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A QUASI-LINEAR CONTROL THEORY ANALYSIS OF TIMESHARING SKILLS

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Human involvement with complex systems often requires the operator to timeshare or perform several tasks concurrently. While it is apparent that performance under multiple- or dual-task conditions often benefits dramatically from practice, the precise sources of improvement are not clear. One possible source is further mastery of the single-task skills themselves. A second possible source is timesharing skills, which are hypothesized to contribute only to multiple-task performance and which do not develop under single-task conditions. To date, the identity, development, and generality of timesharing skills have not been clearly isolated experimentally. The present study examines performance with practice on two dual-task combinations — dual-axis tracking and two discrete information processing tasks — in an effort to identify the presence and development of specific timesharing skills, such as parallel information processing or rapid intertask switching. The generality of timesharing skills also is investigated by examining transfer of these skills between the two qualitatively different task combinations.

METHOD

Design

The experiment employed three groups. The dual-task transfer group, Group 1, received dual-task training on Days 1 and 2. Group 2, the single-task transfer group, received single-task training on Day 1 and dual-task training on Day 2. Group 3, the control group, received dual-task training on Day 2 only. Sixteen subjects were assigned at random to each group. Subjects in Groups 1 and 2 performed two discrete information processing tasks (short-term memory and classification) on Day 1. All subjects performed two tracking tasks on Day 2.

Task

Short-Term Memory (STM). Random digits between one and four were presented sequentially to the subject. The subject retained the most recently displayed digit in memory while responding to the preceding digit. For example, if the first stimulus was a "1" and the second a "3", the correct response to "3" was "1". The subject entered her response via a four-choice keyboard attached to the right side of the experimental chair. As soon as the response was made, the stimulus was erased and the next one presented. The dependent variable was the average interval between correct responses (CRI).

Classification (CL). Two randomly selected digits between five and eight were presented simultaneously to the subject. The digits varied on two dimensions: size and name. The subject determined the number of dimensions on which the stimuli were alike and pressed one of three keys on a keyboard attached to the left side of the subject's chair. As soon as the subject made a response, the pair was erased and a new pair presented. The dependent variable was again the CRI. Under dual-task conditions the visual angle subtended by the STM and CL tasks was 1.09° by $.31^{\circ}$.

Tracking (TR). Two one-dimensional compensatory tracking tasks each required the subject to keep a cursor centered in a horizontal track by appropriate left-right manipulations of a control stick. The two tasks were identical except that one task was controlled by the subject's right hand; the other, by her left hand. The disturbance input to each display was a random forcing function with an upper cutoff frequency of .32 Hz. The inputs to the two tasks were statistically independent. The transfer function of each system was $Y = K\ (.25/S\ +\ .75/S^2)$. Average absolute error was recorded after each trial while the position of the control stick and the error cursor was recorded every 120 msec for later offline analysis.

Figure 1 shows the display for the TR-TR combination. Also presented on the display were two performance bars similar to those described by Wickens and Gopher (1975). The two tracking error displays subtended a visual angle of 4.05° by $.70^{\circ}$.

Procedure

Day 1 Training. On Day 1, Group 1 received predominately dual-task training while Group 2 received training that was as similar as possible to that of Group 1 except that the subject never performed the tasks simultaneously. Subjects in each group received a total of 46, one-minute trials which were grouped into six blocks. During Block 1, the subjects alternated performing each task alone for a total of five trials on each

