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EFFECTS OF LATERALITY, SEX, AND AGE ON COMPUTERIZED SENSORY-MOTOR TESTS

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SUMMARY A battery of 15 computerized tests has been developed for quantification of upper-limb sensory-motor function, with particular attention given to applications where neurological impairment may be involved. The tests comprise 3 pursuit tracking tasks (preview random, step, combination) for measurement of integrated function and 12 tests which aim to break tracking into its various sensory, perceptual, and motor component functions (visual resolution, object perception, static and dynamic visuospatial perception, joint position sense, range of movement, grip and arm strength, reaction time, gross speed, static and dynamic steadiness). Single and multiple session trials with normal adult subjects were carried out to determine the effect of sex, age, and laterality on performance. Males had the same reaction times as females but were superior on all strength, speed, and co-ordination tests. Increasing age had no effect on strength or steadiness but adversely affected visuospatial perception, reaction times, speed, and all forms of tracking. The dominant (= right) arm was superior to the non-dominant arm on strength, speed, and combination tracking but was marginally inferior on the latter's component random and step tracking when performed separately.

Key words: Laterality, sex, age, sensory-motor, tracking

INTRODUCTION

Although innumerable tests have been developed for measurement of various aspects of sensory-motor (S-M) function, there are surprisingly few batteries of tests able to provide quantitative measures of a compre-

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hensive range of interrelated S-M functions. The value of such test batteries lies in the much more complete picture they can provide of an individual's overall S-M system. These batteries tend to be well instrumented, aimed at and achieving both objectivity and sensitivity, and comprised of a number of tests systematically chosen against established frameworks to provide a broad coverage of S-M function.

Fleishman (1972) and his colleagues have assembled and investigated more than 200 tasks administered to thousands of subjects. From factor-analytic studies they were able to establish a taxonomy of 11 psychomotor abilities and 9 physical proficiency abilities which consistently appear to account for the common variance in psychomotor tasks. They were then able to specify which tasks best measure each of these abilities, such as rotary pursuit for the factor called control precision ability.

Whereas Fleishman (1972) derived his optimal battery of tests primarily from experimental evidence on existing tasks, Notterman, Tufano, and Hrapsky (1982) designed a set of tasks based around control theory's pursuit-tracking paradigm of voluntary movement. They have taken a single case of visual-motor organization, eye-hand pursuit tracking, and differentiated it into its static and dynamic, visual and motor components according to equations describing stimulus position and limb force production. This results in a series of 9 tasks arranged to place hierarchically increasing cognitive or perceptual demands upon visual discrimination and motor actions, and are grouped into the following sections: visual discrimination, temporal discrimination, motor actions, visual-motor organization.

In contrast to both of the above test batteries, Potvin and Tourtellotte (1975) have developed a battery aimed primarily at providing objective and quantitative measures of many neurological functions evaluated qualitatively in the standard neurological examination. This places different demands on test design such as the need for greater dynamic range and for greater independence from other S-M functions whose integrity cannot be assumed. Nevertheless many of the instruments used in the tests of upper-limb function (strength, steadiness, reactions, speed, co-ordination, sensation, fatigue) have been the same as those used in normal psychomotor studies. More recently their test battery has become more integrated and automated through computerization (Kondraske, Potvin, Tourtellotte and Syndulke, 1984). Stuart *et al.* (1980) have also developed a computer-based neurological test battery but with a restricted coverage of S-M functions (gait, tremor, reaction and movement times).

The purpose of this paper is to present results from normal studies based around a newly developed computerized battery of 15 tests for quantification of various effects of upper-limb sensory-motor (S-M) function (Jones and Donaldson, 1983). The tests fall into 2 broad categories. First, integrated function tests which aim to provide a global measure of functioning in the overall S-M system, necessitating one or more complex perceptual-motor tasks, of which 3 modes of tracking—random/preview, step/non-preview, and a combination of these—satisfactorily fulfil this role. Second, component function tests which aim to isolate and quantify the various component functions integrated during complex S-M tasks; these include visual acuity and perception, position sense, strength, reaction times, gross speed, and steadiness. Wherever possible, the tests possess high sensitivity, minimization of component test interdependence, and maximization of automation with regard to test administration, scoring, data analysis, and data storage and retrieval.

The philosophy applied in the conceptual design and choice of tests for the overall battery appears as a coalition of two of the above approaches. As with Notterman *et al.* (1982), the pursuit-tracking task is the central task which is differentiated into its various components to form the basis of all the other lower level tests. However, rather than explicitly doing this via a control theory paradigm, the emphasis placed on the component tests parallels subjective measures made in a neurological examination. namely the approach of Potvin and Tourtellotte (1975).

