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THE IDENTIFICATION AND TRANSFER OF TIMESHARING SKILLS *

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Performance on two different task combinations was examined for evidence that timesharing skills are learned with practice and can transfer between task combinations. One combination consisted of two discrete information processing tasks, a short-term memory task and a classification task; the other consisted of two identical one-dimensional compensatory tracking tasks. Three groups of 16 subjects were employed in the experiment. The first received dual-task training on both combinations; the second received single-task training on the discrete-task combination and dual-task training on the tracking combination; the third received dual-task training on the tracking combination only. Evidence for distinct timesharing skills was found in both combinations using a new technique designed to separate improvements in timesharing skills from improvements in single-task performance. Transfer of timesharing skills also was found. Several fine-grained analyses performed on the data from the discrete task combination and a Control Theory Analysis of the tracking data indicated that skills in parallel processing were learned in each combination and transferred between them.

Introduction

Numerous theoretical treatments of attention have been proposed in the two decades since Broadbent (1958) outlined his classic single

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channel theory (e.g., Deutsch and Deutsch 1963; Norman 1968; Treisman 1969; Keele 1973; Kahneman 1973; Norman and Bobrow 1975). Although these theories have successfully accounted for many of the complex aspects of behavior observed in dual-task performance, they have, by and large, assumed an operator who is well trained and approaching asymptotic performance. Few have considered the mechanisms and structure of *learning* to perform under dual-task conditions. In spite or perhaps because of this absence, arguments have been made by Moray (Moray and Fitter 1973; Moray 1976; Ostry et al. 1976) that dual-task or timesharing performance should be considered as a skill and the mechanisms involved in its acquisition should be better understood.

Some concern with the relation between learning and attention is evident in recent theoretical treatments that have emphasized the decreasing demand for processing resources of certain mental activities resulting from practice (LaBerge 1974; Norman and Bobrow 1975; Schneider and Shiffrin 1977). If a task demands less attention with practice and attention is viewed as a commodity or resource of limited availability, then with practice the task should be performed better concurrently with other activities. Such treatments, however, account for improved timesharing performance in terms of a change in the characteristics of single-task demands – a view that has its historical roots in the concept of automation (*e.g.*, Bahrick and Shelley 1958). They fail, in short, to account for the development of timesharing skills that may be unique to the multiple-task situation, such as the parallel processing of information, rapid switching between tasks, or the use of efficient response strategies.

To date, such timesharing skills have not been clearly isolated, identified, or. examined. Therefore, evidence for their existence as distinct psychomotor skills must be obtained from studies which permit performance on a multi-task combination to be attributed in part to performance on the component tasks and in part to timesharing skills, if they are present. Two experimental paradigms, providing what will be designated longitudinal and part-task, whole-task evidence, permit this type of a separation. In the first timesharing skills may be identified by examining changes in multiple-task performance with practice. If single-task performance remains relatively constant during the period in which multiple-task performance improves, then the improvement may be attributed to the development of timesharing skills. Investigations by

Bahrick and Shelley (1958) and Kalsbeek and Sykes (1967), employing visual and auditory choice reaction time, and by Gopher and North (1977), employing visual choice reaction time and compensatory tracking, all obtained longitudinal evidence for the development of timesharing skills. That is, in each case aspects of dual-task performance were observed to improve with practice as single-task performance remained stable.

Part-task, whole-task evidence may be obtained by examining the relation between part-task and whole-task performance for complex tasks. Bilodeau (1955) developed a technique for predicting time-on-target scores for multiple tracking tasks by assuming that the probability of being on target in one task was independent of the probability of being on target in another. Both Bilodeau (1955, 1957) and Hoppe (1974) found part-task, whole-task evidence for timesharing skills by observing that single-task time-on-target scores mispredict dual-axis or dual-task scores. Further evidence of this nature was provided by low correlations obtained between performance on single-task trials of perceptual motor tasks and on their timeshared combinations (Fleishman 1965). These results suggest that different skills are called into play in the timesharing environment from those that are used in single-task performance.

In addition to establishing the existence of unique timesharing skills, it is important to determine if these are general skills. That is, are there one ar more general timesharing skills which can transfer between different task combinations or are timesharing skills much more limited, contributing only to specific task combinations? Evidence of general timesharing skills may be drawn from studies showing either positive transfer between task combinations having no common elements or high correlations between performances on task combinations with no common elements.

Some correlational evidence for general timesharing skills may be inferred from studies of pilot training by Trankell (1959), Damos (1978), and Gopher and North (1976). In all three investigations performance on a dual-task battery administered during the early stages of pilot training correlated with later criterion measures of flight performance while single-task performance failed to do so.

Three studies that examined the intercorrelations between performance on qualitatively different dual-task combinations provided only mixed evidence for a general timesharing ability. McQueen (1917), employing five different task combinations, and Sverko (1977), employing four, failed to find any evidence of a general ability that accounted for performance variance common to more than one dual-task combination. However, Jennings and Chiles (1977), employing six tasks in two combinations, were able to identify a timesharing factor associated with timeshared monitoring.

Considered collectively, the experiments reviewed provide some evidence for specific and general timesharing skills. However, the studies as a whole have two major shortcomings:

(1) Timesharing skills were not isolated clearly in any of the experiments examined. The strongest evidence of identifiable skills comes from the longitudinal investigations. However, each of these studies has an interpretation problem because either the authors did not report all of the relevant data (Bahrick and Shelley 1958; Kalsbeek and Sykes 1967) or because improved single-task performance may have contributed to improved dual-task performance (Gopher and North 1977).

(2) None of the investigations showing evidence of timesharing skills indicated the qualitative nature of the timesharing skills that were present. To provide this type of information, a fine-grained analysis of the responses is necessary. Because the experiments were not designed to study timesharing skills, no such analyses were performed. Only Jennings and Chiles (1977) identified the nature of their timesharing skill as visual scanning. While this is clearly a skill required in timesharing tasks with visually separated displays, it is not concerned with information processing as such and for the purposes of this paper will not be considered a timesharing skill.

The present experiment was designed to provide additional information on timesharing skills and examines three specific questions: First, do distinct timesharing skills develop in different task combinations? Second, can specific timesharing skills, such as parallel information processing or intertask switching, be identified? Third, are there general timesharing skills that will transfer among complex tasks that do not share common elements?

