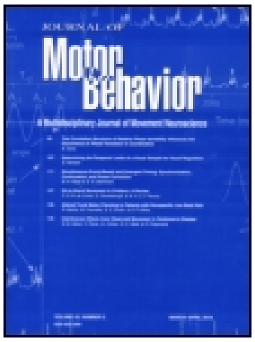

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RESEARCH ARTICLE

A New Method for Tracking of Motor Skill Learning Through Practical Application of Fitts' Law

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ABSTRACT. A novel upper limb motor skill measure, task productivity rate (TPR) was developed integrating speed and spatial error, delivered by a practical motor skill rehabilitation task (MSRT). This prototype task involved placement of 5 short pegs horizontally on a spatially configured rail array. The stability of TPR was tested on 18 healthy right-handed adults (10 women, 8 men, median age 29 years) in a prospective single-session quantitative within-subjects study design. Manipulations of movement rate 10% faster and slower relative to normative states did not significantly affect TPR, $F(1.387, 25.009) = 2.465$, $p = .121$. A significant linear association between completion time and error was highest during the normative state condition (Pearson's $r = .455$, $p < .05$). Findings provided evidence that improvements in TPR over time reflected motor learning with possible changes in coregulation behavior underlying practice under different conditions. These findings extend Fitts' law theory to tracking of practical motor skill using a dexterity task, which could have potential clinical applications in rehabilitation.

Keywords: clinical measurement, Fitts' law, motor learning, motor skill, neurorehabilitation, rehabilitation

The ability to learn and retain manual skills is fundamental to the achievement of physical goals in everyday life, from rehabilitation from injury to elite sporting endeavors (Krakauer, 2006; Nielsen & Cohen, 2008; Yarrow, Brown, & Krakauer, 2009). A number of objective clinical measures of motor skill are available to assess the level of upper limb manual dexterity or motor skill on continuous scales. The majority of these are derived from techniques for assessment of patient or employee dexterity (Yancosek & Howell, 2009). But tests can suffer from floor or ceiling effects, whereby the instrument applied proves insensitive to a meaningful change in the level of function performed by an individual or sample (Andresen, 2000). Though studies have considered the relationship between movement rate and spatial accuracy in standardized motor tasks as a possible solution to the issue (Brenner & Smeets, 2011; Reis et al., 2009; Shmuelof, Krakauer, & Mazzoni, 2012), there is as yet no objective means of capturing spatiotemporal performance within a univariate measure, which makes changes in these measured skill parameters difficult to interpret with confidence.

Fundamentally, the lack of a working definition for motor skill that provides for the measurement of real-world tasks is a barrier both for clinical and laboratory-based study designs (Shmuelof et al., 2012). Skill in any given task is both demonstrated and improved by practice (Yarrow et al., 2009). Whereas performance is concerned with the quality of the execution of a physical activity, skill is defined by the capability to achieve a goal with speed and reliability of precision (Parthornratt, Parkin, & Jackson, 2011; Reis et al., 2009). We therefore defined practical motor skill in the following terms: the ability to achieve a practical goal with spatial success over a limited quantity of time. Under this paradigm skill improvement is concerned with improving the accuracy rate, or productivity, in achieving the spatial goal target. It follows that, if participants are to be assessed on these criteria, the appropriate measurement system needs to detect and record both spatial and temporal domains with precision.

In relation to human performance, Fitts and Radford considered the effect of movement rate on spatial variability with respect to a manual target with the upper limb (Fitts, 1954). In general terms, for a standardized target of difficulty I_D (unit of measure, bits) in an aiming task a subject must on average successfully commit sensorimotor control resources matching or exceeding I_D to achieve reliable targeting accuracy. When repeated attempts at a sequence of n standardized targets were made with proportional success *(n-error count)* over a mean movement time t, the parameter of performance index (I_P) emerged as a *mean rate* of information transfer capacity, effectively an accuracy rate with unit of measure bits/second (Fitts, 1954). Varying the cognitive approach (speed-emphasis, accuracy-emphasis, or self-selected cognitive approaches) under which subjects carried out motor skill tasks it was shown that, although reductions in movement time resulted in increases in task error, the peak information carrying capacity of the human motor system appeared quite constant under different cognitive approaches (Fitts & Radford, 1966). More recent experimental observations provided further statistical evidence that, in a sample of healthy humans carrying out a simple reciprocation task the information carrying capacity rate was not significantly disturbed within the limits of the movement rates imposed on subjects (MacKenzie & Isokoski, 2008). This parameter might represent a ceiling of human performance which is, within limits, insensitive to variations in movement rate and, at least in terms of peak performances under standardized instruction, change in emphasis toward speed or accuracy of movement (Guiard, Olafsdottir, & Perrault, 2011).

We set out to investigate whether these concepts could be generalized as a practical skill measure that was responsive to practice but did not vary significantly across behavioral emphasis and hence might be considered as a bias-resistant

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metric of motor skill. In order to support the gathering of task movement rate and spatial accuracy outcomes a sequential motor skill rehabilitation task (MSRT) was developed. This consisted of an array of standardized targets across each of which the volunteer was required to place a peg (Figure 1). Targeting variability exceeding the margins of each dichotomous target would be captured by the record of the number of errors incurred during each trial. Within a productivity centered interpretation of the Fitts paradigm the scalar task productivity rate (TPR) measure captured the successful utilization of targeting resources as an inverse function of Fitts' I_P, with units seconds per score (s/score).

Fitts and others showed that endpoint spatial variability appears directly proportional to movement rate and vice versa (Fitts, 1954; Meyer, Abrams, Kornblum, Wright, & Smith, 1988). We realized that Fitts' law had potentially important implications for task design, to facilitate both measurement and regulation of motor skill during skill learning. In accordance with Fitts' law, if the difficulty of all targets in the task array were identical then, as movement rate increased beyond a single threshold level, the rate of error would rapidly increase at every target. Sensitivity of the measure to changes in spatial variability would be lost, constituting a floor effect. Furthermore, observation of spatial error is vital both for regulation and learning of motor skill (Novick & Vaadia, 2011). We predicted that, if the task were made up of identical targets then, operating at any given movement rate subjects would observe either very high or very low levels of error during successive trials which might impair behavioral reorganization during skill learning.