The inclusion of a preview display in the present random pursuit tracking task is considered an important attribute of the task as it greatly increases its similarity to everyday S-M activities and hence its validity as a measure of ability to perform such real life tasks. The viability and sensitivity to brain damage of this particular task have been demonstrated in 2 clinical applications: long-term serial measurement of integrated S-M function following acute brain damage (Jones and Donaldson, 1981), and as a central component in a hospital based driving assessment and training program (Jones, Giddens and Croft, 1983).

The broad objectives of this study were firstly to extend an earlier investigation into various aspects of normal S-M function (Jones and Donaldson, 1981) but on the much expanded battery of component and integrated tasks. and secondly to provide a baseline of absolute and incremental performance for application in longitudinal studies involving brain damaged patients. This paper presents results related to the former objective with particular emphasis on laterality, sex, and age.

Laterality was considered to be the most important area of investigation due to the considerable variance in the literature regarding the superiority of the dominant arm, and due to the importance of differential diagnosis in the neurological examination. Most studies have supported the superiority of the dominant arm on strength, speed, and co-ordination (Potvin *et al.*, 1973; O'Donnell, 1983; Borod, 1984) and no asymmetry on reaction time (Potvin *et al.*, 1973; Guiard, 1983).

However the dominant arm's superiority on co-ordination is not universal. Peters (1981) found no asymmetry on the pursuit rotor task and both the author (Jones and Donaldson, 1981) and Guiard (1983) provide preliminary support for the non-dominant left hand being actually superior on preview and ballistic tasks respectively.

While there appears to be no dispute that males are both stronger and, for gross arm movements, faster than females, there is evidence (for reasons which remain unclear) that this superiority also extends to certain aspects of eye–arm co-ordination such as pursuit rotor (Potvin *et al.*, 1973) and more tentatively on random tracking (Jones and Donaldson, 1981). Both this and the laterality issue were closely investigated in the present study.

METHOD

Subjects

Two unpaid groups were involved in the study, corresponding to single and multiple sessions on the test battery. The single session group (Group I) contained 36 subjects divided evenly into sex and 6 age subgroups, with a subset of 12 of these making up the second group (Group II) who undertook a further 10 test sessions (see table 1). The subjects were not matched for employment or educational status but were kept diverse by being drawn from a wide range of employments and backgrounds. All subjects were right-handed and had corrected vision of 6/9 or better for each eye on the Snellen acuity chart.

TABLE 1. Age and sex of subjects

	Group I *1-session* ($n = 36$)		*Group II** *11-session* ($n = 12$)	
	Male	*Female*	*Male*	*Female*
Age Group				
16–25	3	3	1	1
26–35	3	3	1	1
36–45	3	3	1	1
46–55	3	3	1	1
56–65	3	3	1	1
66–75	3	3	1	1
n	18	18	6	6
Mean age	44·9	45·6	44·0	45·3
SD	17·2	17·4	17·7	20·3
Minimum age	20	21	23	22
Maximum age	71	72	69	72

* Group II is a subset of Group I.

Apparatus and Tests

System hardware was based around a PDP11/34 computer with a VT11 graphics screen (279 × 228 mm) for displaying test stimuli (eye-screen distance 132 cm). A steering wheel (395 mm diameter, and minimal 1·0 N friction at perimeter) was used for measuring the subject's motor output except for grip strength for which a "TEC" grip dynamometer was used. The S-M integrated and component tests were generated and analyzed by 2 programs (TRACK and SMC respectively) each which ran within 64 kbytes of memory under the RT11 operating system. The software was written in FORTRAN IV except for the display of dynamic stimuli in the dynamic perception test (DP) and the 3 tracking tasks where the faster MACRO assembly language was necessary.

Integrated Function Tests

While a more detailed description of the 3 tracking tasks comprising this section is given by Jones and Donaldson (1986), a summary is as follows. Each of the tasks took 120 sec.

1. Random/preview tracking task (RAND)—The input target signal was a constant random signal of 0·21 Hz bandwidth which descended from top of screen giving an 8·0 sec preview time before reaching the point of an arrow representing the subject's output. A corresponding 175° range of movement was required on the steering wheel. An error graph was displayed at the end of each run giving immediate feedback of performance to both assessor and subject. Performance parameters calculated were mean absolute error and 6 error biases (inconsistency, side of input, side of screen, direction, lag, undershooting) although only the former is presented in this study.
2. Step/non-preview tracking task (STEP)—This task comprised 32 steps which were both spatially (magnitude and direction) and temporally unpredictable. The unpredictability, together with a response requiring aimed ballistic rather than smoothly changing movements places STEP more at the other end of the S-M spectrum to that of RAND. Both non-ballistic and transient error analyses were automatically undertaken although the mean absolute error is again the only score presented in this study.
3. Combination tracking task (COMB)—In COMB the stimulus alternately cycled between the RAND and STEP modes over 11-sec cycles. This allowed determination of the effect on performance of repeated translation between quite different tracking modes.