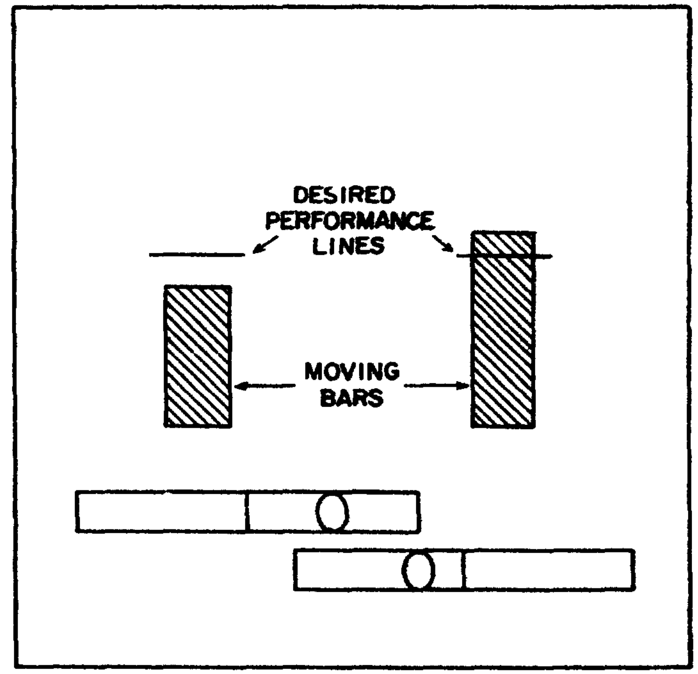

Figure 1. The dual-task tracking display.

task. Beginning with Block 2, the subjects in Group 1 received both single- and dual-task training. In each block, five dual-task trials were followed by one single-task trial on each task. The subjects in Group 2 continued to alternate between the two tasks throughout Day 1.

Day 2 training. Day 2 training was conducted on the day immediately following Day 1 training for Groups 1 and 2. All three groups were treated identically on Day 2. Each subject received a total of 39, one-minute trials grouped into six blocks. Blocks 1 and 6 consisted of single-task trials only and performance on these two blocks was used as a baseline against which to measure the development of timesharing skills.

Apparatus. The stimuli for all tasks were presented on a 10.2 by 7.6 cm Hewlett-Packard Model 1300A cathode ray tube. The tracking tasks employed two identical Measurement Systems Incorporated Model 435 two-axis, spring-centered control sticks. Both sticks were modified to permit movement in the left-right dimension only. All testing was conducted in a light and sound attentuated room. Subjects were seated 116 cm from the front of the CRT for all testing. The position of the input devices (keyboards or control sticks) was adjusted for each subject.

Subjects. Sixty-five right-handed, female subjects completed two pretests, the Bennett Test of Mechanical Comprehension and one trial of the TR-TR combination. Six subjects were eliminated from the experiment because one or both pretest scores were below established criterion scores. All subjects who participated in the experiment were non-pilots and were paid an hourly wage. Monetary incentives for good performance also were given.

RESULTS

Development of Timesharing Skills

Figure 2 presents single- and dual-task tracking error as a function of practice. It is clear that with practice there is a large improvement in dual-task performance while single-task performance remains stable. Thus, the improvement in dual-task performance may be attributed to the development of timesharing skills, not to further improvements in single-task skills.

Performance on tne STM-CL task combination showed a pattern similar to that of the TR-TR combination. Dual-task performance improved with practice while single-task performance remained stable. Again, these results may be interpreted as evidence for the development of timesharing skills in the discrete information processing task combination.

Transfer of Timesharing Skills

The amount of transfer of the timesharing skills from the digit task combination to the TR-TR combination was assessed by calculating the percent transfer and by examining between-group differences as a function of practice. Percent transfer was calculated based on the number of trials required to reach a criterion of 27% average absolute error of the displayed scale on both tasks simultaneously using the formula:

$$\frac{C-E}{C+E} \times 100\% = \text{percent transfer}$$

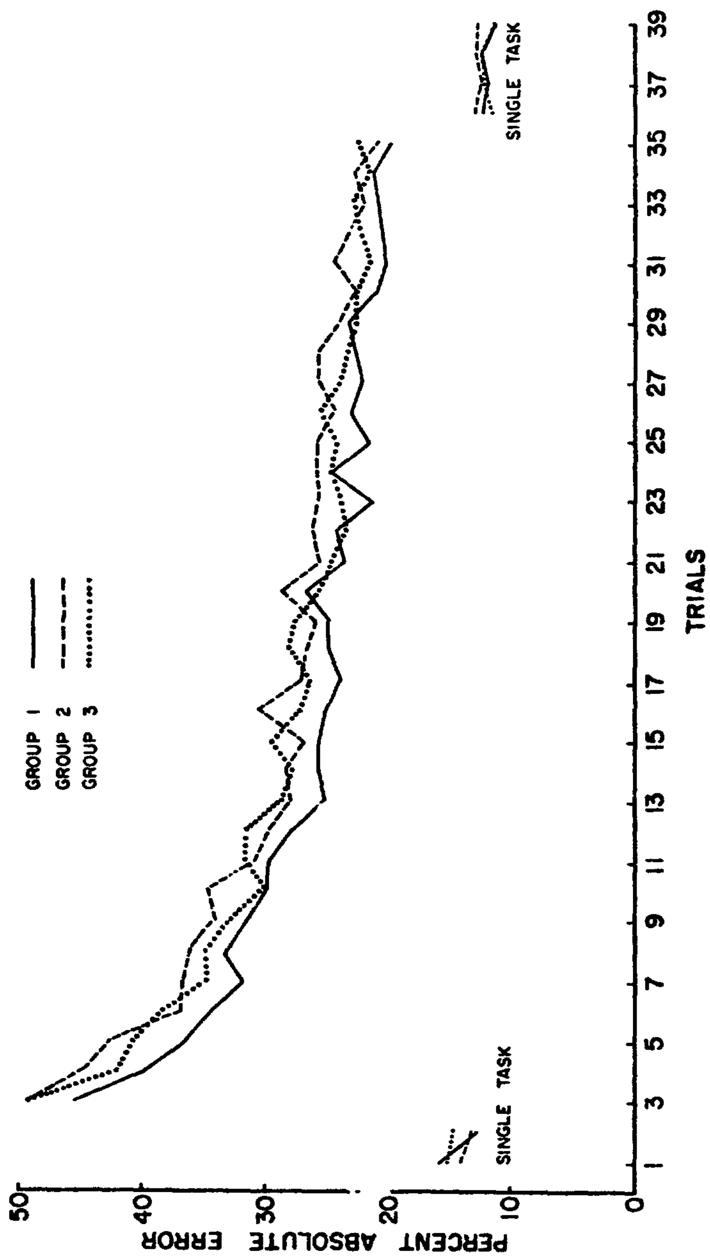

Figure 2. Average percent absolute error as a function of practice for all three groups. The unconnected data points represent single-task performance; the connected ones, dual-task performance.

where:

C is the trials to criterion for Group 3

E is trials to criterion for either Group 1 or 2

Eight subjects (three in Group 1, three in Group 2, and two in Group 3) failed to reach the 27% criterion. Group 1 had 13.9% transfer; Group 2 had .8% transfer, suggesting that the learning of the TR-TR combination benefited from dual-task but not from single-task practice on the digit task.

Between-group differences also were examined as a function of practice using analysis of covariance with the pretest scores as covariates. The main analysis was conducted on the 39 subjects who reached criterion. The main effects of both trials and groups were statistically reliable ($F_{2,\ 133}$ = 115.02, $p < .001$; $F_{2,116}$ = 3.38, $p < .05$ respectively). These between-group differences indicate a reliable transfer of timesharing skills for Group 1. The transfer of these skills may be seen in Figure 1 in which it is evident that Group 1's performance is generally superior to that of Group 2 and 3. To insure that the transfer effect was not an artifact of superior single-task performance, Groups 1 and 2 were compared on their terminal Day 1 single-task performance. These scores did not differ reliably between groups.

Control Theory Analysis

The preceding results indicated that the development of timesharing skills was manifest in the reduced dual-task error with practice. It was hypothesized that two processing changes might underlie the timesharing skills responsible for this performance increase: an increase in parallel processing or an increase in independent processing of the two information channels.

Parallel processing skill. To investigate the possibility that parallel processing increased with dual-task practice, analyses were undertaken of response holds, effective time delay, dual-task open-loop gain, and the linear coherence function. Response holds are periods of time during which the subject makes no control response although it is appropriate to do so (Cliff, 1971). If a subject develops a skill in parallel information processing, the total duration of holds in a given trial should decrease as the subject progresses from a serial to a parallel processing strategy. Furthermore, a decrease in the duration of holds should be accompanied by a corresponding reduction in the average phase lag or effective time delay between error and output (Wickens and Gopher, 1977, in press).

To investigate this possibility, the tracking control outputs of both tasks were scanned by a computer program that identified intervals of time, at least 240 msec in length, during which the output remained within a fixed amplitude window. These intervals were labelled holds and their total duration within a trial was tabulated. A four-way analysis of variance (trials, hand, group, and secondary task load) revealed no reliable effect of practice on hold duration.