As a solution to both of these problems we sought to create a marginal scaling of target difficulty within which subjects could develop motor skill and measures of the skill parameters could be taken. In order to achieve this we took the novel approach of manipulating target I_D by varying the rotation angle of each target in the array over an incremental range because, as a generalization target intolerance rather than target dimension may be a valid means of quantitatively characterizing target difficulty (Guiard & Olafsdottir, 2011). Randomization was applied to the order of target angle orientation to control for possible order and positioning effects, which are known to affect movement times (Pratt, Adam, & Fischer, 2007). To minimize a possible interference with declarative sequence learning (Ghilardi, Moisello, Silvestri,

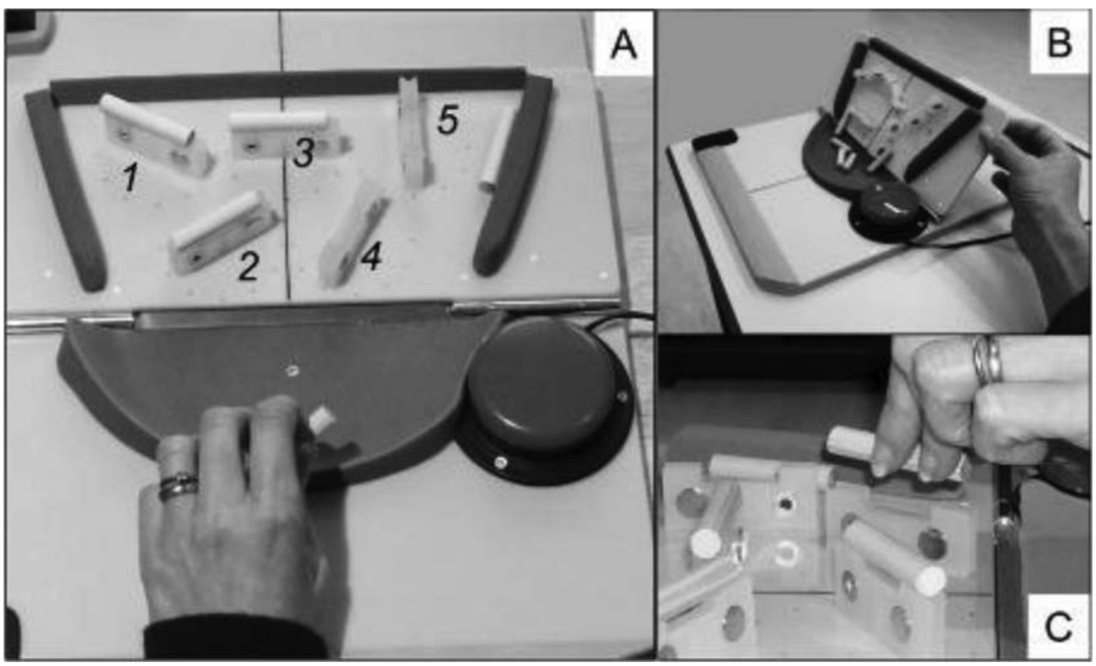

FIGURE 1. Motor skill rehabilitation task apparatus and procedure. All activities were carried out with respect to the left upper limb. (**A**) Rail angles were adjusted for each participant: illustrated are orientation angles 120°, 60°, 90°, 30°, and 0° with respect to the centerline of the apparatus (black line), which was itself aligned to the left acromion process of the shoulder. Trial procedure: The participant triggered the start of the trial by tapping the start–stop button. Pegs were grasped from the dish and placed on rail targets in consecutive order from left to right (1–5). The start–stop button was tapped once more to end the trial. (**B**) The investigator tilted the rail mounting board to return the pegs to the receiver dish in pseudo-random orientation. (**C**) Detail of rail and peg placement. Rails were engineered with a longitudinal groove to securely capture correctly placed pegs, and a central recession limits the effective target footprint dependent on relative orientation angle. An error was scored if a peg failed to retain contact with the upper surface of both raised rail areas following release.

Ghez, & Krakauer, 2009) this was designed to be attempted in consecutive order from left to right in all cases.

Research Questions and Testable Hypotheses

Research Question 1

We sought to answer the primary research question in relation to the importance of behavioral bias on skilled motor output: does the TPR univariate measure of motor skill vary significantly dependent on behavioral variation? Upholding the null hypothesis would not conclusively prove that this measure was stable across all conditions, but it would provide evidence that the TPR skill measure does not vary significantly due to changes in behavioral approach alone. Within the limitations of the study design, this would support our notion that, a common solution might exist to the speed/accuracy trade-off, which provides a stable metric of spatial motor skill.

Research Question 2

Fitts' law holds for static levels of skill (Guiard et al., 2011; MacKenzie & Isokoski, 2008) but ongoing task practice is thought to result from a breakthrough in the trade-off between speed and accuracy (Reis et al., 2009; Shmuelof et al., 2012). In the present study this would be interpreted from a significant improvement in the TPR score. We tested the sensitivity of the TPR measure as an indicator of motor learning, with the null hypothesis that the skill measure did not significantly change during free practice.

Research Question 3

It was theorized that target difficulty, and hence both the sensorimotor resources required to achieve target matching, could be manipulated by varying the orientation of the rail target. We sought to establish whether target difficulty constituted a stable scale for observations of spatial error, hence providing a reliable feedback condition for modulation of movement rate. The null hypothesis was that, based on observations of error, the relative target difficulty did not vary significantly during free practice conditions.

Research Question 4

The skill parameters of motor output and sensory experience are intimately associated in optimization of goal-centric motor performance through adaption (van Beers, 2009), which informs the development of more sophisticated motor engrams (Novick & Vaadia, 2011). As a parsimonious means of considering the relationship between the skill parameters we observed and analyzed the linear associations between the proxy skill parameters of MRST completion time and error rate during each condition. The null hypothesis was applied, that manipulation of behavior would not give rise to a significant difference in the strength of linear association between the skill parameters under the speed- or accuracy-emphasis conditions compared to the normative state.

Method

Recruitment

Eighteen healthy, right-handed (modified Edinburgh Handedness Inventory; median = 100, range = 67–100) adult staff or student members of the university population (10 women, 8 men; median age = 29 years, age range = 22–67 years) who were free from history of neurological deficit, upper limb orthopedic condition, or uncorrected visual impairment provided written consent to participate in this study, which was approved by the Research Ethics Committee of the School of Health Sciences and Social Care, Brunel University, London. Each volunteer carried out the study protocol during a single interval lasting around one hour, at a campus behavioral laboratory facility. All activities were designed and carried out in accordance with the Declaration of Helsinki. No financial or other inducement to take part in this study was provided.

MSRT Study Design, Task Apparatus, and Administration

A novel peg and rail task, termed the MSRT was designed in consultation with healthy and tetraplegic volunteers, in order to ensure that the TPR outcome derived from task performance could be applied to target groups with a wide spectrum of grasping abilities. The MSRT is described at Figure 1.

Study Protocol

The basic unit in this protocol was the block, which comprised 20 consecutive MSRT trials. All task activities were carried out with the left upper limb only, to investigate the formation of skill from a consistent naïve state across the right-handed volunteers. All participants followed the same protocol (Figure 2) with each participant assigned a five-element randomly generated nonrepeating motor sequence code. Following this code, the rotational angles of the MSRT rail components were set, to 0°, 30°, 60°, 90°, or 120° with respect to the centerline of the apparatus. Following two blocks of free practice (from which normative speed was calculated), speed-emphasis, accuracy-emphasis and normative behavioral blocks were carried out in counterbalanced, randomized order with each of the six possible sequences therefore being carried out by three participants.