Component Function Tests

Each of the component function tests was designed such that it isolated and quantified various constituent elements of the integrated function measured during the tracking tasks. Consequently the resemblance between the two was intentionally close and the validity of comparisons of test performances was maximized. In those tests allowing for several attempts, the strategy used for calculating overall scores was to use the best rather than the average or median score. The tests moved progressively through visual (sensory/perceptual), proprioceptive, and motor component functions.

1. Visual acuity (VA)—Corrected visual acuity for each eye as measured on the Snellen chart at a distance of 6 m.
2. Visual resolution (VR)—Visual resolution in the horizontal direction measured by the ability to discriminate the position of a dot with respect to a vertical line in increments of 0·27 mm at 132 cm.
3. Arrow perception (AP)—Perception and comprehension of the components of an arrow identical to that used in tracking tasks with particular emphasis on the arrow point.
4. Static perception (SP)—Perception of an arrow with respect to a static vertical line in 4 trials and a static sinewave in 16 trials.
5. Dynamic Perception (DP)—Determination of whether or not an arrow stayed perfectly on a random input descending with an 8-sec preview time. The duration of the 20 trials decreased from 10–2 sec and various error offsets were simulated.
6. Position Sense (PS)—Joint proprioceptive sensation of the direction of small manually applied and mechanically limited movements to rim of steering wheel while subject was blindfolded. The minimum reliable stimulus was 0·5 mm.
7. Grip Strength (GS)—Best of 3 attempts on "TEC" dynamometer with arm extended by side.
8. Range of Movement (RM)—Comfortable active range of movement on steering wheel while maintaining a firm grip.
9. Steering Wheel Force (SF)—Average of best force of 2 attempts at each of 4 position–direction conditions on steering wheel.
10. Ballistic Movement (BM)—Ballistic arm movement in response to a random non-target stimulus (no accuracy required). This required moving the arrow out of the box and across a pass-line (= 90° on steering wheel) in response to random 3–7 sec latency stimulus. The best reaction time (RT) and peak velocity (PV) over 8 attempts were recorded.
11. Static Steadiness (SS)—Steadiness of extended arm at maximum gravity position on the steering wheel over a 7-sec duration.
12. Steady Movement (SM)—Steadiness of arm during an attempted constant-speed non-pursuit movement on the steering wheel over a range of 116°. The best of 8 attempts within a certain speed range was recorded.

Procedure

The Group I (n = 36) subjects were given a single session only on the test battery, taking between 90 and 120 min each. The tests were administered in the order described above and at a pace to suit the subject; no one felt the need to avail themselves of an extended break offered (fortunately the interest factor was invariably high). Where a motor response was required the subject was requested to commence with the dominant hand.

Group II subjects (n = 12) underwent 11 sessions spaced exponentially over 1 yr: that is, weeks 1, 2, 3, 4, 6, 9, 13, 18, 26, 37, 52.* Order effects which might bias laterality and inter-task analyses were prevented by having the presentation of the 3 tracking tasks follow a 6-session cycle containing all of the 6 pertinent hand and input order permutations. As a means of reducing the average session length to a more acceptable level, the component tests were only given at each alternate tracking session. Repeat component tests were discontinued after a subject had 2 consecutive "perfect" scores. Depending on the number of discontinued component tests, repeat sessions took between 30 and 60 min.

Statistical analysis of results has been through use of BMDP STATISTICAL SOFTWARE (Dixon, 1981). As did Poulton (1974) and Notterman *et al.* (1982), nonparametric statistics have been applied in all cases because of lack of normality in most of the performance distributions.

RESULTS

Practice

A knowledge of the practice effects on performance at the various tests is important for proper interpretation of laterality results as well as for comparison of single and multiple session data. Table 2 indicates that for the tests requiring a motor output there is a significant improvement in performance with practice on all of the tracking tasks, as would be expected with complex integrated tasks. It is reasonable to conclude that the improvement seen in two of the component tests does not reflect increased arm strength or steadiness but rather better technique at

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* Choice of an increasing interval time scale reflects the second (clinical) objective of the normal trials which desires that the normal baseline data be optimal for measurement of the recovery process following acute brain damage. As the typical recovery curve, from say stroke, is crudely exponential (Hiorns and Newcombe, 1979), frequent assessments soon after admission gives high spatial resolution when neurological function is improving fastest. Conversely, acceptable temporal resolution is obtained without unnecessary effort by less frequent assessments when the recovery process has essentially plateaued. Fortunately the high retention of psychomotor skills means that varying the inter-session interval has at most minimal effect on inter-session changes in performance (Jones and Donaldson, 1981). The actual spacing of the 11 sessions is approximately equivalent to 1·4 (= sqrt 2).