Measurement technique

To isolate timesharing skills, it is necessary to partition the improvement found with practice on multiple-task combinations into com-

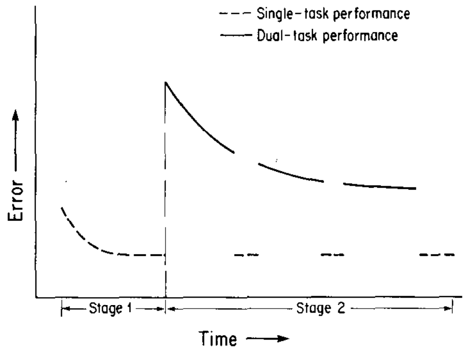

Fig. 1. An example of the measurement technique used to identify timesharing skills. During Stage 2 dual-task performance (solid line) improves with practice. Because single-task performance (dotted line) remains stable during the same period, the improvement may be attributed to the development of timesharing skills.

ponents due to improved single-task skills and a component due to improved timesharing skills. A technique designed to achieve this separation during two stages of training is illustrated in fig. 1. During Stage 1, which involves single-task training, each component task is practiced until performance has stabilized. Then during Stage 2, which is predominantly dual-task training, single-task performance is reassessed periodically to determine its stability. If multiple-task performance improves during Stage 2 while single-task performance remains stable, the improvement may be attributed to the development of timesharing skills.

To demonstrate statistically the development of timesharing skills using this technique, a two-factor (secondary-task load by trials) analysis of variance may be applied to the Stage 2 data. Two effects must be statistically reliable to demonstrate the development of timesharing skills: the effect of secondary-task load indicating a dual-task decrement and the secondary-task load by practice interaction. This interaction in conjunction with stable single-task performance implies that the improvement in dual-task performance is the result of improved timesharing skills, not improved single-task skills.

Task selection

To examine timesharing skills, it is of central importance to select task combinations in which timesharing skills make a significant contribution to multiple-task performance. Simply requiring two tasks to be performed 'concurrently' does not insure that timesharing skills will contribute significantly to multiple-task performance. Although it is currently impossible to specify exactly the types of task combinations in which timesharing skills are significantly involved, it may be presumed that the inputs to the two tasks must be statistically uncorrelated and that the response selection and execution stages of the two tasks can not be integrated. If either of these two conditions is not met, the subject may be able to combine the tasks and reduce the processing load to a single-task rather than a multiple-task level. Task combinations which require timesharing skills also should show a performance decrement when compared to single-task levels of performance indicating that the tasks have not been integrated and that there is some time pressure on the subject to perform the task. In selecting task combinations to examine transfer of timesharing skills, the similarity of the stimulus and response elements of the training and transfer task combinations also must be taken into consideration; as the similarity of the elements of the two task combinations increases, the probability that the transfer of single-task skills will obscure the transfer of timesharing skills increases.

Using the criteria discussed above, two task combinations were selected for use in this experiment. The first combination consisted of two discrete information processing tasks: a short-term memory task (STM) and a classification task (CL). The second combination consisted of two identical tracking tasks (TR-TR). The selection of tracking has an added benefit in that it is amenable to various quantitative analysis techniques that allow a careful examination of the precise nature of the timesharing skills that may develop.

More specifically, fine-grained analyses performed on the tracking data can identify three separate 'modes' of dual-task processing; serial, parallel, and independent. These modes can be identified from parameters yielded by two different analysis techniques – a time-domain analysis of response holds (Cliff 1971) and a quasi-linear analysis to identify the subject's transfer function (Licklider 1960; Wickens 1976). In the latter approach a best-fitting linear differential equation, the transfer function, is used to model the subject's processing of the time-varying error signal to produce the control response and the parameters of this transfer function are identified. Time-dependent changes in the parameters thus derived will be employed to infer development of timesharing skills either via a change in the extent of one mode of processing or a

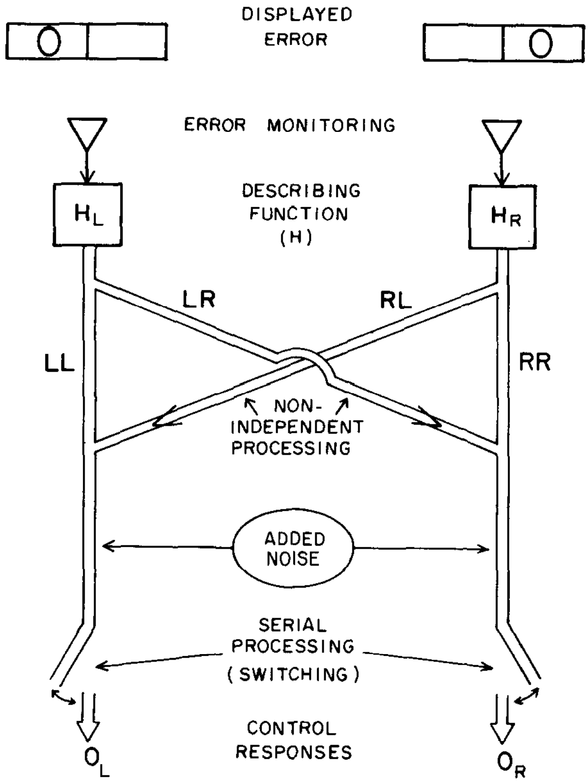

Fig. 2. Schematic representation of the information processing requirements in dual-task tracking.

switch with practice from one mode to another.

To understand the logic with which these analytical techniques will be employed, consider the schematic representation of the subject engaged in dual-axis tracking shown in fig. 2. In this figure the two displayed error cursors are indicated at the top. The processing of these errors by the subject to formulate the corrective response is indicated by the operation of the two transfer or describing functions, H_L and H_R. In the optimal timesharing system the transformed error information is relayed directly to the appropriate responding hand to produce the manual outputs O_L and O_R.

In such a system there exist three potential sources of nonoptimality: (1) serial processing behavior could interrupt the flow of information along one or both channels indicated in fig. 2 by the switch opening as information on the other task is processed, (2) a non-independence of information processing could produce a 'cross-talk' of the two channels with commands intended for one hand inadvertently issued to the other along the paths RL and LR, (3) a decrease in the parallel flow of information along either channel could occur through a decrease in signal strength (an insufficient correction of perceived error) or an increase in 'channel noise' even as processing remains continuous and independent. Each of these sources of non optimality will be discussed in the Results section as they bear on the timesharing skills developed.

