximum rate of information generation in discrete, single, one-dimensional arm movements is between 22 and 24 bits per second, i.e., at least twice the rate calculated by Fitts' formula. The advantage of Kvalseth's measure is that it can be applied to two-dimensional movements, and also gives a meaningful result when $W_s = 0$, i.e., when the target is a line. Kvalseth's approach does not invalidate Fitts' Law - only the information-theory interpretation of it is disputed. He admits that Fitts' Law appears to account very well for an immense amount of empirical data, although there is evidence that a power law provides a better fit in some cases.

Of considerable interest is the possibility that maximum tapping rate may be a reflection of a fundamental limit to neurological function. Keele and Hawkins (1982) reported that speed on many tasks seems to be constrained by the rate at which a person can serially activate a succession of movements. They found that maximum tapping rate correlated substantially across a diversity of articulators (finger, thumb, wrist, arm and foot), suggesting that tapping speed is a fairly general factor that cuts across several different muscle systems. It was also found that tapping rate averaged across articulators correlated 0,63 with normal (i.e., unspeeded) handwriting speed, but did not correlate with large writing using arm movements analogous to writing on a blackboard. Keele and Hawkins hypothesized that this difference was due to the fact that normal handwriting is highly over-learned, while the subjects in the study had had little practice at blackboard writing.

The effect of practice can explain the somewhat contradictory research findings concerning the relationship between tapping rate and typing speed which have been reported in the literature. Seashore (1951) reported no correlation between tapping rate and the typing speed of inexperienced high school students. However, Book (1924) found that the tapping rate of highly skilled professional typists was about 25 to 33 per cent higher than that of matched controls (who were non-typists). The tapping rate of nonprofessional typists was only slightly higher than that of the controls.

This finding could have been due to an increase in tapping rate as a result of typing practice. To control for this factor, Book (1924) followed a group of learner typists through a typing course, and found that maximum tapping rate did not change over the period between being a novice and being an expert typist.

These results seem to imply that it is the factors underlying maximum tapping rate which determine the ultimate speed a typist may reach. This is similar to the finding by Fleishman and Hempel (1954b) that the correlation between Complex Co-ordination scores and Speed of Arm Movement scores increases as subjects receive more practice at Complex Co-ordination. The fact that tapping rate is a good predictor of terminal performance makes it fairly unique amongst psychomotor abilities in general, most of which tend to decline in predictive power as individuals gain expertise on a criterion.

5. COMPUTERIZED DEXTERITY TESTS: DESIGN PRINCIPLES

In order for an apparatus test battery to be cost-effective, the apparatus should ideally be constructed so that as many psychomotor abilities as possible can be measured. To be realistic, however, it is necessary to limit the number of abilities to those which can be assessed by a single, multi-purpose apparatus small enough to stand on a table next to a microcomputer. The abilities measured should be those manipulative dexterities most often required for effective performance in manufacturing industries and other industries requiring manipulative dexterity.

Taking the psychomotor abilities identified in Section 2 as a starting point, the following abilities appear to be candidates for inclusion in a battery of dexterity tests:

(1) manual dexterity,
(2) finger dexterity,
(3) tweezers (or small instruments) dexterity,
(4) speed of gross arm movement,
(5) speed of fine wrist-finger movement.

Bearing in mind the problems associated with the design of dexterity tests mentioned in Section 3, it would be foolish to ignore the lessons learned from previous research. The most important are the following:

(1) Each test must be long enough to ensure adequate reliability. Using the work of Bass and Stucki (1951) as a guide, it would appear that a pegboard test should involve approximately 50 cycles of peg placing operations. This could possibly be reduced if the test design promotes reliability, as explained below.

(2) In pegboard tests, care must be taken to reduce the error variance inherent in these tests, i.e., grasping of pegs should not be complicated by random orientation of the pegs. Possibly

the most satisfactory way of accomplishing this is by having the pegs seated in holes at the beginning of each test, thus requiring the subject to extract pegs from one column of holes and insert them into another. The distance between columns will depend on whether the test is designed to measure finger or hand dexterity (the distance being greater in the latter case).

(3) In tests of manual and finger dexterity, the Movement therblig which comes between Grasp and Position should not change appreciably from one cycle to the next. This implies that: (i) pegs should not have to be obtained from a bin as in many traditional dexterity tests; and (ii) the empty hole should be in a fixed position relative to the hole-with-peg. If pegs are are arranged as described in (2) above, this condition will be very nearly satisfied. The gradual movement of the arm and hand towards the body as the subject progresses through the test cannot, however, be avoided.

