INTRODUCTION

Dynamic decisions are real-time decisions that are interdependent and highly constrained by the decision-making environment (Edwards, 1962). For example, many large manufacturing and distribution systems store and disseminate information in real time about the status of the objects within the system. Decision makers then can use this information to alter the system as events unfold. Despite significant advances in information technology, the high information load generated by such dynamic environments continues to pose problems. For example, plane and automobile accidents are more likely to occur when the involved decision makers (i.e., pilots and drivers, respectively) are under heavy workloads.

Excessive cognitive workload is generated when the satisfactory performance of a task demands more resources from the operator than are available at any given time. Although a wealth of research has been performed to evaluate the effects of task demands on human performance, little attention has been paid to the cognitive resources available or to the relationship between task demands and cognitive abilities as individuals acquire experience in a task. The focus of the present study was the relationship between human cognitive abilities and workload in a complex, dynamic decision-making (DDM) task. The experiments reported here enabled the manipulation of task workload experienced by participants and the assessment of participants' general intellectual ability in order to test the hypothesis that the effect of task workload on DDM depends on cognitive ability.

A brief summary of research pertaining to

the slow condition were presented with a set of events that had to be resolved in 24 min (real time). Participants assigned to the fast and load condition were placed under heavier task workloads than were participants in the slow condition. Individuals in the fast condition had to accomplish the same number of events as those in the slow condition but had to do so in one third of the time (i.e., in 8-min rather than 24-min trials). The load condition participants had to complete the same DDM simulation at the same pace as slow condition participants, but they also had to simultaneously perform two additional, independent tasks. Under each of the three conditions, participants performed the same DDM simulation comprising the same number of events.

Participants ran the DDM simulation on 3 consecutive days. The first 2 days, during which participants worked under one of the three workload conditions, constituted the practice phase. On the 3rd day, during the test phase, all participants performed the same DDM simulation at a fast pace for 48 min. During the practice phase, participants in the slow and load condition groups completed two 24-min trials per day (48 min/day) and participants in the fast condition group completed six 8-min trials per day (48 min/day). During the test phase, participants in all groups completed the same number of trials (six) at the same pace (8 min/trial, 48 total min on task). Thus all participants spent the same total amount of time on the task over the 3-day period: 48 min per day for a total of 144 min. This design facilitated an investigation into the relationship between cognitive ability and workload as individuals transferred from one workload condition to another. Before the practice phase, all participants also completed the Raven Standard Progressive Matrices Test (described later) as a measure of their cognitive abilities.

Dynamic Decision-Making Task

All experimental conditions were based on a DDM task called the (WPP; Gonzalez, Lerch, & Lebiere, 2003). The WPP simulates a water purification system constructed of a series of tanks joined by pipes. A maximum of five pumps can be active at any given time, and the participant needs to select which pumps to open or close to distribute all the water in a series of tanks as various deadlines approach and expire. A screen shot of the WPP simulation is provided in Figure 1. The WPP simulation constitutes a dynamic task for several reasons: Decisions are interconnected because some actions may delay or preclude other decisions; the amount of water in any of the tanks may increase at any time (in response to a preset scenario of water arrival times and locations that is unknown to the users and beyond their control); the level of water in each tank depends on prior decisions (i.e., the user's earlier activation or deactivation of the pumps); and a time delay occurs after the activation or deactivation of any pump (i.e., pump clean-up time). The WPP is a real-time simulation in that the pumps are activated or deactivated by the users while a simulation clock is running.

The WPP simulation requires participants to pump a total of 1080 gallons (4088 L) of water through the series of tanks. Performance in this task is measured by the total number of gallons of water remaining in the system at the end of the simulation. Thus the best performance is zero, and the performance if no action is taken in the system is 1080 gallons. A running counter in the upper left corner of the screen indicates the number of gallons of water left in the system after the expiration of each deadline. For data analysis, the number of missed gallons was converted to the percentage of the total gallons pumped out of the system; therefore performance could range from 0% to 100%. In order to establish a reasonable lower limit for the performance measure, a program called the was created to run the simulation and make random assignments with no idle time (i.e., never leaving pumps idle). Thirty replications of these random assignments generated a mean performance of 83% with a standard deviation of 2.6%. Accordingly, the lowest reasonable human performance should score in the range of 80%.