The experiment

Method

Tasks

Classification. For this task two randomly selected digits between five and eight were presented simultaneously to the *S*. The digits varied on two dimensions: size and name. The *S* determined the number of dimensions on which the stimuli were alike and then pressed one of three keys on a keyboard attached to the left armrest of the *S*'s chair. As soon as the *S* pressed a key, the pair was erased and a new pair presented 40 msec later.

Three dependent variables were calculated for each trial: the average interval between stimulus and response (ARI), the average interval between correct responses (CRI), and the percentage of correct reponses to the total number of responses emitted (PCR). The average CRI differs from the ARI in that incorrect responses are not counted in its calculation. That is, when an incorrect response occurs, the CRI is the time between the preceeding correct response and the next correct response including the time during which the incorrect response was made. Two of these variables, the PCR and the CRI, were displayed to the *S* at the end of each single- and dual-task trial.

Short-term memory. In this task randomly selected digits between one and four were presented sequentially to the *S*. The *S* retained the most recently displayed digit in memory while responding to the preceding digit. For example, if the first stimulus were '1' and the second '3', the correct response to the '3' would be '1'. Responses were made via a four-choice keyboard attached to the right armrest of the experimental chair. The keys were numbered from left to right beginning with '1'. The response to the first stimulus of any trial was always '1'. As soon as a response was made, the stimulus was erased and the next one was presented.

Three dependent variables were recorded: ARI, CRI, and PCR. At the end of each single-task and dual-task trial the CRI and the PCR were displayed to the *S*. Under dual-task conditions the digits for the CL task were presented on the left

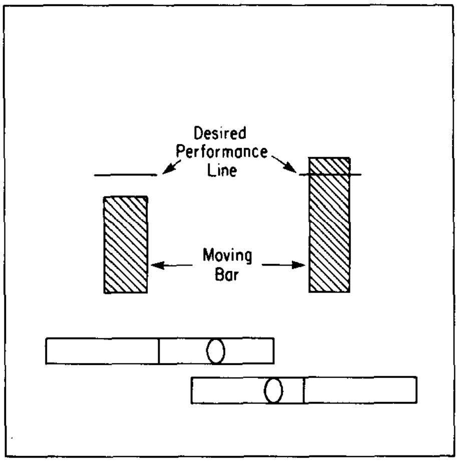

Fig. 3. The dual-task tracking display.

side of the display screen; the digit for the STM task was presented on the right side. The visual angle subtended by the display was 1.09° by 0.31° (0.019 by 0.005 rad).

Tracking. Two identical one-dimensional compensatory tracking tasks each required the *S* to keep a moving circle centered in a horizontal track by making appropriate left–right manipulations of a control stick. One task was controlled by each hand. The inputs to the two displays were independent random forcing functions with an upper cutoff frequency of approximately 0.32 Hz. The control systems had mixed first- and second-order dynamics with weightings of 0.25 and 0.75 respectively.

Average absolute errors were calculated for each task and presented to the *S* at the end of each trial, one indication for single-task trials and two for dual-task trials. Additionally, the positions of the control stick and the error cursor were recorded every 120 msec for later offline analysis. Fig. 3 shows the display of the TR-TR combination. The tracking tasks that were controlled by the left and right hands were appropriately offset to the left and right of the display center. The visual angles subtended by the display were 4.05° by 0.70° (0.07 by 0.01 rad).

Desired performance lines ('goal lines') and actual performance bar graphs, similar to those used by Gopher and North (1976, 1977) and North (1977), were employed to control the *S*'s task priorities and provide concurrent feedback (see fig. 3). Each performance bar reflected the absolute error averaged over the last 5 sec for its associated tracking task. The height of the bar was related inversely to the error. The height of the goal lines represented 27% absolute error of the displayed scale length, which was the transfer criterion. The *S*'s goal was to make both performance bars reach their respective goal lines as quickly as possible. Criterion was reached on the first trial during which the average height of the feedback bars reached or exceeded the goal lines.

Apparatus
The stimuli for all tasks were presented on a 10.2 by 7.6 cm Hewlett-Packard Model 1300A cathode ray tube. A Raytheon 704 computer generated all inputs for the tasks, recorded and processed all of the *S*'s responses, and timed all the trials. The keys on the STM and CL keyboards were arranged linearly on each keyboard and placed in a comfortable position for the average female hand. The tracking tasks employed two identical Measurements Systems Incorporated Model 435 two-axis, spring-centered control sticks. Both sticks were modified to permit movement in the left-right dimension only.

Design
A three-group transfer of training design was used in this experiment. The Dual-Task Transfer Group received dual-task training on both Day 1 (STM-CL) and Day 2 (TR). The Single-Task Transfer Group received single-task training on the STM and CL tasks on Day 1 and dual-task TR training on Day 2. The Control Group recieved no training on Day 1 and dual-task TR training on Day 2. Sixteen *S*'s were assigned randomly to each group.

Subjects
Sixty-five right-handed female *S*s were recruited from advertisements placed in campus buildings. None of the *S*s were pilots. Before beginning the experiment, all of the *S*s completed two pretests that were used as screening devices. One pretest was the Bennett Test of Mechanical Aptitute, a timed, written test. The second consisted of one trial on the TR-TR combination. Before performing the TR-TR combination, the *S*s completed one trial on each component task alone. Because one of the purposes of the experiment was to study transfer of timesharing skills, the pretest scores were used as selection measures to identify *S*s who were not likely to reach the transfer criterion. Six *S*s were eliminated from further participation in the experiment based on their pretest scores. The *S*s who subsequently participated in the experiment were paid by the hour. In addition monetary prizes based on performance were established at the outset as incentives. The three *S*s with the best performances on Day 1 in the Dual-Task Transfer Group and in the Single-Task Transfer Group received bonuses of \$ 10, \$ 6, and \$ 4 respectively. Additionally a \$ 5 bonus was awarded to the *S* in each group who had the lowest average error on the last two dual-task trials on Day 2 and another \$ 5 bonus to the first person in each group to reach criterion.

Procedures

Day 1 training. The training for the Dual-Task Transfer Group followed the plan discussed for identifying timesharing skills. That is, blocks of dual-task training trials were interrupted periodically by single-task trials to assess the stability of single-task performance. The Single-Task Transfer Group received training that was as similar as possible to that received by the Dual-Task Transfer Group except that the *S*s never performed the two tasks simultaneously.