(4) In tests of finger dexterity, large movements of the arm or hand should be avoided. The distance between the hole-with-peg and the empty hole should be small enough to ensure that the Move and Reach therbligs involve wrist movement only.

(5) It should be possible to accommodate different work factors (e.g., fit, symmetry, and ease of handling) so that tests can be customized for maximum performance in individual applications. Customizing can be achieved most easily if the apparatus is constructed as an assembly of modules.

(6) The apparatus needs to have dimensions of at least 50 cm if the speed of gross arm movement is to be measured.

Another factor which needs to be considered is the need for tests involving bi-manual operations (the co-ordination of both hands) as well as single-handed operation. The Purdue Pegboard is a good example of a test which is specifically designed to assess bi-manual operations. In this test the first two sub-tests involve single-handed placement of pegs using the right and left hands respectively. In the third subtest, both hands are used in synchronized placement of pegs into two adjacent columns of holes. The last subtest involves the construction of peg-washer-collar-washer assemblies. Tiffin and Asher (1949) emphasize the importance of the simultaneous operation of both hands in this subtest, i.e., while the subject is inserting a peg with his/her right hand, the left hand must be grasping the first washer, etc.

An example of a computerized apparatus for the assessment of "upper-limb function" which embodies some of these principles is the Sensor Pegboard, developed in Japan for the selection of workers for industries requiring fine dexterity (Okada, 1985). The philosophy behind this test is that the test method should be "capable of dividing manual dexterity ... into several multiscale items ranging from simple to complex levels."

The test apparatus, a pegboard with a number of touch-sensitive surfaces, measures approximately 24 cm by 33 cm, and is designed to enable the administration of eight separate tests. These range from a simple tapping test through dexterity tests requiring the extraction and insertion of pegs, and finally to a multiple choice test of Response Orientation where the subject has to tap various patterns on the pegboard according to patterns or symbols displayed on the microcomputer screen. The length of each test is optimised to allow learning effects to stabilize, resulting in a test battery which is reported to be both efficient and reliable. (Unfortunately, reliability coefficients are not quoted in the article.)

6. INSTRUMENTATION FOR THE MEASUREMENT OF WORK PERFORMANCE.

As mentioned in Section 3.1, one of the earliest techniques for data gathering employed by the Gilbreths was high speed cinematography. Although this technique is still in use, vast amounts of film are consumed and excessive time is spent in analysis of the film on a frame-by-frame basis. This has encouraged the development of other methods of work measurement which are more suited to application in tests of manipulative dexterity.

The simplest systems measure the times of onset and offset of a sub-threshold electric current flowing through the subject's body as he/she makes or breaks manual contact with the various objects or controls which are manipulated in the task. In apparatus constructed before the computer era, the making or breaking of the current triggered electronic "flip-flop" circuits to start or stop precision timers or other recording devices. In more recent applications, the on/off signals are conditioned for interfacing with a microcomputer, which then starts or stops timing subroutines on an interrupt basis. A typical setup illustrating equipment for motion analysis of an assembly-type job is shown in Figure 1.

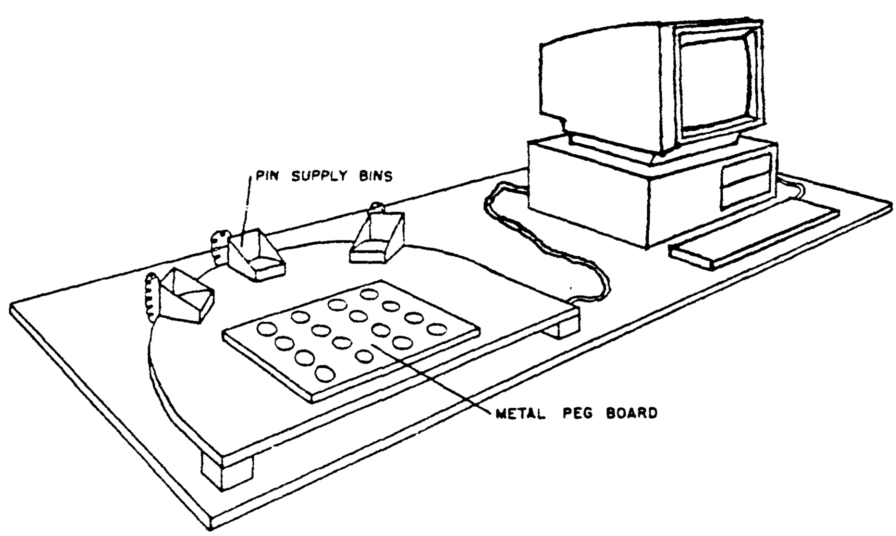

Figure 1. Apparatus for the measurement of assembly work (adapted from Smith and Smith, 1962).