Instructions and Applied Motivation

Standardized guidance observed by the researcher, and instructions to participants are available on request from the authors. Specific instructions in relation to behavioral conditions were issued as indicated subsequently.

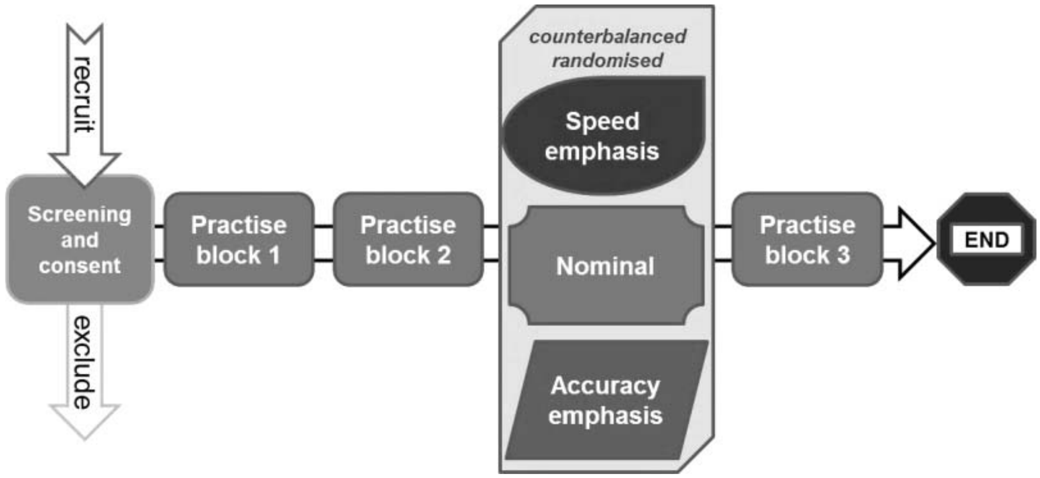

FIGURE 2. Study design schematic. The mean completion time of two blocks of 20 Motor skill rehabilitation task trials provided the metronome tempo guiding the completion rate of the subsequent movement-rate guided blocks. Behavioral manipulation is applied in three blocks, which are presented in counterbalanced randomized order: each block emphasizes completion speed, task accuracy, or nominal (combined speed and accuracy) conditions. Subjects were allowed 4–6 practice trials before each practice block and condition. A final block of trials at self-selected speed were gathered in order to assess short-term learning effects.

Practice Blocks

Participants were asked to carry out the task using any preferred grasp pattern or approach and using the left arm only, but as accurately and quickly as possible. This motivational statement was repeated once at the start and twice during the course of every block of 20 MSRT trials, with the terms *quickly* and *accurately* spoken in alternating order, in order to prevent biasing of behavioral approach to the task practice. First, after explaining the procedure, participants were directed to carry out practice 4–6 trials of the MSRT to demonstrate understanding of the instructions. Immediately following this, each participant carried out two blocks of 20 practice trials, in blocks 1 and 2. The mean completion time from these 40 calibration trials was immediately calculated from the spreadsheet record and generated the movement rates for normative, speed- and accuracy-emphasis blocks as per Table 1.

Participants then carried out a total of 60 behavioral manipulation trials, with the behavior manipulated by guidance of movement rate as discussed subsequently. Following these, participants carried out a final free practice block of 20 trials under the same conditions at practice blocks 1 and 2 in order to evaluate the sensitivity of the outcome measure to motor learning over the duration of the protocol.

Behavioral Manipulation: Effect of Speed on Spatial Accuracy

After the approach of MacKenzie et al. (2008), we manipulated the movement rate as the independent variable. A metronome was used to impose a movement rate, which would reliably guide participants to complete MSRT trials at a rate of our choosing.

In order to analyze the consequence of changing approaches to a task on spatial accuracy, we applied a movement rate (cadence) at the normative (guide) speed, 10% faster during speed-emphasis trials and 10% slower during accuracy emphasis trials. In order to entrain manual performance, participants were instructed to attend to the sound of an aural metronome tempo (Aroma Scroll-Wheel AM-703, Shenzhen City, China) as a guide to the desired movement

TABLE 1. Calculation of Metronome Guide Rates for Behavioral Conditions

Behavioral emphasis	Target completion time relative to measured calibration time (*G*)	Movement rate calculation (60*11)/*xG*	Example solution (assuming calibration time of 5.00 s), BPM
Normative	1.0	(60*11)/*G*	132
Speed	0.9	(60*11)/*0.9G*	147
Accuracy	1.1	(60*11)/*1.1G*	120

Note. Because the motor skill rehabilitation task (MSRT) comprised 11 idealized movement intervals between 12 spatial point positions in a full trial, 11 metronome beats signal the start of successive movements with each trial ending on the 12th beat. The calibration movement rates are derived from the mean MSRT completion time calculated from 40 trials over practice blocks 1 and 2. BPM = beats per minute/metronome cadence.

rate between each of the 12 critical point-to-point reaching movements involved in a single full trial of the MSRT task.

At each movement rate participants carried out 4–6 practice trials followed by a block of 20 trials at each metronome-guided movement rate in counterbalanced, randomized order. Task completion times were monitored online and volunteers advised to adjust movement rate accordingly if this diverged from the target. In all behavioral conditions participants were asked to maintain the best accuracy possible while moving at the indicated cadence. Completion times were monitored online throughout and, if necessary, participants verbally motivated to attend more closely to the required movement rate.

Data Capture and Calculation of TPR Skill Measure

The on–off trigger switch on the MSRT task assembly (JellyBean Twist, art. 4088, Inclusive Technology Ltd., Oldham, England) was connected to a Simple Switch Adaptor (Inclusive Simple Switch Box, art. 3208, Inclusive Technology Ltd.) into the USB port of a computer running Microsoft Windows software and program Microsoft Office Excel 2007. A stopwatch application was utilized as a freeware add-in for Excel (Filho, 2012). The layout of the apparatus was as shown in Figure 3.

During MSRT practice, repeated operation of the stopwatch button at the start and end of each trial automatically generated a spreadsheet output of trial durations, while the investigator recorded the number and the position of errors within the rail array as they occurred, for later analysis. The TPR score was then calculated as the completion time for each individual trial divided by the residual number of accurate placements achieved during that trial (Equation 1) to provide a parsimonious measure of task-specific information carrying capacity over the sampling period.

$$TPR = \frac{completion\ \ time\,(s)}{residual\,accuracy\ \ score\ \ (n)}(s/score) \qquad (1)$$

Equation 1: TPR, derived arithmetically from time score and residual accuracy score (number of correct placements).