*S*s in each transfer group received a total of 46, 1-min trials grouped into six blocks of 10, 8, 7, 7, 7 and 7 trials. There were 1-min breaks between trials within a block, 2-min breaks between Blocks 1, 2, and 3 and 4, 5, and 6, and a 15-min break between Blocks 3 and 4. Block 1 consisted of ten single-task trials during which *S*s alternated performing the two tasks. Half of the *S*s in each group began with the STM task, half with the CL task.

For the Dual-Task Transfer Group, Block 1 training corresponded to the Stage 1 training discussed previously (p. 19) and training thereafter to Stage 2 training. Beginning with Block 2, these *S*s first received five dual-task trials followed by one single-task trial on each task. The order in which a given *S* received the single-task trials was alternated between blocks. If under dual-task conditions a *S* emitted a long series of responses on each of the tasks before switching to the other task (a strategy that will be referred to as massed), instructions to limit this type of behavior were given during breaks between blocks. The *S*s in the Single-Task Transfer Group continued to alternate between the two tasks throughout Day 1.

Day 2 training. Day 2 training for the transfer groups was conducted on the day immediately following Day 1. All groups were treated identically on Day 2. The *S*s received a total of 39 1-min trials grouped into six blocks of 2, 9, 8, 8, 8, and 4 trials. There were 2-min breaks between trials within a block, 2-min breaks between Blocks 1, 2, and 3 and 4, 5, and 6, and a 15-min break between Blocks 3 and 4. Blocks 1 and 6 consisted of single-task trials only. One-half of the *S*s in each group performed the left-hand TR task first in each of these blocks; the other half began with the right-hand task. Again, Block 1 training was equivalent to Stage 1 training. Pretest data indicated that repeated single-task trials during Stage 2 were unnecessary to estimate the stability of single-task performance for this task combination. Therefore, the only set of single-task trials administered during Stage 2 occurred in Block 6. Performance on Blocks 1 and 6 was used as a baseline to measure the development of timesharing skills.

Results

Development of timesharing skills in the STM-CL task combination

To demonstrate the development of timesharing skills, the data must demonstrate a reliable effect of secondary-task load and a reliable secondary-task load by trials interaction. Additionally, single-task performance should remain stable with practice. In fig. 4 the data for each task show a large effect of practice on dual-task performance, a small effect on single-task performance, and an apparent trials by secondary-task load interaction.

Performances in terms of CRI on the first dual-task trial on each block, the last dual-task trial of the experiment, all Stage 2 single-task trials, and the last two Stage 1 single-task trials were analyzed for each task. Both the STM and the CL data were found to violate the assumption of homogeneity of variance ($F_{\max_{15,12}} = 20.75$, $p < 0.01$; $F_{\max_{15,12}} = 208.66$, $p < 0.01$, respectively). However, STM data transformed by the equation $x' = \log(x + 1)$ did meet the assumption ($F_{\max_{12,15}} = 4.05$, $p > 0.05$), and a two-way, fixed-effects ANOVA was performed on the transformed data. The main effects of secondary-task load and trials were reliable ($F_{1,15} =$

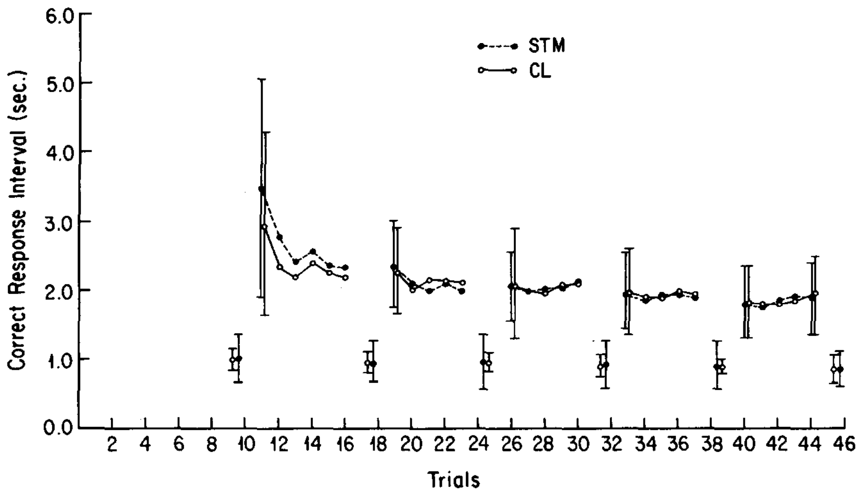

Fig. 4. The correct response interval (CRI) as a function of practice for the Dual-Task Transfer Group on Day 1. The upper connected points represent dual-task performance. The lower points represent single-task performance.

222.36, $p < 0.001$; $F_{5,75} = 13.04$, $p < 0.001$, respectively). Additionally, the load by trials interaction was reliable ($F_{5,75} = 6.67$, $p < 0.001$). The improvement in CRI for dual-task performance was 1034 msec over trials. The corresponding change for single-task performance was 108 msec.

For the CL task one data point from the last single-task trial was approximately 3σ below the distribution mean and 2σ below the S's own mean. With this datum included in the distribution no suitable transformation could be found. Therefore, this point was classed as an outlier and was replaced with the average of the S's three preceding single-task trials. The CL data then were transformed using the equation $x' = 1/x$ and found not to violate the assumption of homogeneity of variance ($F_{\max 15,12} = 3.83$, $p > 0.05$). A two-way, fixed-effects ANOVA (trials by secondary-task load) conducted on the transformed data indicated reliable main effects of load ($F_{1,15} = 572.95$, $p < 0.0001$) and trials ($F_{5,75} = 27.34$, $p < 0.0001$) and a reliable load by trials interaction ($F_{5,75} = 3.44$, $p < 0.01$). The improvement in dual-task performance with practice was approximately 1575 msec while the corresponding change in single-task performance was 166 msec. Thus, the improvement in dual-task performance again was approximately ten times the improvement in single-task performance.

Identification of timesharing skills in the STM-CL combination

Several fine-grained analyses were performed on the digit data to examine the nature of the timesharing skills developed in this task combination. These analyses were designed to determine if certain response strategies were associated with good dual-task performance and to examine changes in switching time and parallel processing as a function of practice.

Response strategies. Three distinct strategies could be identified for the STM-CL task combination: simultaneous, alternating, and massed. A simultaneous response strategy was defined as one in which the *S* responded consistently to both stimuli within 99 msec of each other. An alternating strategy was defined as one in which the *S* alternatively made one response on each task. If more than two responses were emitted consistently before switching to the other task, the strategy was classified as massed.