In a system such as this, measurement of therblig times would proceed as follows:

(1) The subject starts with his hand in contact with (for example) a metal pegboard at a standard starting position. A small current flows from the pegboard through the subject's body and to an electrode attached to the subject's ankle (or other hand, if this is not being used).

(2) At the "start" signal, the subject raises his hand and moves it towards a bin containing pegs which are to be inserted into the pegboard holes. The break in contact between hand and pegboard causes the Reach timer to commence timing.

(3) When the hand makes contact with a bin, an electric current is again set up, causing the Reach timer to stop and starting the Grasp timer. Any fumbles (rapid making and breaking of contact with the peg/bin) are recorded here.

(4) When the hand holding the peg breaks contact with the bin, the Grasp timer is stopped and the Move timer is started.

(5) When the hand/peg makes contact with the metal pegboard near the hole, an electric current causes the Move timer to stop and starts the Position timer.

(6) As soon as the peg is correctly inserted into the hole (indicated by a microswitch), the Position timer is stopped and the cycle is completed. The next cycle begins when the subject lets go of the peg, thus starting the Reach timer.

In older equipment the clocks measuring therblig times simply recorded cumulative time for each therblig over the duration of a "test". A microcomputer-based data logger is able to store each time measurement in memory so that a more sophisticated time series analysis can be performed off-line if required. The flexibility of a computerized system enables many different types of tasks to be studied with a minimal change to software. Examples of tasks which have been studied are panel control operations, dial setting and scale setting movements, assembly operations and handwriting (Smith and Smith, 1962).

6.1 Electronic sensors for the detection of movements

Hancock and Foulke (1962) list several classes of input device used in laboratory and industrial situations. The most frequently employed are position indicators, used to determine when a motion arrives at or passes a fixed point. These include:

(1) Microswitches, which can be positioned in a work station so as to be tripped by the placing of an object or the movement of a lever.

(2) Contact devices, which indicate the touching of an object by an operator by providing an electrically conductive surface in the work station (which itself is electrically insulated from ground). A very sensitive electronic circuit detects the small electric current flowing from the object through the subject's body.

(3) Photocells, which can be used to indicate the presence of an object or the operator at a specific location by the interruption of a light beam.

(4) Potentiometers, which can be used to determine the amount of displacement of a handle or a shaft.

(5) Deflection devices, such as a leaf spring with a strain gauge attached, which can be utilized for position measurement. The deflection of the spring gives rise to strain which causes the resistance of the strain gauge to vary.

(6) Capacitative switches, flush with a surface and electrically insulated from ground, which can detect the presence of the operator by sensing the 50 Hz mains electric field which is concentrated near the operator.

Other indicators give information about different variables: Strain gauges can be used to provide analogue signals proportional to the force exerted on an object such as a lever. Accelerometers output an analogue signal proportional to the acceleration being experienced by an object (accelerometers have a single axis of activity, and can thus only be used effectively when the orientation of this axis is constant).

Pressure sensitive paint has an electrical resistance which varies with the force exerted on the surface on which it is painted. It can be used to detect when an object (of appreciable mass) has been removed or placed on a work surface.

Other more exotic techniques have been evolved recently. Fleischer and Lange (1983) employed an electroacoustic technique which has the advantage of enabling the recording of hand position without the need for any intermediate contact device such as a lever or switch. A small piezo-electric ultrasound transmitter is mounted on the back of the subject's hand. Three ultrasound-sensitive microphones located above the work station detect the exact time of arrival, and thus the delay time, of 32 kHz pulses emitted 50 times per second by the transmitter. Using this information, the exact location of the transmitter in three-dimensional space can be calculated off-line. If a transmitter of the correct combination of size and frequency is chosen, a point source can be approximated, and a resolution of 1 mm can be achieved. If hand velocity is less than 1 m/s, the Doppler effect can be neglected.