The phase data then were analyzed to determine if these supported the conclusions drawn from the hold analysis. A spectral analysis (Biomedical Computer Programs, 1973) was performed on the tracking error and response data of all subjects on the first two, the middle two, and the last two dual-task trials. The phase lag data indicated, like the hold data, no change over dual-task practice and, therefore, also provide no evidence for the development of a parallel processing skill.

The emergence of parallel processing skills also was examined through the linear coherence function between error and output. A perfect parallel processing system should show a unity coherence between each error signal and the appropriate responding hand (ipsilateral coherence). As a consequence the emergence of parallel processing should be reflected by an increase in ipsilateral coherence toward the ideal unity value, even as single-task coherence remains constant. The uppper portion of Figure 3 presents the single-task coherence and the ipsilateral dual-task coherence averaged across spectral estimates (.1-2.0 Hz) and subjects at the early, middle, and late stages of practice. Single-task performance remains essentially constant while dual-task coherence for both groups increases with practice. This provides some evidence that a skill in parallel information processing developed.

This increase in linear coherence apparently is related to a corresponding increase in dual-task open-loop gain as single-task gain remains stable. This trend is shown in Figure 4 which presents a plot analogous to Figure 3 of the average amplitude ratio across spectral estimates. The characteristics of these data are almost identical to those of the coherence data.

Independent processing skill. While the extent of parallel processing may increase with practice, independent processing, the extent to which motor commands issued to each control are unaffected by simultaneous commands to the other control, also may increase. If a skill in independent information processing develops with practice, this motor "cross-talk"

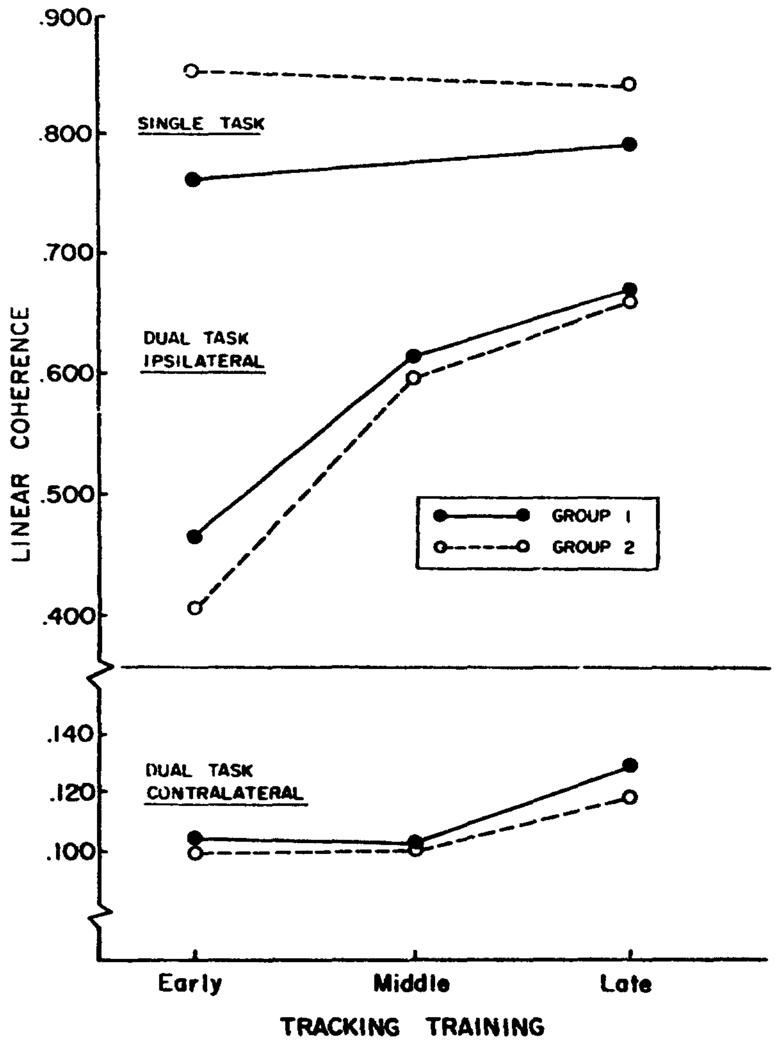

Figure 3. Linear coherence as a function of practice and secondary-task load.