Analysis

Data Summarization

The data were analyzed as absolute scores on interval scales, or as normalized data on ratio scales as indicated in the text.

Block Summary

For a standard analysis of completion time, aggregate error, or TPR score, each parameter was summarized by taking the arithmetic mean of the 20 trial scores within each block. Data were normalized to the relevant baseline condition score for each volunteer: the normative behavioral condition, or normalized to the baseline block 1 score for free practice.

Trial-by-Trial Summary

This was adopted as an approach to investigate the systematic association between the skill parameters underlying the skill measure during each of the free practice and behaviorally guided block conditions. The skill parameters of Task completion time and error score were separately summarized, creating datasets of 20 values for each practice block by taking the arithmetic mean of the raw values for each individual consecutive trial across the 18-strong participant sample. It was reasoned that the effect of synchronous, non-zero mean associations between the skill parameters over each 20-trial sampling interval would emerge.

Error Distribution Summary

For each participant and 20-trial block condition, the rate of errors counted from at each rail angle was expressed as a proportion of the sum of error across all angles. This provided for analysis of the interaction between target angle and the effect of the applied condition on the distribution of errors across the array.

Statistical Tests

Research questions 1 and 2 were tested by one-way repeated measures analysis of variance (ANOVA) with the main factor of practice/behavioral emphasis block to control for the possibility of rejecting a null hypothesis. Tests were applied to assess the effect of task practice on error rate, completion time and the TPR skill measure relative to the normative/baseline state. The factor of block (3 levels) was applied in each case.

Approaching research question 3, separate analyses on the error distribution-summarized datasets across free practice and behaviorally manipulated blocks was made by two-way ANOVA, with main within-subjects factors of Block (3) and Angle (5) in each case. The same analysis was applied to investigate variations in error distribution observed under behavioral manipulation. For further analysis of the differences in error distribution between paired behavioral conditions ANOVAs were carried out with Block (2) and Angle (5). Mauchly's test of sphericity was applied to all analyses and, where significant, degrees of freedom were adjusted using the Greenhouse-Geisser epsilon correction. Bonferroni corrections were applied for paired and post hoc comparisons of main effects as indicated in the text.

For research question 4, parametric associations between the error trial-by-trial summarized skill parameter datasets were calculated between the trial-by-trial summarized datasets using Pearson's product moment correlation coefficient (PMCC) to test the null hypothesis that the strength of association between paired correlations was not significantly different. Following this, comparisons of differences in correlation across paired conditions were made using the Steiger's test method advocated by Meng, Rosenthal, and Rubin (1992), following r-to-z transformation (Fisher, 1921).

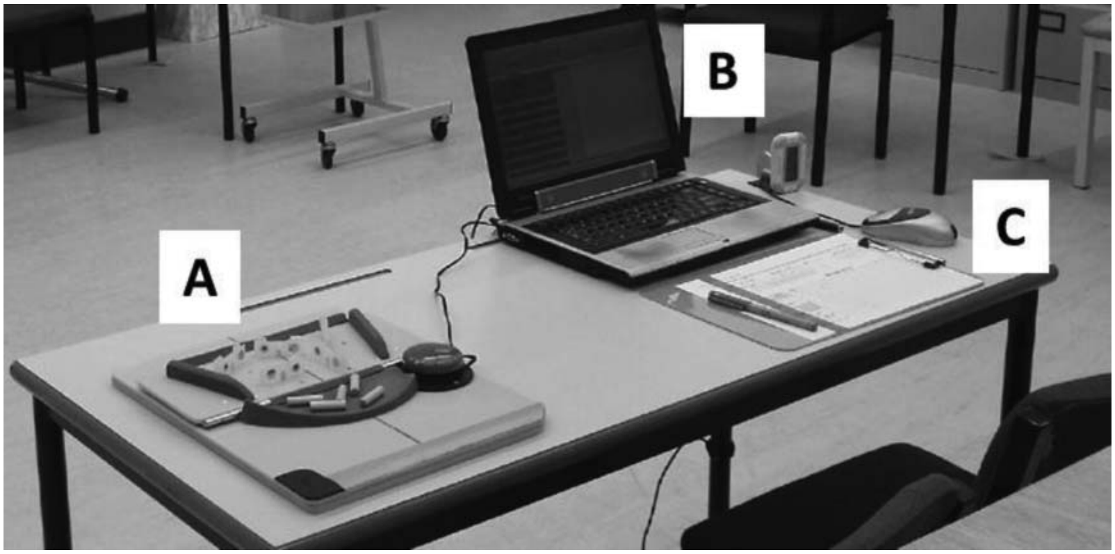

FIGURE 3. Layout of the motor skill rehabilitation task (MSRT) apparatus for left-handed training. The participant was seated with the MSRT apparatus (**A**) to the front. The MSRT start–stop button was linked to the computer (**B**) via a switch box and USB link. The investigator sits to the right of the participant, which provides for good surveillance of performance and physical access to reset the task without physically disturbing the participant. Resetting of the software-driven stopwatch via the computer mouse, and administration of the error log (**C**) was carried out by the same investigator.

The two-tailed significance of the z values was established from tables (Field, 2005). r_x dependencies between the predictor variable time series were calculated as the PMCC r between the time series for the relevant behavioral conditions. A Bonferroni correction was applied for multiple comparisons such that the level of significance was 2.5%.

Effect and sample size calculations were derived from Cohen's d (Lerman, 1996) where d values of 0.2, 0.5, and 0.8 represent small, moderate, and large effect sizes, respectively (Cohen, 1992). All statistical tests were performed using SPSS (version 15).

Results

The Effect of Manipulating Behavioral Approach on TPR

Results of the one-way ANOVA are given in Table 2. Behavioral manipulation of mean movement rate had a highly significant effect on task completion time in the accuracy-emphasis condition at 109.9 ± 1.4% and speed-emphasis at 90.6 ± 0.5% completion times, respectively, compared to the norm condition, $F(1.184, 20.133) = 144.96$, $p = .001$. Pairwise, there were highly significant differences ($p < .001$) in completion time compared to the normative movement rate (for accuracy, 95% CI [0.08, 0.11]; for speed, 95% CI [–0.14, –0.06]).