While this apparatus is unlikely to find much application in anything but basic research, a more likely candidate for use in a selection test is the Digitech described by Kvalseth and Mohn (1983). This is a fully automated motor control test facility built around a microcomputer-digitizer combination, and was designed with three requirements in mind: (1) to be applicable to the various proposed experimental paradigms concerned with spatial and temporal variables affecting movement, such as those of Fitts (1954), Fitts and Peterson (1964) and Kvalseth (1979, 1981); (2) to provide the values of those measures of performance that have been proposed by various researchers; and (3) to be capable of analysing both one- and two-dimensional movements. The apparatus is built around a digitizer - a flat, graphic tablet which can sense the co-ordinates of a stylus held by the subject on its surface.

The digitizer in Digitech has a resolution of 0,064 mm - for non-research purposes resolution would not have to be as high as this. The particular digitizer chosen was relatively cheap, and both the digitizer and stylus were of robust design so that the subject could exert considerable force without damage to either component.

The advantage of such an apparatus is that the information-processing capacity of the motor system can be measured in a wide variety of different positioning tasks. Due to the interactive nature of the digitizer-microcomputer system, performance feedback can be provided in real time, and the response of the subject to different learning paradigms, for example, may be assessed.

A drawback of this technique is the appreciable cost of the digitizer: by 1982 prices in the U.S.A., the cost of the digitizer alone was more than 50% of the cost of the microcomputer. While this reduces the cost-effectiveness of the apparatus for the private user, its versatility is such that it could probably pay for itself when used at a test centre.

It is possible to assess performance in certain positioning tasks by using the Video Display Unit (VDU) of a computer for the display of visual information, and requiring the subject to touch marked areas on the screen. If a touch-sensitive screen is used, the position of the subject's finger can be obtained without further instrumentation; with ordinary VDU or television screens a light pen could be employed for this purpose.

A possible drawback of this technique is that the dimensions of the VDU screen limit the scope of arm movements considerably. This could to some extent be overcome by using a larger television screen. Also, where a light pen is used, there is always a possibility that extremely rapid movements (as in the Fitts tapping task) could be associated with the exercise of a considerable amount of force, which has the potential to damage the light pen and the screen. Although light pens are available with a rubber tip (Ridgway, MacCulloch and Mills, 1982), the safety of the system would have to be evaluated carefully before the test is put on the market.

A drawback of the touch-screen method is that its resolution for the determination of finger co-ordinates is much less than the resolution for visual stimulus generation. As an example, in the PLATO system the VDU resolution is 64 characters by 32 lines, whereas the touch-sensitive system registers position on a 16 by 16 grid. As a consequence of this, the accuracy of a given positioning movement can only be measured very grossly. The capability of the light pen method appears to be superior in this respect.

The use of a keyboard seems, on the face of it, to be the obvious method of response measurement for tests which assess tapping rate. There are, however, several factors which must be taken into account when considering a keyboard for this purpose: (1) tapping (especially the tapping of alternate keys) may involve the exertion of considerable force which, in the long term, can lead to the premature failure of the key switches concerned; (2) tapping rate is a function of both the size and separation of the targets, and the test constructor may, therefore, want to vary both in a tapping test; and (3) a keyboard may disadvantage subjects who are relatively "keyboard naive".

Keyboard tapping primarily involves movements of the fingers, hand and wrist, and therefore a keyboard should not be used in a selection test for jobs where extensive arm/hand movements are important (e.g., packing or sorting fruit on a conveyor belt). In cases such as this, a customized response panel would be the better choice. The need for an accurate duplication of arm and hand movements follows from the factor-analytic work described in Section 2. In addition, as mentioned in Section 4, it is known that the information capacity for movement of different articulators differs substantially. Failure to duplicate the extent and timing of the movements of a job can therefore give a misleading indication of the capability of the subject. If the job requires extensive arm movement while the test only allows for hand/wrist movements, a grossly inflated estimate of the subject's information capacity for large movements will be obtained.

A legitimate use of the keyboard would be in a test designed to select individuals for an occupation where movements similar to typing are involved - for example, data entry, using an adding machine, operating a keyboard-type control panel, etc.