TABLE 2. Improvement in performance on motor tests between first and last sessions

Test	*Improvement* (%)
Component functions	
Grip Strength	−1·1
Arm Strength	14·5†
Reaction Time	−3·0
Gross speed	2·2
Steadiness	85*
Steady movement	3·9
Integrated function	
Random	45·5‡
Step	17·5‡
Combination	28·1‡

Note Last session is session 6 for component tests and session 11 for tracking tasks. Significance of differences between first and last session scores by Wilcoxon signed-rank matched-pairs test

* $p<0{\cdot}05$; † $p<0{\cdot}01$; ‡ $p<0{\cdot}001$; all 1-tailed.

performing these particular tests. Increasing the number of attempts allowed during the static steadiness test, from say 2 to 4, particularly on the first session, would most likely have resulted in negligible practice effect between sessions.

Laterality

Table 3 presents the average percentage differentials between right and left arm performances for each of the motor tasks (except Range of Movement). For a single session only, no significant difference was found between sides on any of the component tests except grip strength where the left is 6·3% (2·7kg) less than the right hand. Significant differences were found between sides on all of the 3 tracking tasks but because the tasks were performed first by the dominant arm in the first session the superiority of left over right arm cannot be said to be a real difference for both the random and step tasks. Because the benefit of practice would have worked in the other direction (and fatigue is not considered to have been present to any degree), the superiority of right over left side for combination tracking is considered real. Overall from the single session results alone it can be stated that the right (dominant) arm is superior to the left arm in both grip strength and combination tracking.

Analysis of the multiple session averaged results allows balancing out of any order effects but because of the smaller Group II ($n = 12$) minor

TABLE 3. Mean percentage laterality differentials: dominant relative to non-dominant

	Group I (n = 36)	*Group II (n = 12)*	
Test	*1 session*	*1 session*	*11 session average**
Component functions			
Grip strength	6·1¶	4·9	4·9
Arm strength	0·4	0·1	4·6‖
Reaction time	−1·3	−3·1	−1·8
Gross speed	0·4	−0·7	1·8§
Steadiness	10·0	263·2‡	36·3
Steady movement†	11·8	15·3	0·2
Integrated functions			
Random	−14·1¶	−14·3‖	−0·3‡
Step	−2·0§	−5·7‖	−0·2‡
Combination	12·1¶	14·8‖	7·0‖

Note Percentage differentials: Magnitude = $(D-N)/D \times 100\%$; Sign = "+" if D better than N, "−" if D worse than N; i.e., differential is positive if D better than N irrespective of whether score is actually positive (performance score) or negative (error score).

Significance of absolute difference between sides by Wilcoxon signed-rank test.

* The long term differentials are the averages of differentials at each of the 6 alternate sessions for component tests and 10 of the 11 sessions for tracking tasks, the first session being excluded from the tracking analysis to prevent any anomaly remaining, even after averaging, due to substantial practice effect on very first attempt (most of 12·9% seen between D and N on Random task).

† The mean of individual % differentials is not valid for steadiness due to division by zero (perfect) R-hand score in several cases; the overall group %-differential is given in this case.

‡ $p<0{\cdot}1$; § $p<0{\cdot}05$; ‖ $p<0{\cdot}01$; ¶ $p<0{\cdot}001$; all 2-tailed.

differences are less likely to be demonstrated even where they may be real; this is well illustrated by the 1-session mean grip strength differential for Group II of −4·9% which is non-significant ($p = 0{\cdot}15$) whereas the similar value of −6·3% for Group I ($n = 36$) is highly significant ($p < 0{\cdot}001$). For the component tests, the right arm was superior to the left by 4·6% (5·0N) on arm strength and by 1·8% (25·4°/sec) on gross speed. The initial difference seen for grip strength was not demonstrated over the longer term but this is considered a consequence of lower group numbers as explained above (i.e., Type II error). With the integrated tests, the combination tracking task retained its right over left superiority (7·0%) which contrasts with the random and step tasks where the right is marginally inferior to the left (0·3% and 0·2%), if with borderline significance ($p = 0{\cdot}07$ and $p = 0{\cdot}08$).

Sex

For the first session, females had significantly inferior scores to males on all motor tests except reaction time and steadiness (see table 4).