The WPP task for individuals in the load condition group was exactly the same as described, except that these participants were also asked to simultaneously and independently perform two additional tasks, labeled and . Figure 2 shows the layout of the WPP with these additional tasks.

These two tasks are components of the Multi-Attribute Task Battery developed at the National Aeronautics and Space Administration by Comstock and Arnegard (1992). These two tasks are not integrated with the WPP but, rather, run in parallel with and independently of the WPP. The tasks stop concurrently with the WPP simulation. The system monitoring task requires users to monitor two warning lights (a green light and a red light) and four vertical gauges that report system abnormalities. The communications task requires users to discriminate audio signals and respond to their own call sign (e.g., NGT504) by making frequency changes on the proper navigation or communication radio. The performance measures in these two additional tasks were the percentage of correct responses and the response time. Training for the two additional tasks was separate from the training in the WPP. Before the start of the experiment, participants were asked to pay equal attention to the WPP and the loading tasks during their simultaneous performance.

Cognitive Abilities Measure

The Raven Standard Progressive Matrices Test was used to evaluate the participants' cognitive abilities (Raven et al., 1977). The Raven test is nonverbal and relatively free of cultural bias. Although the use of this measure to evaluate people's ability to perform DDM tasks is unproven (Rigas & Brehmer, 1999), research in psychology suggests that the Raven test is a good indicator of an individual's ability to dynamically manage a large set of goals in working memory and results, which indicate a main effect of Raven score, $F(1, 45) = 7.79$, $< .01$, and two significant interactions: Phase × Condition, $F(2, 45) = 4.12$, $< .05$, and Phase × Condition × Raven Score, $F(2, 45) = 3.93$, $< .05$.

These findings indicate that performance in the practice and test phases varied with condition and with Raven score. Figure 3 shows the average performance in the practice and test phases by condition. Repeated measures analyses by condition were performed to evaluate the effect of the phase and the Raven score. The results revealed that only those individuals who practiced under the slow condition (i.e., low workload) improved their performance significantly when subsequently placed under high time constraints during the test phase, $F(1, 17) = 5.72$, $< .05$. The performance of individuals who practiced under the fast condi-

on the WPP task and the percentage of correct responses while performing each additional task, the average response time, or the between-day response time (WPP performance on Day 1 and monitoring performance: $r = -.241$, $= .33$; WPP performance on Day 2 and monitoring performance, $r = -.053$, $= .83$; and WPP performance on Day 3 and communications performance, $r = -.223$, $= .37$). Moreover, differences remained insignificant even when Raven score was partialled out.

DISCUSSION AND IMPLICATIONS

The findings from this study indicate that both high task workload (in the form of time constraints and loading tasks) and low cognitive abilities (as measured by Raven score) hindered performance and transfer in DDM tasks. Moreover, these experiments demonstrate that high workload had a greater effect on individuals with low cognitive ability than on individuals with high cognitive ability.

While interpreting these results, one must remember that the study groups differed only in regard to the training phase conditions, not the testing phase conditions. Although participants ran the DDM simulation under different types of workload during the training phase, all participants completed the same number of trials (six) while under the same high workload (fast: 8 min/trial) during the testing phase.

The results suggest that low workload during training enabled participants to improve their performance more markedly after transfer to high workload than in the case of individuals who trained under high-workload conditions (either time constraints or loading tasks). Furthermore, participants in the low-workload (slow) condition completed a total of 4 trials during the training phase, whereas participants in one of the fast conditions ran the simulation 12 times during the training phase. As indicated by the higher number of trials in the fast condition and the nonsignificant difference between this and the load condition, this detrimental effect of high workload occurred independently of the number of practice trials. It is also possible, however, that a higher number of practice trials in the fast condition produced slightly better (but nonsignificant) performance as compared with the load condition. This particular hypothesis about the effect of time constraints and amount of practice has been tested in a different but related study (Gonzalez, 2004).

The study also demonstrates that the effect of task workload depended on the available cognitive resources of the decision maker. Regression analysis revealed that Raven score was a good covariate in this study and a significant predictor of performance. The analyses by condition showed a significant effect of Raven score under all conditions and an interaction between Raven score and study phase in slow condition participants only. Comparisons between the slow condition group and each of the other two high-workload groups also indicated a significant effect of Raven score and an interaction between Raven score and phase, but a comparison between the fast and load condition groups revealed no difference. These results indicate

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