Cory, Rimland and Bryson (1977) have noted that one of the principal advantages of computerized tests over paper-and-pencil tests is the ability of the former to present moving stimuli, and to measure the subject's response when this varies on a continuous basis. It is not surprising, therefore, that computers have been used for the assessment of tracking performance and reaction time for a much longer period than the recent history of computerized psychometric testing would tend to suggest. Another impetus for the development of computer-based tracking tests has been the important role tracking has to play in the military and aerospace fields (Kantor and Bordelon, 1985; Hunter and Burke, 1987).

This report will not discuss tracking tests in depth, as these tests are not useful for the assessment of manipulative dexterity. However, they will always be required for the measurement of Multilimb Co-ordination, Rate Control and Control Precision. Tracking tests are to a large extent unproblematic as computer tests, and there are numerous examples in the literature which the test constructor may use in test design. From the point of view of hardware, the implementation of a one-degree-of-freedom tracking task on a Personal Computer is simple if the computer is supplied with a games card which has a "joystick" input. For greater flexibility and accuracy, however, it is preferable that an instrumentation analogue input/output interface is used. This normally has provision for a number of analogue-to-digital and digital-to-analogue channels, and is therefore suitable for use in multidimensional tracking tests.

7. DISCUSSION AND CONCLUSIONS

The first commercially available tests of manipulative dexterity go back to the post World War One period. This literature survey has shown that dexterity tests have not, on the whole, advanced much since that time. Although the factor-analytic work of Fleishman and others has helped to clarify the structure of psychomotor abilities, and several design problems inherent to dexterity tests have been identified, this seems to have had little impact on the development of new tests or the revision of old ones.

Despite the inertia of test designers and distributors, a few researchers have done pioneering work which has pointed the way to new developments. The three most important conclusions to be drawn from this work are: (1) the low reliability of dexterity tests is to a large extent a function of test design, which results in changing stimulus conditions as subjects progress through the tests; (2) the validity of a dexterity test depends on the amount of overlap between the pattern of motion elements of the test and that of the criterion, and in addition work factors (e.g., class of fit, degree of symmetry, ease of handling, distances moved) are important; and (3) the breakdown of test performance into components yields scores which can be better predictors of the criterion than the score for the test as a whole.

The fact that these conclusions were all based on research which made use of the the methodology of motion and time study indicates that this methodology should be the basis for the design of future tests of manipulative dexterity. This can be accomplished at a fraction of the cost of the instrumentation used in the original research, thanks to the development of the now ubiquitous Personal Computer. In addition to the adoption of the measurement techniques of motion and time study, the use of its terminology for the specification of the therblig structure of dexterity tests should be encouraged. This will reduce the uncertainty when choosing or designing tests for specific applications. However, since a motion and time analysis of a job leads only to a description of the job's therblig structure, additional (psychologically relevant) information in the form of a psychomotor ability profile needs to be obtained before appropriate selection tests can be determined.

Procedures designed to provide a reliable estimate of the abilities required in a given job are available, and could be incorporated into a computerized battery of psychomotor tests. Alternatively, the application of such a procedure by the test distributor could be offered as a service to the test user.

An instrument for the determination of the ability profile of tasks, and which uses Fleishman's taxonomy of psychomotor abilities as well as other cognitive abilities, has been described by Mallamad *et al.* (1980). This involves a systematic procedure in which a series of binary decisions are made as to whether or not each of 40 abilities is required in the performance of a job or task. The sequence is organised in the form of a flowchart, and is therefore very amenable to computer implementation. The output of the instrument is a profile of the psychomotor and cognitive abilities important for efficient performance on the job in question, and a list of appropriate selection tests could, no doubt, also be provided. Mallamad *et al.* report that the decision flow diagram method is more reliable and superior to a rating scale approach for identifying abilities, but is best used in conjunction with rating scales, the former to identify required abilities and the latter to quantify the degree of involvement of each identified ability.

When the problems inherent in the use of dexterity tests are considered (in particular, their extreme specificity), it is evident that the development of a reliable method of job analysis, such as the instrument described above, should receive as much, if not more, attention as the development of the dexterity test battery. If this is neglected, then the full potential of computerized dexterity tests cannot be fully realized, despite the improved performance of these tests.

In order to exploit the power of modern technology to the full, it is desirable that a computer-based test of manipulative dexterity be able to assess as many components of dexterity as possible. The simplest approach would be to have a single apparatus sophisticated enough to encompass all the major tests. However, this may incur a cost penalty due to the large amount of built-in redundancy, and may not appear to be attractive to those who would only need to use a small portion of the system. In addition, the requirement that the apparatus be capable of modification to suit the motion patterns and work factors of a particular application is not easily met by this approach.