TABLE 4. Mean percentage sex differentials: male relative to female

	Group I	*Group II*		
Test	*Sess-I*	*Sess-I*	*Sess-II*	*Reduction(%)**
Component functions				
Visual Resolution	−3·0			
Arrow Perception	18·2			
Static Perception	−16·5			
Dynamic Perception	58·1			
Grip Strength	40·3‖	36·4§	35·8§	−1
Range of movement	−7·4‡			
Arm Strength	43·5‖	37·8§	33·1‡	−12
Reaction time	4·3	0·4	5·7	
Gross Speed	19·5‖	17·8	17·6	−1
Steadiness	0·0	−21·4	−66·7	
Steady Movement	34·3‖	42·5‡	24·3	−76
Integrated functions				
Random	33·7‡	46·4	11·0	−76
Step	7·3†	6·7	1·1	−84
Combination	12·2§	16·1†	5·6	−65

Note Percentage differentials between male(M) and female(F) means: Magnitude = $(M-F)/M \times 100\%$; Sign = "+" if M better than F, "−" if M worse than F. Significance of absolute differences between M and F by Mann–Whitney test.

* Reduction in differential scores between first and last sessions only given where differential significant for Group I.

† $p<0{\cdot}1$; ‡ $p<0{\cdot}05$; § $p<0{\cdot}01$; ‖ $p<0{\cdot}001$; all 2-tailed.

However for the final session Group II (subset of Group I) had only grip and arm strengths maintained significant differences. As with laterality, much of this loss of significance is attributed to lower numbers in long-term Group II. The most dramatic example of this is gross speed on session 1 where a drop in sample size from 36–12 has minimal effect on mean difference (19·5 % vs 17·8 %) but severely reduces significance ($p < 0{\cdot}001$ vs $p = 0{\cdot}11$). Comparison was also made of performances on the non-motor tests for single session only (see table 4). No significant differences were found on visual resolution, or any of the arrow, static, and dynamic visuo-perceptual tests.

The one test for which females were superior to males was range of movement (24°, 7·4 %; $p < 0{\cdot}05$). This could be due to greater joint flexibility in females (quite noticeable in several cases) but could also be explained by their having slightly less restriction at bottom of steering wheel due to smaller thighs. Either way, the difference is minimal and of no consequence to performance on any of the main motor tasks, as the minimum comfortable range of 232° is comparable with the maximum required of 242° in the combination tracking task.

TABLE 5. Performance correlation and decline with age (single session: n = 36)

Test	rho*	Decline over 20–70 age span	
		Absolute†	*Percentage*‡
Component functions			
Visual resolution	0·22	0·6 bit	N/A
Arrow perception	0·29§	0·9 correct	N/A
Static perception	0·40‖	2·7 correct	N/A
Dynamic perception	0·60¶	5·1 correct	N/A
Grip strength	0·26	7·0 kg	14·0
Range of movement	0·31§	39°	11·4
Arm strength	0·12	12·5 N	10·7
Reaction time	0·32§	23 ms	10·3
Gross speed	0·49¶	267°/sec	19·8
Steadiness	0·20	0·012°/sec	N/A
Steady movement	−0·10	−0·26°/sec	−8·7
Integrated functions			
Random	0·59¶	10·6 bit	99·2
Step	0·48¶	6·7 bit	20·3
Combination	0·60¶	10·6 bit	25·7

Note The sign of each rho (Spearman rank correlation co-efficient) and decline is such that "+" means decrement in function with increasing age, irrespective of whether a performance or error score.

* Pearson correlation coefficients, r, were also calculated and were at most 0·07 different from Spearman rho values. The latter are used in this table as they are less stringent with respect to linearity and symmetry, and with negligible loss of significance in this case.

† Absolute decline = Linear regression coefficient × 50 yr.

‡ Percentage decline = (Absolute decline)/(Mean 16–25 yr group) × 100%. "Not applicable" values are due to the 16–25 yr subgroup having essentially zero (floor effect) mean scores on the 3 perceptual tests, resulting in meaningless high percentage decrements.

§ $p<0{\cdot}05$; ‖ $p<0{\cdot}01$; ¶ $p<0{\cdot}001$; all 1-tailed.

Age

Of the 14 test measures in Table 5, significant overall decrements in performance over the 20–72 yr range investigated were found on all 3 perceptual tests, range of movement, both the reaction time and gross speed in non-target ballistic movements, and all 3 tracking tasks. No decrement with age was found on visual resolution (vision corrected), grip and arm strength, and both static and dynamic steadiness.

DISCUSSION

Laterality

The significantly stronger grip strength of the dominant hand for the single-session group is confirmed by several earlier studies (Schmidt and Toews, 1970; Potvin, 1971; Potvin *et al.*, 1973; Lewandowski, Kobus, Church, van Order, 1984). An exception to this is a study by Fraser and Benton (1983) who found no overall statistical difference between the right and left hands of 120 adult subjects; this discrepancy might be explained methodologically, if not physiologically, by their use of an air-filled rubber bulb to measure the pressure of a grip rather than the more widely used hand dynamometer which measures force directly. While the general finding is that the dominant hand has on average the strongest grip, this superiority is relatively small (e.g., Group I = 6·3 %, Group II = 4·6 %). It is also not a reliable predictor as evidenced by both Schmidt and Toews (1970), Lewandowski *et al.* (1982) who found that approximately one-quarter of subjects show superiority of the non-dominant hand.