The relation between the response strategy adopted and dual-task performance on the discrete task combination was examined using the Kruskal-Wallis one-way ANOVA. The response strategy groups were found to differ reliably ($\chi^2_3 = 9.06$, $p < 0.05$) on the mean CRI for the last dual-task trial. Of the four groups (the two *S*s using a mixed strategy were classified as one group) the simultaneous response group had the lowest mean CRI. The difference between single- and dual-task mean CRI averaged over both tasks and summed over all dual-task trials also was examined using this test. Again the groups were reliably different ($\chi^2_3 = 9.49$, $p < 0.05$) with the simultaneous-response group having the lowest total difference between single- and dual-task performance.

One possible explanation for the superiority of the simultaneous response group was that individuals with high single-task dexterity adopted this strategy. This hypothesis was tested by analyzing the *S*'s single-task data. A Kruskal-Wallis one-way ANOVA of the CRIs indicated no reliable between-group differences on single-task performance ($\chi^2_3 = 4.69$, $p > 0.05$). Thus, between-group differences on single-task reaction time did not account for the differences in dual-task performance.

Parallel processing. A fine-grained analysis also was performed to investigate the development of parallel information processing with practice. The simultaneous response group, which consisted of six *S*s, was selected for examination because this group had the highest probability of developing a skill in parallel information processing. The development of such a skill was examined by comparing dual-task to single-task ARI. If the *S* processed information in serial but responded to the stimuli simultaneously, the dual-task ARI should be approximately equal to or greater than the sum of the single-task ARIs for the STM and CL tasks. If the dual-task ARI is less than the sum of the single-task ARIs, then some overlap of processing the two stimuli may be inferred.

Because some improvement in single-task performance did occur with practice on both tasks, single-task performance was averaged across each block of dual-task trials to obtain a more stable and representative baseline for the corresponding dual-task block. Thus, ARI scores of the single-task trials preceding and following a given block were averaged by task and summed to obtain the estimated dual-task ARI under the assumption of serial processing. Performance on the middle dual-task trial was selected for analysis to avoid any warm-up effects or fatigue effects that might be associated with the first and last trials of each block. The dependent variable for analysis then was the difference between the estimated and obtained ARI measures. A positive difference indicates that the obtained ARI was larger than the predicted ARI and no parallel processing occurred while a negative score provides evidence of overlapping (parallel) processing. The difference scores were analyzed using a random walk procedure. The direction of change from each trial to the next for each S was scored as +1 (an increase), −1 (a decrease), or 0 (no change). The final score for four Ss was negative, one was positive, and one was zero indicating respectively a decrease, an increase, and no change in the difference score. Using the binomial distribution, the overall probability of obtaining the observed results was $p = 0.081$.

Rapid intertask switching. A third fine-grained analysis was conducted to examine changes in switching behavior as a function of practice. The five Ss who employed the alternating response strategy and the three Ss who employed the massed strategy were selected for examination because changes in switching behavior were determined most easily for these Ss. To examine switching behavior, it was assumed that the S processed information from only one task at any given time. The switching time then could be estimated by examining the difference between the single- and dual-task ARI for those stimuli that were followed by a switch.

Again, the middle dual-task trial of each Stage 2 training block was selected for examination. Single-task performance was estimated from the single-task trials preceding and following the block. A mean switching time was obtained by comparing the dual-task ARI averaged over both the STM and the CL tasks to the single-task ARI averaged over both tasks. A positive difference indicates that the mean dual-task ARI averaged over both tasks was larger than the corresponding mean single-task ARI. Using the same procedure described in the Parallel Processing section, the difference scores for five Ss decreased with practice, two increased, and one showed no change. The overall probability of obtaining the observed results was $p = 0.062$.

Development of timesharing skills in the TR-TR combination

The same technique employed in analyzing the STM-CL data was used to demonstrate the development of timesharing skills in the tracking combination. Fig. 5 shows tracking performance for all three groups as a function of practice. Again, the data show a large effect of practice on dual-task performance, a very small effect on single-task performance, and a strong secondary-task load by trials interaction. Performance on the first dual-task trial, the last dual-task trial, the second single-task trial, and the third single-task trial (Trial 36) were analyzed. These data violated the assumption of homogeneity of variance ($F_{\max_{12,15}} = 6.30$, $p < 0.05$). However, because the cell means and variances were not related in any systematic fashion and the violation was not strong, the untransformed data were analyzed using a three-way, mixed-effects ANOVA (Lindquist 1953). The main effects of load ($F_{1,45} = 1113.67$, $p < 0.0001$) and trials ($F_{1,45} = 217.20$, $p < 0.0001$) were reliable. The main effect of groups was not reliable ($F_{2,45} = 0.39$, $p > 0.05$). The load by trials interaction was the only reliable interaction ($F_{1,45} = 319.21$, $p < 0.0001$). The average improvement in dual-task tracking performance was 27.1% while single-task performance improved 0.9%.

Fine-grained analyses of the tracking data

The fine-grained analyses discussed previously were designed first to determine which processing mode (serial, parallel, or independent) was being used at a given

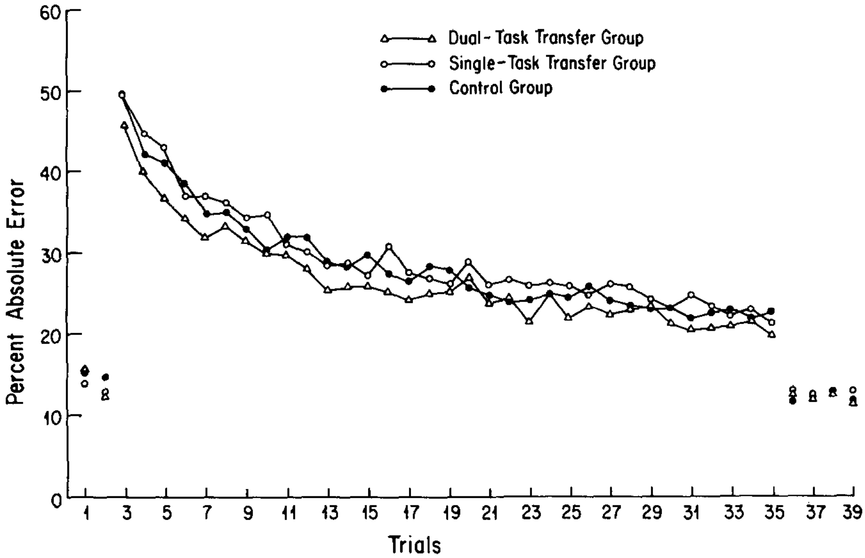

Fig. 5. Average percent absolute error as a function of practice for all three groups. The unconnected data points represent single-task performance; the connected ones, dual-task performance.

stage of practice and, second, to examine changes in the extent or type of processing mode used as a function of practice.