This problem is probably best countered by designing the apparatus around a modular concept. At the core will be a framework containing electrical connectors and the electronics necessary for interfacing with the microcomputer. Each test will be based on a plug-in module, the different modules being standardized in terms of physical dimensions and electronic connections. To cater for users who may want a "minimum" system, the framework can be constructed so that a few basic tests can be administered, e.g., speed of wrist and finger movement, and finger dexterity.

As it is not possible to cater in advance for each and every unique application, a limit on the amount of variation in modules needs to be imposed. In view of the the ease with which a pegboard-type test can be instrumented, and the undoubted validity of some of these tests, it is reasonable to assume that a pegboard will be the basis for most tests. The variation in peg dimensions will have to be optimized to cover a reasonable range of conditions. Modules for tests of tool-using ability will also have to be considered.

In conclusion, it is recommended that the following steps be taken in order to implement such a system:

(1) Some of the more popular dexterity tests need to be studied in detail - in particular the Purdue Pegboard, the Minnesota Rate of Manipulation Test, and the One-Hole Test (this is the only commercially available test which can be interfaced with a computer with a minimum of modification). This assessment will aid the design of the computerised tests, and will give an indication of the standards of workmanship to be aimed for.

(2) The module concept and the measurement of therblig times need to be thoroughly evaluated in terms of robustness, reliability, safety, and cost. In order to accomplish this, it is proposed that a prototype apparatus be constructed for the measurement of finger dexterity and wrist/finger speed. This test will be modelled after the Purdue Pegboard, and will be interfaced to an "IBM compatible" Personal Computer. The hardware associated with this test will comprise the framework for the modular system described above.

(3) When this system has been found to work satisfactorily, a module for the measurement of hand dexterity and speed of arm movement should be constructed. By proceeding in this rather conservative way, it will be possible to evaluate and improve the system in an orderly fashion before any tests are marketed. Once the reliability and usefulness of the system has been demonstrated, it should be easier to attract customers - in particular those who may require tests tailored to their particular requirements.

(4) In parallel with the above work, a computer program for the analysis of jobs and the determination of ability profiles should be developed. As this may be a fairly large project on its own, some time may be saved by basing the program on instruments already in existence.

(5) The feasibility of using a VDU screen in conjunction with a light pen for the measurement of Speed of Arm Movement should also be investigated. This technique may be useful as a replacement for paper-and-pencil tests measuring hand steadiness and delicate finger control (an important ability in jobs such as the soldering of electronic equipment, or hand painting of pottery). This work will establish the extent to which "co-ordination" tests may be developed without the need for apparatus other than a Personal Computer.

(6) The incorporation of several computerized information processing or cognitive tests should be considered in the long term. By targeting these tests at various categories of worker, the attractiveness of a computer-based package of tests will be increased, and the multipurpose capability of such a system will be exploited to the full.

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APPENDIX A. Dexterity tests used by Fleishman et al.

1. Apparatus tests

O'Connor Finger Dexterity: The subject is provided with a bin containing 300 pins and a board containing 100 small holes. He is required to pick up three of the small pins at a time with the preferred hand and place them three at a time in each small hole. The score is the number pins placed in a single trial of five minutes (TRT reliability = 0,76).

Purdue Pegboard: the subject is provided with a pegboard having two columns of small holes (25 holes in each) and four small bins containing either pegs, washers, or collars. There are four trials. In trial 1 (30 seconds), the subject is required to pick up one peg at a time and place it in a hole as rapidly as possible with the right hand. The score is the number of pegs placed (TRT reliability = 0,70). In trial 2 (30 seconds), the subject is required to do the same, but with the left hand (TRT reliability = 0,68). In trial 3 (30 seconds), the subject has to pick up two pegs at a time, one with each hand from different bins, and place them simultaneously in adjacent holes (TRT reliability = 0,70). In trial 4 (60 seconds) the subject is required to make as many complete peg-washer-collar-washer assemblies as possible by merging the operation of both hands (TRT reliability = 0,74).

Minnesota Rate of Manipulation: In the turning subtest, the subject is provided with a large board containing 60 holes and 60 cylindrical blocks. He is required to remove the blocks from the holes with one hand, turn them over with the other hand, and replace them in the same holes, moving from block to block as rapidly as possible. The score is the number of blocks turned in two 35-second trials (S-H reliability = 0,79). In the placing subtest, the blocks are arranged outside the board.