Compared to the normative state, when speed was emphasized to reduce the completion time by 10% the mean aggregate error approximately doubled to 200.6 ± 50.6% of the norm value. In contrast, when we increased completion time thereby allowing for increased accuracy, error was reduced to 78.8 ± 20.4% of that in the norm state. The main effect of varying movement rate on the occurrence of error was significant, $F(1.055, 17.943) = 6.291$, $p = .021$, with pairwise comparisons indicating a significant difference between the speed and accuracy conditions ($p = .005$; 95% CI [0.36, 2.08]). However, error during either of these

TABLE 2. The Effect of Free Practice and Behavioral Manipulation on Skill Parameters and Task Productivity Rate (TPR)

Behavioral condition	Main effect–interaction	F	df	p
Free practice	Error	2.193	2, 34	.127
	Time	51.553	2, 34	<.001***
	TPR	4.745	2, 34	.006**
Behavioral manipulation	Error	6.291	1.055, 17.943	.021*
	Time	144.960	1.184, 20.133	.001**
	TPR	2.465	1.387, 25.009	.121

Note. Results of separate one-way analyses of variance for the effect of free practice, or manipulation of behavioral conditions, across three blocks of 20 MSRT trials. TPR = Task Productivity Rate. Significant at $^{*}p \le .05$. $^{**}p \le .01$. $^{***}p \le .001$.

conditions relative to the normative state was not significantly different.

Although varying movement rate away from the normative condition in either direction resulted in an increase in the TPR score (speed emphasis: 7.1 ± 3.0%, accuracy emphasis: 2.3 ± 2.3%) the main effect of behavioral manipulation on TPR was not significant, $F(1.387, 25.009) = 2.465$, $p = .121$.

In order to test the limitations of the present study design and statistical power on the stability of TPR under behavioral manipulation we further analyzed the contrast between TPR datasets for control and speed-emphasis conditions under hypothetical conditions as follows. Greatest mean differences in TPR scores were observed between speed-emphasis and normative conditions. Simulating a two-condition crossover study design and applying a two-tailed hypothesis, paired *t* testing revealed a significant between-conditions difference, $t(17) = –2.360$, $p = .031$. The effect size for the difference between these paired conditions was calculated (with the recommended multiplier for paired data) as $d_{\text{paired}}\ \sqrt{2.d} = 1.110$, and the cohort size $n = \frac{15.7}{(1.110)} + 1 = 13.8$, indicating that under these quasiexperimental conditions a cohort sample size made up of 14 individuals would be required to reject the null hypothesis, with statistical power 80% and significance set at 5%.

A further, hypothetical experimental study design was considered where two well-matched, independent groups might produce the datasets under the speed-emphasis versus control conditions. Under independent *t* testing, the number of individuals per group required to reject the null hypothesis, where $d_{\text{independent}} = 0.785$ would be: $n = \frac{15.7}{(0.785)^2} + 1 = 26.5$. Thus, 27 individuals per group would be required to reject the null hypothesis under conditions involving independent groups.

The Effects of Free Task Practice on TPR

The main effect of practice on task completion time was highly significant, $F(2, 34) = 51.553$, $p < .001$ (Table 2). Normalized mean completion times relative to baseline for block 2 were 5.0 ± 1% reduced compared to baseline, and block 3 were 11.2 ± 1.2% reduced compared to baseline. Contrasts showed that successive changes in completion time were highly unlikely to be due to chance ($p < .001$; blocks 2 to 1, 95% CI [–0.08, –0.02]; blocks 3 to 2, 95% CI [–0.10, –0.03]; blocks 3 to 1, 95% CI [–0.15, –0.09]).

While, relative to the baseline condition, the error rate was increased slightly by 4.1 ± 15.0% in the second block and by 31.5 ± 13.1% in the final block the main effect of practice on targeting error was not significant, $F(2,34) = 2.193$, $p = .127$.

The main effect of practice on the derived TPR skill measure was significant, $F(2,34) = 4.745$, $p = .006$, between the first and final free practice blocks with the pairwise change in the mean TPR score indicating a highly significant improvement in skill between practice blocks 1 and 3 ($p = .001$, 95% CI [–0.16, –0.04]). However, pairwise contrasts showed the change in normalized score between *successive* blocks was not significant, with the block 2 mean score at 95.1 ± 3.3% and final block 3 mean score at 89.9 ± 2.2% of baseline TPR value.

Distribution of Error by Rail Orientation Angle

Observation of error distribution by target orientation (angle) showed that, in general peg placement at rail orientations of 30° and 60° were most reliably achieved while the highest spatial error occurred with placement attempts at rails oriented 120° and 0° from the apparatus midline (Figures 4 and 5). Because error was expressed proportionally in these analyses, comparisons by the main effect of block were not relevant.

Separate 2-way ANOVAs were carried out to establish the stability of apparent target difficulty in the datasets gathered, first under free practice conditions to address research question 3 (Table 3). Here, we found a highly significant effect of rail angle, $F(2.67, 45.415) = 4.836$, $p = .007$. Pairwise comparisons by angle showed a significant difference in proportional error between targets oriented at 0° and 60° ($p = .012$, 95% CI [0.02, 0.16]; Figure 4). The block by angle interaction was not significant, $F(8,136) = 0.691$, $p = .699$,

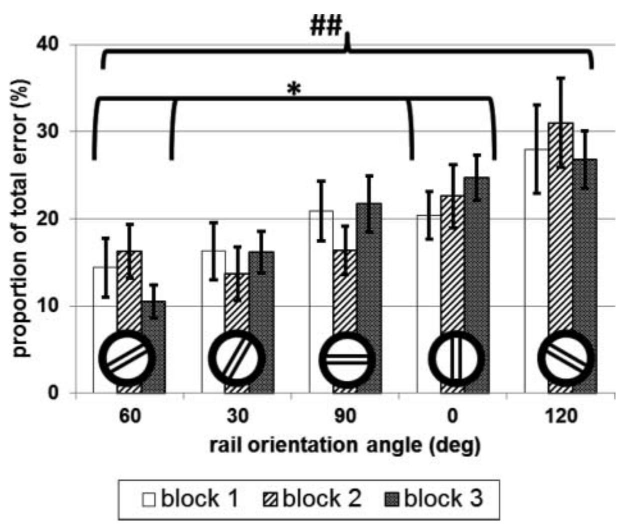

FIGURE 4. Proportional error distribution over successive blocks of free task practice. Proportional scaling of observed error distribution did not vary significantly over successive practice intervals and was quasi-linear according to the angle of target rail orientation. Two-way analysis of variance. Rail angle in increasing order of observed error, left to right. Distribution of error count per rail angle as a proportion of the total error count across all angles per interval ± standard error of the mean, over successive blocks. Angle graphic illustrates the respective rail orientation as seen by the participant. ## = significant main effect ($p \leq .01$); * = significant paired contrast ($p \leq .05$).