Serial processing. If timesharing behavior is initially serial (the tracking strategy analogous to the massed or alternating strategies identified with the discrete task combination), then such seriality should be revealed by a pattern of response 'holds' – periods in which no control action is initiated on one axis even though it is appropriate to do so (Cliff 1972). With extreme serial processing, as in the massed or alternating strategy, these holds will be multiplexed between the two axis such that control action will only be exerted on one axis at a time. If serial behavior attenuates with practice, hold frequency and/or duration will decline accordingly.

The total duration of holds was calculated for each *S* on two dual-task trials (Trials 3 and 35) for each tracking task separately and for the first two single-task trials (Trials 1 and 2) and the first two single-task trials following dual-task tracking (Trials 36 and 37). A four-way, mixed-effects ANOVA did not indicate reliable main effects for groups, tasks, secondary-task loads, or trials. Additionally, no interaction was reliable. Since the average total time holding was only 2.1 sec (considerably less than the length of the tracking trial), it is clear that during much of the trial the *S*s were responding simultaneously.

Parallel processing. The mere demonstration that serial responding does not dominate, as demonstrated in the obtained pattern of simultaneous responding, does not by itself establish that parallel *processing* is present. To accomplish this it also must be established that responses are coherently and consistently related to the preceived error information on each axis, and in this endeavor a quasi-linear analysis of the data was performed.

The quasi-linear modeling approach (Licklider 1960; Wickens 1976) assumes that the S in either single- or dual-axis tracking operates as a processor or transmitter of signal information to which is added a noise process referred to as *remnant*. The characteristics of the transmission process are revealed by the linear transfer function or describing function between input (perceived error) and the linearly correlated portion of the output. Those of the noise or remnant are expressed as the ratio of output power uncorrelated with the error to total output power. When this ratio is subtracted from unity a measure referred to as *linear coherence* is produced which expresses the proportion of total output variance that is linearly correlated with input – a kind of signal to noise ratio.

Given the close association between the linear coherence measure in tracking and the measure of continuous information transmission (Baty 1970; Sheridan and Ferell 1974), it is proposed that the development of parallel information processing – an increase in the bandwidth or signal-to-noise ratio of the two information channels – may be revealed by identifying an increase in the coherence measure with practice. Following the logic of timesharing skills analysis described in the section on measurement technique, it should be noted that such an increase must be obtained in the absence of any corresponding increase in the single-task coherence measure.

Three different measures of coherence were examined. The first, ipsilateral coherence, reflects the coherence between each error signal and its appropriate control response (see fig. 2). The second, contralateral coherence, indicates the coherence between an error signal and the opposite hand (channel cross-talk). The third reflects coherence between the two error signals. To obtain estimates of these values, four data signals – error and stick position for the left and right tasks – were employed as inputs to the Biomedical Spectral Analysis Program (BPMDO2T). This program computed discrete fast Fourier transforms on the time series and generated the linear coherence and amplitude ratio spectra between each error signal and both outputs. For single-task conditions only the coherence and amplitude ratio spectra between the error and appropriate output were computed. Both amplitude ratio and coherence data were averaged across subjects and hands. Because of the cost associated with these analyses, only the data of the Dual-Task Transfer Group and the Single-Task Transfer Group were analyzed.

Before the statistical analysis was performed, it was noticed that ipsilateral coherence varied with frequency. Because frequency was of no interest, an average value of coherence was calculated at each component frequency. Deviation scores at each level of load, practice and group then were computed at each frequency component and an analysis performed on the deviation scores with frequency as the replication factor.

A three-way ANOVA performed on the ipsilateral coherence scores indicated reliable effects of load ($F_{1,144} = 675.199$, $p < 0.001$) and trials ($F_{1,144} = 265.869$, $p < 0.001$) but no reliable effect of group ($F_{1,144} = 3.022$, $p > 0.05$). Both the load

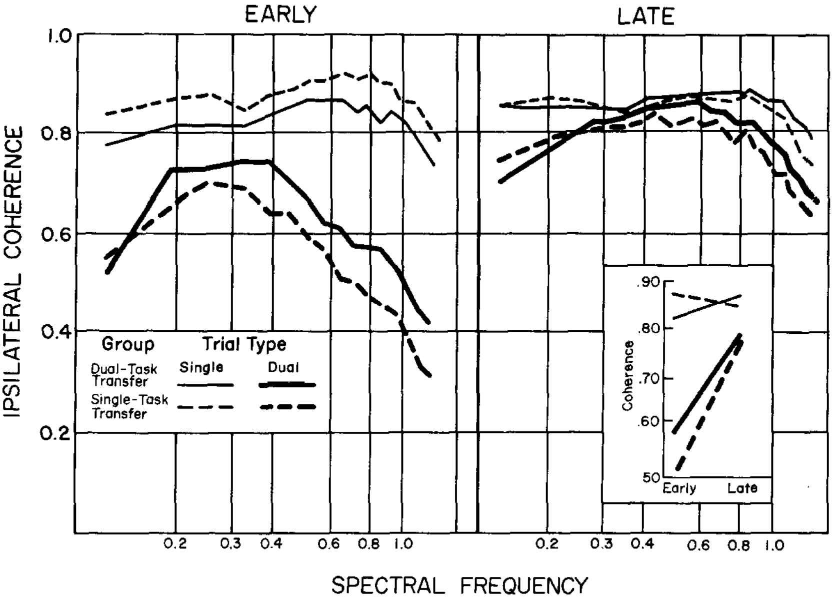

Fig. 6. Ensemble averages of ipsilateral coherence for the Dual-Task and Single-Task Transfer Groups as a function of task load and practice. The insert shows the ensemble averages averaged across the frequency spectrum.

by group interaction ($F_{1,144}$ = 17.478, $p < 0.001$) and the load by trials interaction ($F_{1,144}$ = 238.582, $p < 0.001$) were reliable. The three-way interaction, load by group by trials, also was reliable ($F_{1,144}$ = 16.914, $p < 0.001$).