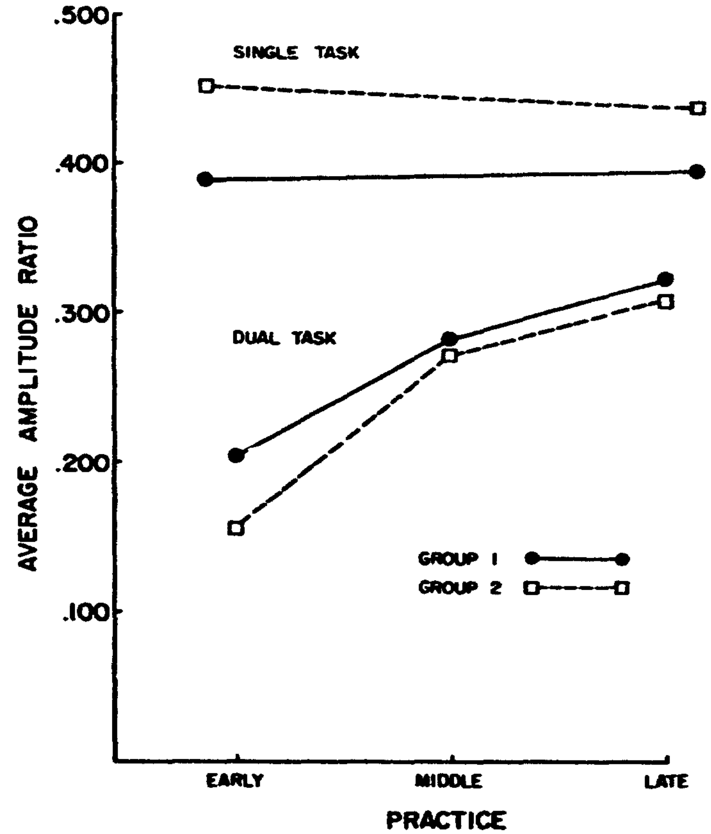

Figure 4. Average amplitude ratio as a function of practice and secondary-task load.

should decrease. To examine the extent of this crosstalk and its change with practice, the linear coherence function between each error and the opposite control response (contralateral coherence) was calculated at the three stages of practice. These data are shown in the bottom section of Figure 3. It is obvious that the contralateral coherence changes very little with practice and the change which does occur is an increase rather than a decrease.

Transfer of parallel processing skills. A fine-grained analysis of the performance of Group 1 on Day 1 revealed that some of the subjects developed a skill in parallel information processing. Because the control theory analysis indicated that a similar skill developed in the TR-TR combination, it was of interest to determine if the transfer of a parallel information processing skill between Days 1 and 2 could account for some of the transfer found using percent transfer and analysis of covariance. If such a skill transferred between the two days, the index of parallel processing shown by the subjects in Group 1 should have been initially superior to that of Group 2. With practice, however, this superiority should have diminished.

Figures 5 and 6 show the ipsilateral coherence spectrum and the amplitude ratio function as functions of practice for each group. Both measures show a change in performance with practice for both groups. More importantly, both graphs show that Group 1's performance early in practice was superior to that of Group 2, but with practice the two groups became indistinquishable. This indicates that the timesharing skill that transfered between Days 1 and 2 was, in fact, a skill in parallel information processing.

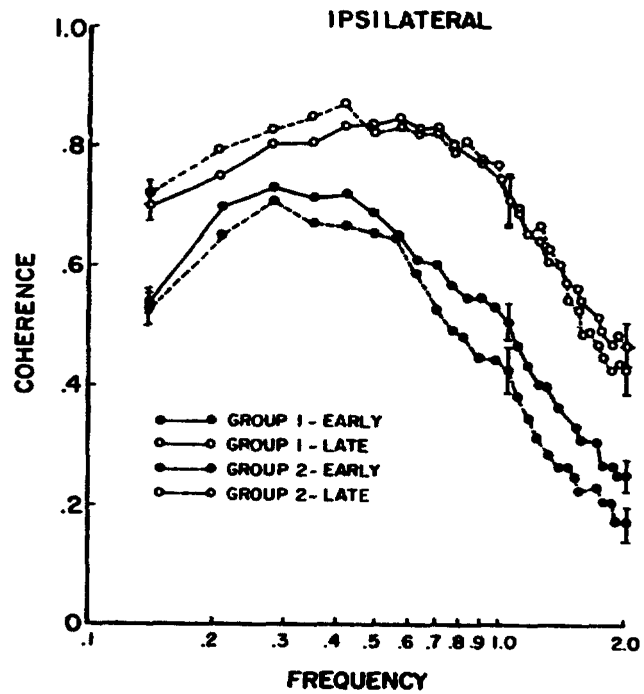

Figure 5. Ipsilateral linear coherence spectrum early and late in practice.