Overall superior strength of the dominant side was also found for arm strength which in the steering wheel case demands simultaneous use of muscle groups at shoulder, elbow, wrist, and hand. This advantage has also been shown for isolated movements at wrist and shoulder (Potvin, 1971) and elbow (Borod, 1984). The fact that no difference in arm strength was seen between the two sides on the first session is clearly a consequence of a practice order effect as all subjects commenced with dominant arm. The arm strength test was one of only 2 component tests to show significant improvement between first and final sessions (see table 2) and highlights standardization difficulties met in attempting to control the positioning of a subject's limbs and torso during maximal isometric exertion without artificial restraints.

No difference was seen between reaction times of the two sides in terms of initiating ballistic arm movements, in agreement with Guiard, Diaz, and Beaubaton (1983). Potvin (1971) similarly found no difference in reaction times on a simple finger release task. Conversely the gross arm speed achieved in the same non-target ballistic movement test was marginally but significantly superior in the dominant arm. The small 1·8 % difference could well be explained by the dominant arm's greater strength and hence acceleration. Other laterality studies have required rapid alternation of digits as in tapping (Potvin, 1971; Potvin *et al.*, 1973; Peters, 1981) or wrist as in dotting circles (Borod, 1984), and all have found superiority of the dominant right hand. The explanation for this is more likely to be related to superior dexterity of the dominant hand than that of greater strength as is considered the case in the ballistic movement test which requires single undirectional full arm movements.

No laterality bias was seen on the arm static steadiness test in agreement with Edwards (1948) and Albers, Potvin, Tourtellotte, Pew, and Stribley (1973). While Potvin, Stribley, Pew, Albers, and Tourtellotte (1975) state that "no important differences were found between sides" young adults were still significantly better on the dominant side in 5 of the 8 tests in their steadiness test battery. Simon (1964) also found superiority of dominant side on a hole-steadiness task. As with the arm strength test, the inability to demonstrate any laterality bias on a single session may be due to a practice order effect (see table 2) or a relatively low test sensitivity and ceiling effect (10 of the 36 subjects in Group I had "perfect" scores). These deficiencies do not apply to the dynamic steadiness test for which no laterality effect was evident.

Several studies of eye–arm co-ordination have shown superiority of the dominant arm on tasks such as pursuit rotor (Barnsley and Rabinovitch, 1970; Potvin *et al.*, 1973), lateral reaching/tapping (Potvin, 1971; Potvin *et al.*, 1973), and accuracy writing (Borod, 1984). Conversely, Peters (1981) found no asymmetries in the pursuit rotor task and suggests that "right/left performance asymmetries should not be considered an established fact". Tentative support for the non-dominant being actually superior to the dominant hand on a tracking type task has been put forward by the author in an earlier study of normal performance on the review random task (Jones and Donaldson, 1981). In 7 of the 8 normals (all but one right-handed) the average mean absolute error over 12 counter-balanced sessions was better with the non-dominant hand and by an overall 3·7%, although this was not significant ($p = 0{\cdot}2$). The current study confirms the superiority of the left hand on this task with a smaller but still marginally significant ($p = 0{\cdot}07$) difference of 0·30%. A similar result was found for the quite dissimilar step tracking task with a left hand advantage of 0·2% ($p = 0{\cdot}08$).

While the degree of superiority of the left over the right side on these 2 tracking tasks is trivial from a practical viewpoint, that this inverse superiority exists at all is of theoretical interest considering that the right (dominant) side is at least equal and in many cases superior to the left (non-dominant) side in all of the above component tests. The distinguishing feature of the tracking tasks is their high visuo-spatial content. As the superiority of the right hemisphere for the processing of visuo-perceptual and spatial relationships in right-handers has been largely accepted (Bradshaw and Nettleton, 1983), the slight superiority of the left hand must arise from its predominant motor control by the same hemisphere. Guiard *et al.* (1983) provide experimental support for this in a task requiring open-loop ballistic aimed movements. Their data suggests that right-handers program ballistic aimed movements with a greater accuracy when using their non-dominant hand although with a higher variability of movement execution.

An unexpected finding in the present study was that performance on the combination tracking task was markedly in favour of the right-hand (7·0%; $p < 0{\cdot}01$) while lateral superiority on both of its 2 constituent tasks, RAND and STEP, was in the opposite direction, if to a much lesser extent. This tends to indicate that the left hemisphere must be more capable of handling the repeated transition between 2 quite different tracking modes, to an extent sufficient to offset the spatial processing advantage of the right hemisphere. This is in agreement with the well established specialization which the left hemisphere has for sequential, as opposed to spatial, processing of information (Guiard *et al.*, 1983; Bradshaw and Nettleton, 1983).