Fig. 6 shows single- and dual-task ipsilateral coherence as a function of tracking frequency for the Dual-Task and Single-Task Transfer Groups. The reliable load by trials interaction is represented in the figure by an improvement in dual-task performance for both groups with no corresponding change in single-task performance. This provides evidence for the development of a skill in parallel processing. Furthermore, the load by group interaction suggests that the Dual-Task Transfer Group showed a higher coherence value under timesharing conditions than did the Single-Task Transfer Group. However, on single-task conditions the order was reversed. Finally, the three-way interaction suggests that this coherence superiority of the Dual-Task Group under dual-task conditions diminished with practice, presumably as the Single-Task Transfer Group acquired the coherence-related timesharing skill (see fig. 6).

Insight into the nature of any dual-task coherence change can be revealed by examining the open-loop gain (the square root of the ratio of the output power linearly correlated with error power to the error power) of the fitted describing function (Wickens 1976). If a coherence increase results from a decrease in noise (remnant level), gain should remain constant. If, however, it is due to an increase in signal level such that larger control responses are exerted with each hand in response to error, gain should increase in correspondence with the increase in coherence. A three-way ANOVA performed on the gain measures obtained from the Biomedical Program discussed above revealed a pattern of results similar to that shown by coherence. That is, there were reliable main effects of load ($F_{1,144}$ = 236.891, $p < 0.001$) and trials ($F_{1,144} = 48.050$, $p < 0.001$), an unreliable main effect of group ($p > 0.005$), and reliable load by group and load by trial interactions ($F_{1,144} = 9.666$, $p < 0.01$ and $F_{1,144} = 32.225$, $p < 0.001$, respectively). Once again, the load by trials interaction represents the development of timesharing skills; single-task performance remained steady with practice while dual-task performance improved. The load by group interaction represents the fact that the control group showed higher gain than the transfer group under single-task conditions while the order was reversed under dual-task conditions.

Independent processing. For a two channel system in which each channel is perturbed by independent noise sources, processing may become increasingly parallel (coherence increase) with more information from each display transmitted to the appropriate control. At the same time the system may undergo an unrelated change in the extent to which information processing is *independent* between the two channels. That is, tracking commands intended for an ipsilateral control may be increasingly uninfluenced by commands delivered along the contralateral channel. Thus, to evaluate the extent of independent processing the contralateral coherence spectra also may be examined as a function of practice. A brief inspection of the coherence data revealed that generally the contralateral coherence was low, indicating little motor cross-talk. Additionally, there was no evidence of systematic differences as a function of practice or group. Therefore, these data were not analyzed further.

While the analysis of tracking holds and contralateral coherence indicated that independent processing was demonstrated along the two axes, this conclusion also was verified by examining the error-error coherence measure. A serial processing, alternating, or switching strategy should produce some out-of-phase coherence between the error signals to the extent that operators allow error on one task to build up while correcting that on the other task. This will be emphasized to the extent that there exists periodicity in the switching strategy. Like the contralateral measures, the mean error-error coherence was uniformly low (less than 0.20) and did not differentiate between either the level of dual-task practice or the two experimental groups. Furthermore, examination of both the error-error and the contralateral coherence spectra failed to reveal any systematic peaks that might be indicative of intermittent timesharing behavior but whose contribution to the mean spectral values would be lost in the averaging process.

Transfer of timesharing skill

Before examining transfer of timesharing skills, the performance of the Single-Task and Dual-Task Transfer Groups must be compared on the CL and STM tasks. If the Dual-Task Transfer Group's performance were reliably better than that of the Single-Task Transfer Group, and if the Dual-Task Transfer Group had greater transfer from Day 1 to Day 2 some of the transfer could be attributed to single-task skills rather than timesharing skills. Performance on all Stage 2 single-task trials was examined for the Dual-Task Transfer Group and the corresponding trials for the Single-Task Transfer Group. The data were examined using a three-way (groups, trials, and task), mixed-effects ANOVA. Only the main effect of practice was reliable ($F_{4,120} = 13.47$, $p < 0.001$) indicating that the groups did not differ reliably on single-task skills.

Fig. 5 indicates a superiority of the Dual-Task Transfer Group over the other two groups that is consistent across the duration of the session. To asses the extent of this transfer of timesharing skills, a transfer formula proposed by Murdock (1957) was used to calculate percent transfer for the two transfer groups. This formula is:

$$(C - E)/(C + E) \times 100\% = \text{percent transfer}$$

where:

C is the trials to criterion for the control group,
E is the trials to criterion for either transfer group.

Three *S*s in the Dual-Task Transfer Group, three in the Single-Task Transfer Group, and two in the Control Group did not reach the criterion of 27% average absolute error during the 33 dual-task trials. No attempt was made to readjust the criterion level because these eight *S*s evidently would never have reached a reasonable level of timesharing performance. For those *S*s who reached criterion, the Dual-Task Transfer Group had 13.9% transfer between Days 1 and 2 and the Single-Task Transfer Group had 0.8% transfer.

Discussion

The purpose of this experiment was to investigate the development and transfer of timesharing skills and to examine the characteristics of any timesharing skills that developed in the task combinations under study. To examine the development of timesharing skills, a new measurement technique was devised and used in the experiment. Evidence for the development of timesharing skills was found in both the STM-CL and the TR-TR combinations.

For both task combinations single-task performance was not totally stable in Stage 2. However, the small changes in performance (166 msec for CL, 108 msec for STM, and 0.9% for TR) are desirable in that they indicate that performance had not yet reached asymptote on any of the three tasks and avoided a single-task ceiling effect that would have made interpretation of subsequent improvements in dual-task performance difficult. Additionally the change in single-task performance was so small in each task compared to the corresponding dual-task change that it seems evident that timesharing skills developed in each combination.

Although the interaction between task load and practice observed in both task combinations is interpreted as evidence for the development of timesharing skills, there are, however, at least two alternative explanations that must be considered. One explanation is that the interaction indicating the development of timesharing skills rests on a number of questionable assumptions about the metric of the dependent variables. Therefore, it may be argued that a transformation of the data could eliminate the interaction. To test this hypothesis, a log transformation, which represents an extreme transformation for these data, was performed on the tracking data. An ANOVA on the transformed data revealed reliable main effects of load ($F_{1,45} = 785.4209$, $p < 0.01$) and trials ($F_{1,45} = 119.3718$, $p < 0.01$) and a reliable load by trials interaction ($F_{1,45} = 135.4506, p < 0.01$).