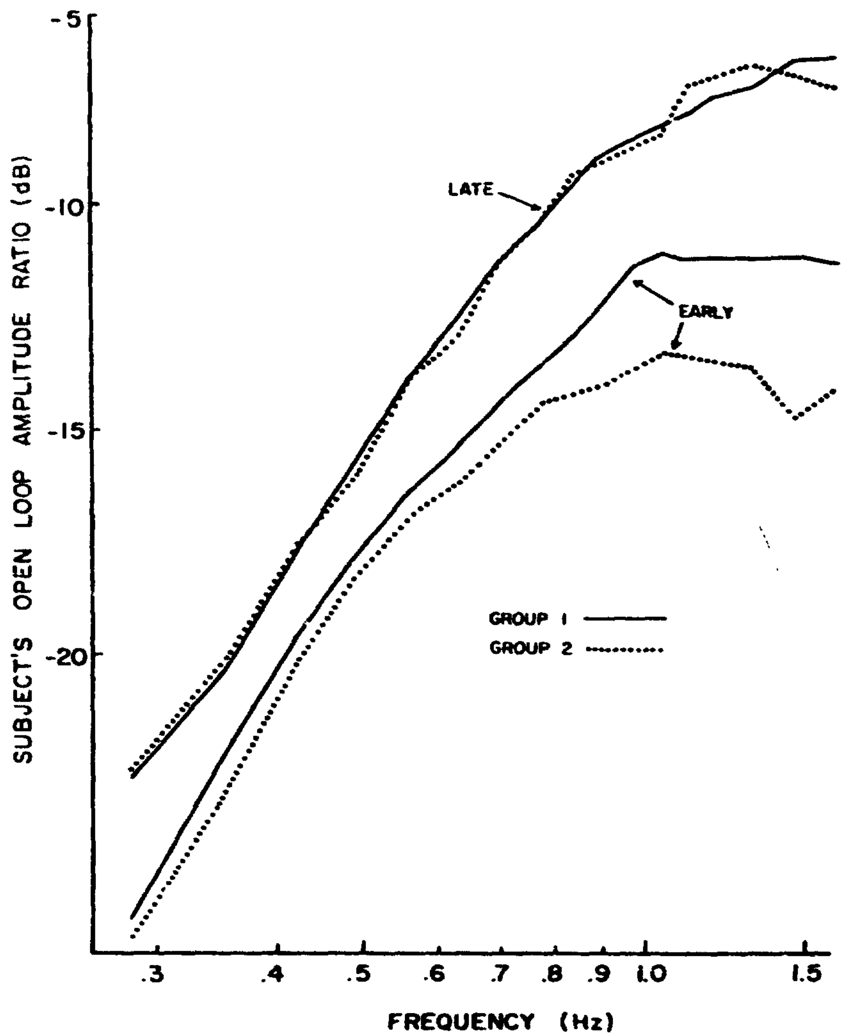

Figure 6. Amplitude ratio function early and late in practice.

SUMMARY

This experiment provides evidence for the development of timesharing skills in two qualitatively different task combinations. The calculation of percent transfer between the two combinations and an examination of between-group differences using analysis of covariance indicated that timesharing skills transfered between the combinations. A control theory analysis was performed on the TR-TR combination, the transfer task, to determine which parameters reflected the development and transfer of time-sharing skills and to identify the specific skills that developed in this combination. The ipsilateral linear coherence, open-loop gain, effective time delay, and response holds were examined for evidence of the development of a skill in parallel information processing. The development of this skill was reflected in the ipsilateral linear coherence and the open-loop gain. The contralateral linear coherence was examined for evidence of a skill in independent information processing. No evidence of such a skill was found. Examination of the ipsilateral linear coherence and the gain as a function of practice revealed that a skill in parallel information processing transfered between Days 1 and 2.

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