In summary, the existence and degree of performance laterality of the motor tests in the computerized test battery appears to be governed by 4 major interacting factors: (i) morphological asymmetry of the pyramidal tracts leading to stronger innervation of the right side by motor fibres in 80% of the population (Yakovlev and Rakic, 1966), (ii) practice reinforcement of congenital dominance by preferential and considerably greater use of that arm in everyday tasks, (iii) right hemisphere specialization in spatial processing, (iv) left hemisphere specialization in sequential processing. In the case of right handers, only the first 2 factors are relevant to strength, hence the superiority of right side on grip strength, arm strength, and arm speed. There are no specific tests in the current battery which measure the precision and rapidity of fine, skilled, distal movements but as these are the primary function of the pyramidal tracts (Brodal, 1981; Bradshaw and Nettleton, 1983) they would also have a right hand advantage. This is confirmed by studies on hand (rather than arm) function, such as tapping and pencil tests, and is presumably the basis for classic dominance as defined through natural writing hand.

None of the 4 factors is likely to have a major influence on initiation or constancy of movement and this is in agreement with lack of laterality seen on reaction time and steadiness tests.

As the spatial complexity and integration of the visual stimulus and desired motor response increase significantly, such as in the random and step tracking tasks, the spatial processing advantage of the right hemisphere appears sufficient to offset the first 2 factors to the extent that the left hand has a slight advantage. Finally, merging these 2 tasks into 1 dramatically increases the sequential processing load placed on the left hemisphere resulting in an additional advantage to the right arm and a return to its superior performance.

Sex

Males were markedly stronger than females on the 2 strength tests (grip 40%, arm 45%) which, as expected, is in full agreement with previous studies on grip strength (Potvin *et al.*, 1973; Agnew and Maas, 1982; Fraser and Benton, 1983) and arm strength (Potvin *et al.*, 1973). Greater arm strength means greater maximum acceleration which in turn explains the superior gross arm speed attained by males within a

309 mm movement. This might also explain male superiority on a gross peg moving task (Kilshaw and Annett, 1983) and hand tapping (Potvin, 1971) although co-ordination might also be a factor.

Potvin (1971) found that males had significantly shorter reaction times on a finger release task which was not the case in the present study requiring a full arm movement, although the bias was in the same direction. It is possible that such small differences are simply a reflection of the male's greater acceleration, even though only a minimal movement is being measured, rather than the sensory-motor reaction time; EMG would elucidate this distinction.

There is some disparity on whether females have the same or better static steadiness than males. No difference was found in present study at holding arm stationary on steering wheel (maximum gravity positions), as did both Simon (1964) and Potvin *et al.* (1975) on hole-steadiness tasks, but for measures obtained from using a force stick and accelerometer Potvin *et al.* (1975) found females to be steadier than males. It seems reasonable to conclude that females do have a steadier arm when suspended but to measure this a test needs to be sensitive enough to measure physiological tremor; presumably the steering wheel's inertia is sufficient to dampen such movement completely. It is therefore somewhat surprising and contradictory to find that males were 36% ($p < 0{\cdot}001$) superior on the constant speed steadiness test. This is not co-ordination in the conventional eye–hand sense (once required speed is being repeatedly approximated the test can be just as accurately performed with eyes closed) and no reason is put forward for this particular differential between the sexes.

On more complex S-M tests, males were superior on all 3 tracking tasks, in agreement with the trend in an earlier study by the author (Jones and Donaldson, 1981) on the preview tracking task (although the 9·1% difference on session 2 was not significant) and Potvin *et al.* (1973) on the rotary pursuit task. This difference in eye–arm co-ordination cannot be explained in terms of visual acuity or perceptual differences (which were insignificant—see table 4), or strength, where steering wheel friction of 1·0 N is only 2·5% of minimum arm strength seen for normal subjects. Possible reasons are tenuous. First, males have greater co-ordination due to greater practice on a related task; this is particularly pertinent where the input device is a steering wheel and due to the fact that men tend to drive more often than women. Second, females are slower at learning a new task, hence taking longer to reach their plateau performance. Evidence that this is partly the case is seen by an average 75% reduction in the male–female differential between first and final (= 11th) session on the tracking tasks (see table 4): the average differential was still 5·9%, though not demonstrably significant.