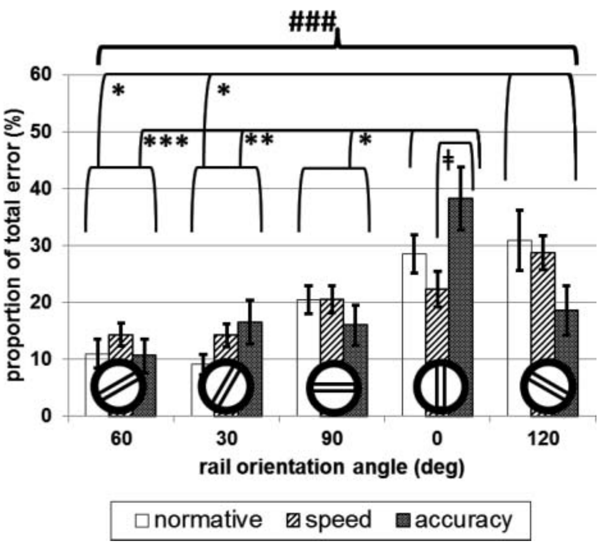

FIGURE 5. Highly significant variations in error distribution occur as a result of behavioral manipulation. Behavioral manipulations: normative speed, speed-emphasis and accuracy-emphasis conditions. Two-way analysis of variance. Angle graphic illustrates the respective rail orientation as seen by the participant, ordered left to right as per Figure 4. ### = highly significant main effect ($p < .001$) of rail angle with pairwise comparisons across conditions. Significant pairwise comparison at five rail angles between speed and accuracy emphasis conditions, Bonferroni corrected ǂ$p \leq .01$. *$p \leq .05$. **$p \leq .01$. ***$p \leq .001$.

demonstrating that the there was no effect of practice experience on the distribution of errors across the array.

The two-way ANOVA of the effect of behavioral manipulation on error distribution revealed a highly significant main effect of rail target angle, $F(2.505, 42.588) = 10.475$, $p < .001$, and also a significant interaction between behavioral block and angle, $F(4.142, 70.407) = 2.571$, $p = .043$ (Table 3). Pairwise comparisons of variations in error distribution between target orientations revealed significant pairwise differences $p \leq .05$ between target orientation 0° and targets at 30°, 60°, and 90°; 30°, and between the 120° orientation and the 30° and 60° targets (Figure 5).

Further investigating the contribution of behavioral manipulation to the distribution of error, three separate two-way ANOVAs were carried out for pairwise comparison of the differences in error distribution between specific guided states (normative speed, normative accuracy, and speed accuracy) with Bonferroni correction at the level 1.67%. In all comparisons, the within-conditions effect of rail target angle on the distribution of error was very highly significant (Table 4). For the block by angle interactions only the comparison between speed-accuracy was significant, $F(4, 68) = 3.542$, $p = .013$. Paired t testing was carried out within each rail orientation angle, with Bonferroni correction to 1%. Significant differences between conditions were identified only at the 0° target, $t(17) = -2.932$ $p = .009$ (95% CI [–0.275, –0.045]; speed vs. accuracy emphasis; Figure 5).

TABLE 3. Independent Effect of Free Practice and Behavioral Manipulation Conditions on Error Rate Distribution Across Target Orientations

Comparison condition	Main effect–interaction	F	df	p
Free practice	Rail angle error	4.836	2.671, 45.415	.007**
	Block by angle error	0.691	8, 136	.699
Behavioral manipulation	Rail angle error	10.475	2.505, 42.588	<.001***
	Block by angle error	2.571	4.142, 70.407	.043*

Note. Separate two-way analyses of variance on effects of free practice and behavioral manipulation. In each analysis, main effect of rail angle (5 levels) and interaction with block condition (3 levels) on the dependent variable proportional error rate across target orientations. Rail angle order was randomized per participant.
*$p \leq .05$. **$p \leq .01$. ***$p \leq .001$.

Coregulation Behavior Between Task Completion Time and Error Rate

The association between the trial-by-trial summarized skill parameters over each block condition was separately compared by PMCC with r and p values shown in Table 5.

TABLE 4. Separate Two-Way Analysis of Variance Comparisons of Error Distribution Between Paired Manipulated Behavioral Conditions

Comparison between behavioral condition	Main effect–interaction	F	df	p
Normative-speed	Rail angle error	7.833	2.256, 38.359	< .001***
	Block by angle error	1.640	2.346, 39.880	.203
Normative-accuracy	Rail angle error	10.220	4, 68	< .001***
	Block by angle error	2.191	4, 68	.079
Speed-accuracy	Rail angle error	6.730	4, 68	< .001***
	Block by angle error	3.542	4, 68	.013*†

Note. Repeated comparisons of the separate and interaction effects of rail angle (5 levels) and practice block (2 levels) on error distribution across targets of varying orientation. Rail angle order was randomized per participant.
*$p \leq .05$ ***$p \leq .001$. †$p \leq .0167$.

TABLE 5. Associations Between Sample Mean Trial-by-Trial Summarized Task Completion Time and Error Score Under Respective Block Conditions

	Practice blocks			Behaviorally guided blocks		
	1	2	3	Speed	Accuracy	Normative
PMCC *r*	.219	.292	.015	–.250	.015	.455
p value	.355	.212	.962	.287	.952	.044*

Note. Skill parameters summarized as sample means over successive trials. Cognitive manipulation blocks took place following practice block 2 and prior to practice block 3. PMCC r = Pearson product moment correlation coefficient.
*$p \leq .05$.

No significant correlations between completion time and error rate were found to occur over any of the free practice blocks. Furthermore, associations between skill parameters under speed and accuracy conditions were found to be non-significant. However, constraint of movement under the moderate, normative condition revealed a significant, moderate positive association between the skill parameters ($r = .455$, $p = .044$).

Paired differences in correlation coefficient for behaviorally manipulated conditions relative to that found in the normative condition were compared using the method described, applying r_x calculated as follows: $r_{x\,speed_{normatives}} = 0.299$; $r_{x\,speed_{normatives}} = 0.245$.
Paired z scores were calculated as $z_{paired\,speed_{normatives}} = -2.333$, and $z_{paired\,accuracy_{normatives}} = -1.407$.
From tables (Field, 2005) these z values equated to a two-tailed significance of $p = .020$ for the paired difference in correlations between speed-emphasis and normative, and $p = .159$ for the difference between accuracy-emphasis and normative conditions. With Bonferroni correction to level of significance 2.5%, the two-tailed alternative hypothesis was accepted only for the comparison between speed-emphasis and normative completion time and error correlation coefficients.

Discussion

TPR Did Not Vary Significantly Across Behavioral Conditions

Despite highly significant variations in guided movement rates the TPR skill measure did not vary significantly compared to the normative rate condition, upholding the null hypothesis. As variations in movement rate were imposed during behavioral guidance, there was a corresponding systematic impact on spatial accuracy such that TPR was not significantly affected. The results suggest that, when the variable of learning experience was controlled for, the sample of healthy subjects maintained a stable mean level of skill as we defined it, even when movement rates varied systematically by as much as 20%. The null hypothesis for research question 1 was upheld.

The generalizable inference is that, within limits, around an optimal peak performance specific to the individual and the task, there exists a common solution to the speed/accuracy trade-off function. This result is consistent with Fitts' law (MacKenzie & Isokoski, 2008) but is, we believe, the first time that the theory has been applied in respect of a practical manual visuomotor activity involving complex movement sequences.