The second explanation is that single-task processing becomes more efficient with practice (consumes less of the operator's attentional resources) even as single-task performance remains unchanged. Norman and Bobrow (1975) have proposed that the performance-resource function – that function which relates performance to the quantity of resources invested – can be differentiated into resource-limited regions in which the quality of performance is proportional to the resources invested and data-limited regions in which performance is unchanged by investment or withdrawal of resources. The explanation of the effects described above would posit that single-task performance is data limited and that the amount of resources required to reach that data-limited region becomes progressively less with practice. Thus, the combined resource demands of the two component tasks performed concurrently fall into a resource-limited region and become correspondingly less after practice than before. Therefore, dual-task performance will improve even as data limited single-task performance remains constant.

Two arguments, however, suggest that this interpretation cannot account for the data, particularly as it applies to the results of the tracking-tracking combination. First, the processing demands of the tracking task are such that it is unlikely that this task could be described as data-limited. The tracking task *per se* does not impose demands that would excede any processing characteristics that might represent sources of data limitation (*e.g.*, capacity of short-term memory, speed of response, or resolution of perceptual processing). Second, direct evidence was presented by the fine-grained analysis of tracking behavior supporting the view that timesharing skills *were* developed and could account for the obtained interaction. This evidence will be summarized below.

The present data also provide evidence that some aspects of the skills acquired in the discrete task combination transferred to timesharing performance of the tracking tasks. This transfer is evident in fig. 5 and was substantiated by a net percent transfer score favoring the Dual-Task Transfer Group. However, the ANOVA on the tracking data did not show a reliable main effect of group. This may be attributed to a large increase in variance with practice for the dual-task data which could have masked the effect.

A main effect of groups also may have been masked by the fact that a given amount of tracking error can result from a number of behavioral strategies requiring different timesharing skills. To determine if specific timesharing skills transferred and to determine the nature of the information processing changes that underlie the development of timesharing skills, a series of fine-grained analyses were performed on the data for both tasks. The pattern of results suggests that parallel processing skills were acquired in both tasks. Although the evidence for parallel processing in the discrete task combination was less pronounced than in tracking, two phenomena were observed that suggest its presence: (1) the group that clearly demonstrated a simultaneous response strategy out-performed those subjects who failed to do so; (2) the estimated amount of temporal overlap in processing of the two task stimuli increased monotonically with practice; the ARI difference scores were 0.070, 0.004, −0.074, −0.103 and −0.121 sec. Although this latter increase was not statistically reliable, it should be noted that the number of subjects was small with a resulting loss of power.

In the tracking data evidence for improvement in the parallel operation of information processing activities was provided by changes in two parameters: the ipsilateral linear coherence measure and the dual-task gain measure. The improvement in ipsilateral coherence with practice indicates a decrease in serial processing behavior and a concomitant increase in continuous processing. The increase in gain indicates an increase in the parallel flow of information along the noise-perturbed channels through an increase in the strength of the information signal. It should be noted that the improvement in the discrete task performance index (CRI) was manifest both in an improvement in accuracy and a reduction in latency. The former change would appear to be a direct analog of the increase in signal strength observed with the tracking task combination.

Because parallel processing skills were developed in each combination, it is logical to assume that a skill in parallel processing transferred between the combinations. The ANOVAs performed on the gain and coherence data support such a hypothesis; the pattern of interactions suggests that the superiority of the Dual-Task Transfer Group over the Single-Task Transfer Group was present in dual-task performance only. Furthermore, the superiority diminished with practice, as the Single-Task Transfer Group acquired some level of dual-task proficiency through training and thereby effectively 'caught up' to the skill level of the Dual-Task Transfer Group.

If a skill in parallel processing were learned and transferred between the task combinations, it is of some interest to determine which stages of information processing were affected by the development of this skill. However, the nature of the tasks do not permit the stages to be readily identified. The stages affected in the discrete task combinations are particularly difficult to identify because of the different response strategies employed by the subjects. For the subjects who employed the simultaneous response strategy, the response selection and execution phases seem to be the best candidates, especially since Sanders and Keuss (1969) demonstrated that subjects could learn to emit discrete responses simultaneously with practice. For the other two response groups the improvement in dual-task performance may be attributed more to the development of skills in rapid switching than to parallel processing. For the TR combination the changes in ipsilateral coherence and gain indicate that the response phases of processing again are the stages most likely to have been processed in parallel.

Some attention should be devoted to the question of individual differences in multiple-task performance. Evidence for consistent differences comes primarily from the different response strategies used in the discrete task combination; of the 14 subjects who adopted an identifiable strategy all selected the strategy within the first 2 minutes of practice and continued to use it throughout the session. Although this might indicate that subjects 'lock on' to strategies initially formulated, adopting a sort of response set from which it is difficult to shift even if it clearly hinders performance, two findings imply that the response strategy may reveal a more basic dimension of individual differences. First, the simultaneous response group had marginally better tracking scores and no subject in this group failed to reach criterion on Day 2. Second, subjects who used the masssed response strategy apparently were unable to initiate a different response strategy even when requested to do so.

Finally, it is of some interest to examine the implications of the identification of timesharing skills to the interpretation of some other dual-task research. Although any comments concerning the role of these skills in human information processing are necessarily speculative, the results of this experiment and those of Ostry *et al.* (1976) seem to indicate that timesharing skills decrease the extent of structural interference. That is, as practice continues and these skills develop, performance becomes more subject to capacity rather than structural limitations.

If timesharing skills do affect structural interference then these skills can be used to explain some puzzling results found in timesharing studies with tracking by Wickens (1976), Wickens and Gopher (1977), and Levison *et al.* (1971). All of these experiments found no increase in processing time between single- and dual-task conditions. Additionally, experiments by Levison *et al.* (1971) and Wickens (1976) found little evidence of sequential (single-channel) processing. These results can be explained by noting that all of these experiments employed either experienced pilots or highly trained subjects, who may be presumed to have highly developed timesharing skills. If timesharing skills reduce structural interference, then these results can be explained easily.

As noted in the Introduction few of the current models of attention take the effects of practice into account. If future research indicates that timesharing skills do indeed reduce structural interference, then a comprehensive model of attention would have to include a gradual change from structural to capacity limitations as these skills develop to give an accurate description of human performance.

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