Overall, males are predictably superior on strength and gross speed tasks while females may have marginally superior steadiness. Male superiority on the tracking tasks and steady movement task are less readily explained. While dexterity was not tested, it appears that females are better at finer hand tasks such as writing and manipulating small objects (Agnew and Maas, 1982). Anatomic and physiologic distinctions between the sexes apparently favor males in many gross motor activities but sociocultural influences have compounded this by acting to restrict female involvement and achievement in many psychomotor endeavors (Singer, 1972).

Age

The significant decline in performance on the 3 perceptual tests over the 20–72 age range confirms the finding of several other studies (Eriksen *et al.*, 1970; Fozard and Nuthall, 1971; Farver and Farver, 1982; Concha, 1984). This deterioration cannot be said to be simply a result of poorer visual acuity as no decline was seen on the visual resolution test where spectacles are worn if desired (see also Potvin *et al.*, 1973). Botwinick (1981) has stated that older adults tend to score less well in fluid intelligence (perceptual function) than younger adults, but that they score much the same in crystallized intelligence (verbal function). Specifically, older adults take more time to perceive and integrate visual stimuli (Eriksen *et al.*, 1970; Botwinick, 1981).

There are conflicting reports as to what extent strength declines with age. The present study found Spearman correlations to be non-significant for both grip and arm strength over the 20–72 age range. This is supported in both cases by Potvin *et al.*, (1973) but not in reasonably large studies on grip strength by Agnew and Maas (1982) and Fraser and Benton (1983). Closer examination of all of these studies indicates that strength peaks slightly in middle rather than young adulthood (Potvin *et al.*, 1973; Agnew and Maas, 1982), then follows a gradual decline until about the mid-60's whereupon the decline becomes more dramatic. Grip and arm strength were the only functions in the current study which were not monotonic with increasing age; this tends to invalidate their Spearman correlations but classical and Kruskal-Wallis ANOVAs were also unable to demonstrate any significant trend in strength against age.

A 27% decline in ballistic arm speed cannot be explained by lesser strength, as has been done earlier for laterality and sex speed differentials, and hence must be part of a general slowing up process. Evarts, Teravainen, and Calne (1981) and Kilshaw and Annett (1983), but not Potvin *et al.* (1973), have demonstrated a similar decline. This slowing up is demonstrated further with unanimity with the present study regarding the lengthening of reaction times with age (Potvin, Syndulko, Tourtellotte, Lemmon, and Potvin, 1980; Evarts *et al.*, 1981) with a gradual decline occurring after approximately 26 yr (Hodgkins, 1962).

No significant change was observed with increase in age on either the static or dynamic steadiness tests in line with Potvin *et al.* (1975) who found no decrement on their unsupported arm steadiness test; surprisingly a decrement was evident once the arm was supported.

Significant deterioration in visual-motor co-ordination with age was found on all 3 tracking tasks, as has been found previously on rotary pursuit (Potvin *et al.*, 1973; Surburg, 1976) and preview tracking (Jones and Donaldson, 1981). This consistent and often considerable decline of perceptual motor skills with age (Fozard and Nuthall, 1971; Levison, 1981) must be a summation of the deterioration seen in the perception and speed related component tests (AP, SP, DP, BM) and probably a sensory-motor integrating element as well. The common denominator in all of these appears to be more a reduction in speed, than capacity, of central processing.

A consequence of this is that older subjects are slower at learning (Potvin *et al.*, 1980) which accentuates performance differentials on first exposure to new tests. This, at least in part, explains why Random, the first tracking task in the first session, has a much higher difference (73 %) than the following Step and Combination tasks (21 % and 24 %). Given practice older adults are able to considerably reduce their performance differential with younger adults. In an earlier study on preview tracking (Jones and Donaldson, 1981), after 9 sessions the age regression coefficient dropped to 10 % of its first session value.

Conclusion

The most important findings from this study of upper-limb function were in the areas of laterality and sex. While the dominant arm is used more in everyday life and, as expected, was found stronger and faster than the non-dominant arm, its performance was slightly inferior on both the random and step tracking tasks. This inferiority was however reversed when the same 2 tasks were combined into a single task requiring repeated translation between the 2 tracking modes. Further investigation will be required to confirm whether this crossover in performance superiority can be attributed to the lateralized visual and sequential processing specialization of the cerebral hemispheres and their more direct connections with the left and right hands respectively.

Males were found to be superior to females on the steady movement and all 3 tracking tasks, although the differences decreased markedly with practice. This apparent superiority in eye–arm co-ordination might reflect greater practice by males on related everyday tasks such as driving or it may indicate a slower accommodation to new S-M tasks by females.

On a more general note, this paper helps to demonstrate the applicability of the computerized test battery for quantification of component and integrated aspects of upper-limb S-M performance. The battery is objective, high-precision, comprehensive, and largely automated. As such, the battery is considered a powerful and convenient tool for investigation of normal and abnormal S-M function.

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