The results concur with those found in analysis of performance levels in a simple reciprocation task, which likewise did not significantly differ over a range of movement rates (MacKenzie & Isokoski, 2008). Though the mean scores between behavioral conditions were not significantly different the data did show that reducing or increasing movement rate relative to the normative level resulted in a negative impact on TPR scores. The ability to demonstrate information carrying capacity of the individual may fall off away from an optimal central value, which could be partially dictated by the spatial parameters of the target (Fitts, 1954) or, indeed the behavioral approach (Guiard et al., 2011). In the interest of rigorously testing the limits of stability of the TPR outcome measure we further tested two different hypothetical scenarios. These results showed that TPR is only stable within limits and that the extent of behavioral manipulation alone may interact with the study design and sample size to give rise to large effect sizes. These findings are noteworthy when considering the statistical power of future study designs.

Skill Improved Significantly During Motor Practice

We additionally interrogated the data for evidence that the TPR skill measure was sensitive to practice and did, in fact, significantly vary over practice time as an indicator of motor learning. TPR responded significantly to MSRT practice, indicating that the improvement in motor skill seen was highly unlikely to be due to chance. As a straightforward quantitative finding consistent with other approaches to measurement of learning-dependent changes in the speed-accuracy tradeoff (Reis et al., 2009) the null hypothesis for research question 2 was rejected.

Even under the standardized instruction motivating subjects to prioritize the accuracy and speed of movements equally, highly significant reductions in completion time were found between successive practice blocks. But we found that the improvements in the TPR skill outcome were much less marked, and achieved significance relative to the naïve state only over an extended period of practice. Thus, though the increases in error rate over successive free practice blocks were not statistically significant, it was apparent that variation in spatial end-point variability must have had an important effect and skill improved more conservatively than we might otherwise have assumed if considering task completion time as the skill outcome. This suggests that the speed-accuracy relationships observed during behavioral manipulation may operate to some extent during free practice of the task.

As a potential limitation that may undermine direct comparisons between free practice and externally modulated behavioral conditions, there are thought to be differences in the coupling between changes in speed and accuracy depending on the demands of the task. Under velocity constraint a linear relationship between speed and accuracy is thought to hold (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), which may not be the case when accuracy and reaching distance alone are constrained and a logarithmic relationship might apply (Fitts, 1954). More fundamentally, these outcome relationships may be driven by differences in kinematic behavior that emerge from the specific temporal and spatial constraints of the task (Bongers, Fernandez, & Bootsma, 2009) and the particular behavioral motivation (Guiard et al., 2011). Despite these considerations, in comparing the datasets gathered during free practice against those gathered during the behaviorally constrained, normative movement rate the mean of sample absolute TPR measures obtained from free practice blocks 1 and 2 (during calculation of the normative movement rate) differed by only 1.2% from the mean TPR score measured during the subsequently performed normative guided state. This is an impressive convergence of skilled behavior in view of the possible statistical noise introduced by the complexity of the sequential targeting task and the external factor of auditory behavioral guidance.

It has been suggested that discontinuities in the speed-accuracy tradeoff (Sleimen-Malkoun et al., 2012) and related changes in velocity-time plots during reaching (Huys, Fernandez, Bootsma, & Jirsa, 2010) may arise primarily due to the precision constraints of the task because they are seen in relation to targets of higher difficulties. Because the reaching amplitude and targeting constraints of the present MSRT task were fixed within-subjects, these parameters probably interacted with net decreases in end-point reaching precision which arise with increasing movement rate (Meyer et al., 1988; Schmidt et al., 1979).

Even given a generous reach time (as in the accuracy-emphasis condition) the mechanism of on-line correction can statistically never fully control for random motor errors which arise during the enactment of target approach and placement movements (Meyer et al., 1988) or imperfect systematic sensory estimates of the true end-effector or target positions (Shadmehr, Smith, & Krakauer, 2010). But because the target scoring of the MSRT is dichotomous rather than continuous (e.g., as a standard deviation relative to an ideal target centre) any behavior-dependent differences in TPR score might be difficult to observe at low movement rates.

Spatial Error as a Modulating Parameter in Skilled Motor Activity

In the MSRT design paradigm target difficulty was manipulated, not by the conventional method of modifying component dimensions but by employing a reverse kinematic principle (Faraway, 2003; McFarland, Krusienski, Sarnacki, & Wolpaw, 2008) to enforce more or less complex grasp combinations across the motor sequence. The aims of this design criterion were twofold: to provide for target difficulty scaling in a fashion designed both to improve the linearity of measurement, and to facilitate a naturalistic motor learning experience. The design also provided for control for order effects by implementing true randomization of target orientation across the sample.

We found that the scale of target difficulty, as inferred from observations of error distribution, did not vary significantly when analyzed across free practice blocks and maintained a reliable distribution constituting a continuous quasilinear scale. In relation to research question 3, the null hypothesis was upheld.

By varying the single parameter of target orientation, the difficulty of otherwise identical sub-task elements was modulated to increase the range and sensitivity of the aggregate error measure, which we theorize provided for explicit feedback of spatial error to inform aspects of future performances, including movement rate. The finding that over successive practice sessions the error distribution did not significantly vary also lends support to the theory that skill learning reflects improvements in global control parameters such as refinement of reaching kinematics rather than improvements based on the accuracy constraints of specific targets (Shmuelof et al., 2012). The behavioral advantage of varying movement rates based on recent feedback of targeting error may be that movement rates can be regulated over the short-term, around a level that achieves the task objective according to the behavioral emphasis under operation (Brenner & Smeets, 2011).

Significant variations in the distribution of error were detected between the extremes of speed and accuracy emphasis behavioral conditions. It is thought motor learning results from reduction, not negation of net spatial variability (Müller & Sternad, 2009) with minimal correction of spatial error to optimally achieve the goal outcome (Todorov, 2004) while the variability of spatial trajectory in reaching increases as a function of movement planning both in relation to the accuracy demands of the task (Burge, Ernst, & Banks, 2008; Sleimen-Malkoun, Temprado, Huys, Jirsa, & Berton, 2012) and the intensity of muscle activations (Schmidt et al., 1979). It has been found that subjects' movement rate during a simple reciprocation task can be rapidly modulated by ongoing observations of accuracy during motor performance (Brenner & Smeets, 2011) and we also found that behavioral manipulation of mean movement rate during task execution had a significant and directly proportional effect on overall error rate.