The subject is required to place as many of the blocks as he can in the proper holes as rapidly as possible. The score is the number of blocks placed in two 40-second trials (S-H reliability = 0,91).

Santa Ana Dexterity: The subject is presented with a pegboard having 48 pegs in square holes. The pegs have square bottom pieces and larger round tops. Half of each round top is painted blue and the other half is painted yellow. When the board is presented to the subject, all pegs have the same coloured side facing him. The subject lifts each peg from its hole, turns it 180^{o} clockwise and resets it in its hole, moving from peg to peg as rapidly as possible. The score is the number of pegs rotated in two 35-second trials (S-H reliability = 0,91).

Pin Stick: The subject holds a rod containing a column of ten pins protruding on each of its four sides. He is required to take the thread attached at the bottom of the rod and make one loop around each pin as rapidly as possible, going up then down each column of pins on the rod. The score is the number of pins "looped" correctly in four 15-second trials (S-H reliability = 0,77).

Punch Board: The subject is presented with a small board covered by a hinged metal plate. This plate contains a pattern of 200 tiny holes spaced very close together. The subject is required to punch through the holes with a small pin, punching from hole to hole as rapidly as possible around the pattern. His punches are recorded on a sheet of marked paper which fits under the plate. The score is the number of punches completed in two 60-second trials (S-H reliability = 0,85).

Precision-Steadiness: The subject is seated before a long, rectangular box-like apparatus containing two openings. Each opening is the entrance to a straight passageway which the subject must negotiate with a long stylus, without touching the sides. The score the the number of seconds in contact with the sides of the passage during six trials, each of which consists of a complete traverse of both passages.

Ten Target Aiming: The subject is seated before a panel containing 10 holes at equal intervals in an ellipsoid pattern. Behind each hole a circular target can be seen, these targets varying in size from one hole to the next. The subject is required to strike at these targets with a stylus, moving from target to target in a clockwise direction. Only one strike per hole is made, both speed and accuracy count, and the subject must work as fast as he can. The score is the number of errors which are recorded each time the subject strikes outside a hole or around the target area

Hand-Precision Aiming: The subject is seated before a small panel consisting of two parallel metal plates, which are tilted towards him. The upper plate contains 25 holes, each 3/8 inch in diameter, in five rows of five holes each, all holes being equidistant from each other. The subject must punch through the holes with a small stylus and strike the lower plate, working as rapidly and as accurately as possible. The score is the number of times the subject strikes the upper plate in error in six 30-second trials.

2. Paper-and-pencil tests

Square Marking: The subject is required to mark an "X" in each of a series of 1/8 inch squares. Each "X" must be placed completely within the small square with no part of it outside. The score is the number of correctly marked squares in one 60-second trial (S-H reliability = 0,92).

Tapping, Large: The subject holds a pencil in his preferred hand and is required to place three dots successively in each of a series of 7/16 inch circles. The score is the number of circles dotted correctly in one 60-second trial (S-H reliability = 0,94).

Tapping Medium: The subject is required to make three dots in each of a series of circles 3/8 of an inch in diameter, working as rapidly as possible. The score is the number of circles completed correctly in a single trial of 30 seconds.

Tapping, Small: The subject is required to place one dot in a number of 1/8 inch circles. The score is the number of circles dotted correctly in one 60-second trial (S-H reliability = 0,89).

Pursuit Aiming: The subject is required to follow a linked pattern of small circles 3/16 inch in diameter, placing one dot in each circle around the pattern. The score is the number of dots placed in a single trial of 30 seconds. The second version of this test is basically the same, except the pattern is more difficult and the circles are smaller (1/8 inch). The score is the number of dots correctly placed in a single trial of 60 seconds.

Tracing: The subject is required to trace a continuous line through a maze pattern. He must trace only in a prescribed direction and must go through a series of 1/16 inch openings in the lines of the maze without touching these lines. The score is the number of openings negotiated correctly minus the number of errors or "touches" in one 50-second trial (S-H reliability = 0,85).

Marking Accuracy: The subject is provided with a standard IBM marking sheet and is required to mark in the slot circled for each item going from item to item as quickly as possible. The score is the number of corrects minus the the number of errors in two 40-second trials (S-H reliability = 0,91).

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ISBN 0 7969 0665 3