Taken together, our results suggest not only that movement rate during free practice of the MSRT could have been modulated partially by the effects of target difficulty on the observation of error, but also that systematic variations in error at the most challenging targets were most evident to potentially inform the subsequent actions of subjects. Sensory observations of error are thought to interact with prior experience to modify ongoing motor performance (Novick & Vaadia, 2011). Thus, both the stability of the TPR outcome measure across behavioral conditions and the improvement in TPR scores over the duration of the session may reflect the operation of a simple mechanism for modulation of human behavior in complex motor tasks, whereby subjects' movement rate may be a response to systematic changes in the distribution of errors across targets of varying difficulty, as well as the overall rate of targeting errors as task repetitions continue. The possibility that individuals may be sensitive to errors incurred at more challenging targeting elements in a complex task concurs with the recent finding that, in a simple cyclic reciprocation task accurate targeting is immediately followed by increased movement rate while targeting error has a slowing effect on subsequent movement (Brenner & Smeets, 2011). Thus, rather than basing future physical strategies on an abstract knowledge of uncertainties which accrue in the human motor system, observations of spatial error may regulate completion time in an ongoing adaptation of the movement plan (Burge et al., 2008).

Systematic Associations Between the Skill Parameters

Our results in respect of the calculated TPR skill measure were consistent with Fitts' law in showing that, despite modification of behavioral approach under parallel skill states the construct of motor skill based on information transfer (of which the TPR is a derivative) was statistically robust. We have suggested that the criterion governing movement rate in the MSRT task was observation of spatial error. But was there any direct evidence of co-regulation between the skill parameters and, furthermore, was there evidence that behavioral manipulation significantly altered coregulation behavior?

A significant linear correlation between sample mean movement rate and spatial error scores, where error rate varied proportionally with completion time was only observed when behavior was constrained at the normative movement rate. Because normative movement rate was individually matched to the previously observed average of self-selected task completion times, it is appealing to generalize that the ideal movement rate emerged as a result of coregulation between the two skill parameters. We might consider this as further evidence that error-based feedback is a necessary and significant factor in regulation of movement rates about an ideal average in reciprocating reaching tasks, because motor skill is thought to arise through effective coregulation between goal-oriented motor activity and sensory detection of the result in relation to the goal, i.e., the degree of spatial error (Diedrichsen, White, Newman, & Lally, 2010).

A statistically significant difference in coregulation behavior between behaviorally manipulated conditions was found such that the alternate hypothesis for question 4 was accepted, providing further circumstantial evidence that co-regulation of movement rate and spatial error as a basis for motor control are found around a modulated, moderate movement rate. But the difference was only found between the speed-emphasis and normative conditions. Others have observed that, both in cyclic (Huys et al., 2010) and discrete (Sleimen-Malkoun et al., 2012) reaching–targeting task, reaching kinematics were abruptly disturbed above a breakpoint level of target difficulty. This discontinuity was considered to be inferential of the interaction between the limitations of the neuromusculoskeletal system and the accuracy constraints of tasks (Sleimen-Malkoun et al., 2012). As already discussed, because time is required in order to incorporate corrective motor actions toward the target, on average this may be proportional to the extent of motor noise in the control system (Meyer et al., 1988) which is perhaps the fundamental factor determining the outcome of skilled performance (i.e., precision) in manual tasks (Churchland, Afshar, & Shenoy, 2006).

We did not observe significant systematic co-regulation between the outcomes inferential of movement rate and spatial accuracy during free practice. It has been considered that, in a non-perturbed, stable environment, on-line sensory information should become *less* important to spatial accuracy as the adaptive elements of the motor system are tuned to the environment (Shadmehr & Mussa-Ivaldi, 1994). Thus systematic error, which arises through mismatches between the estimated and actual end-effector (object) and target positions (Missenard, Mottet, & Perrey, 2009; Shadmehr et al., 2010), is thought to be countered by the evolution of internal forward predictive models for environmental interaction that is recalibrated through ongoing experience (Burge et al., 2008; Kawato, 1999) via an estimate based both on immediate and historic sensory observations (Shadmehr et al., 2010). On the other hand, previous findings in respect of the importance of vision in aiming movements found that sensory feedback of both the target and hand position was important not only for learning of the skill but continued optimal movement accuracy in a spatially demanding task following learning (Proteau, Marteniuk, Girouard, & Dugas, 1987). That is, the random component of error due to innate noise in the CNS (Churchland, Afshar, & Shenoy, 2006) must continue to be corrected for through online processes close to the target, although estimation of the magnitude of spatial corrections required may inform task learning and future performance (Worringham, 1991). Thus, both the accuracy of the forward model based on experience (Smeets, Van Den Dobbelsteen, De Grave, Van Beers, & Brenner, 2006) and ongoing feedback of performance (Proteau et al., 1987; Sabes, Jordan, & Wolpert, 1998) are critical to the total effect of noise on the outcome. The developing forward model mitigates the combined effects of motor noise and systematic planning errors, with the systematic component tending to zero over time (Shadmehr et al., 2010; van Beers, 2009) while the component of random variability remains (Burge et al., 2008).

Taken together, the behavior observed under the normative condition may be predictive of a skill that is refined through experience, such that the speed-accuracy relationship acts to minimize the effect of random error on kinematic precision. As internal and external force environments governing systematic error are subject to change and an accurate knowledge of these is necessary for gain calibration of the sensorimotor system (Yarrow et al., 2009) the experience-dependent forward model may not remain stable between successive practice sessions. These notions could be tested by the gathering of data using the present task over longer periods of experience.

Conclusions

This study was concerned with investigating the properties of a novel univariate outcome measure inferential of task-dependent motor skill learning. In contrast to highly significant changes in the component skill parameter of task completion time, the TPR measure was statistically stable over large perturbations in behavioral approach. On the basis of this finding, highly significant changes in the TPR skill measure found over successive periods of task practice were considered unlikely to be due solely to behavioral adaption and were therefore true reflections of skill learning, although statistically significant outcomes due to behavioral bias may arise to an extent depending on the sample size or study design employed.

Altering rail target orientation was a reliable means of manipulating target difficulty during free task practice, constituting a reliable feedback condition against which movement rate might be modulated to improve performance in relation to the behavioral goal. Behavioral manipulation resulted in significant changes in error distribution and co-regulation behavior between the skill parameters, providing evidence that even during practice of complex motor tasks skilled behavior might emerge from direct observations of, and short-term response to, targeting error.

The constructs embodied by the TPR measure accord with Fitts' theories and can be related to previous findings in relation to the influences on motor control and learning. The univariate TPR outcome measure represents a simple approach to quantitative analysis of intervention-dependent changes in task-dependent skill that may reduce the effect of behavioral influences. MSRT trial measurements do not depend on full targeting success as a prerequisite and therefore accommodates the abilities of those with quite severe limitations in grasping and prehension abilities. The findings of the present study might inform the development of wide-spectrum measurement systems, to further unify findings in motor learning studies obtained from populations with diverse levels of physical ability. External validity and reliability should be further investigated both in healthy populations and neurological populations.

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