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Effects of Sleep Loss on Information-Processing in an Absolute Judgment Task as a Function of Task Difficulty

Frieda O'Steen Carlton
Old Dominion University

EFFECTS OF SLEEP LOSS ON INFORMATION-PROCESSING

IN AN ABSOLUTE JUDGMENT TASK

AS A FUNCTION OF TASK DIFFICULTY

by

Frieda O'Steen Carlton
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Approved by:

Ben B. Morgan, Jr. (Director)

Glynn D. Coates

Frederick G. Freeman

ABSTRACT

EFFECTS OF SLEEP LOSS ON INFORMATION-PROCESSING IN AN ABSOLUTE JUDGMENT TASK AS A FUNCTION OF TASK DIFFICULTY

Frieda O'Steen Carlton
Old Dominion University
Director: Dr. Ben B. Morgan, Jr.

The effects of 36 hours of sleep loss on information-processing were assessed in an absolute judgment task. Of the 24 subjects employed, 12 served in the sleep-loss (experimental) and control conditions, respectively. All subjects were tested individually for a total of ten sessions; the control group was tested on ten consecutive days, whereas the experimental subjects were tested every four hours over a 36-hour period of sleep loss, and at a recovery session following approximately 12 hours of rest and recovery. The task required subjects to make absolute judgments of the size of two small circles of light and to identify each stimulus presented as the larger or smaller of the two. In each session, subjects worked with four different pairs of circles, at four levels of discrimination difficulty (difficulty level was defined in terms of the similarity of the sizes of the circles in each pair). Performance was assessed in terms of reaction times, errors, and rates of information transmission. The study was designed to determine if sleep loss reduces the efficiency of information-processing, if these effects are reflected in speed or accuracy of response, and finally, if task difficulty (as defined by stimulus discriminability, or similarity) influences the magnitude of these effects. The results indicated that sleep loss had adverse effects on information-processing, as reflected in increased

reaction times and decreased information transmission rates in the experimental group; performance in the control group improved across test sessions on both measures. Response accuracy did not change significantly across sessions in either group. A significant interaction between task difficulty and sleep loss was obtained, but only with the reaction time measure. The magnitude of the increase in reaction times increased monotonically with task difficulty; the same trend was noted in the rate of information transmission measure, but was not of sufficient magnitude to attain statistical significance. The results are consistent with the hypothesis that sleep loss results in a general degradation in the efficiency of information-processing, to an extent determined by task difficulty or cognitive processing "load".

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Since World War II, there has been an explosive growth in technology, and a concomitant increase in the complexity of the operational systems in which the human operator serves as a component. As a result of this dramatic increase in systems complexity, man's ability to meet the performance requirements of the system in which he works has taken on an increasing importance; indeed, the performance efficiency of systems is often a direct function of the performance capacities and limitations of the human component in the system. Recognition of this fact has provided the impetus for an intensive research effort designed to develop a better understanding of the functional mechanisms which mediate performance in a broad range of tasks (in terms of the capacities and limitations of these mechanisms) so that these factors can be taken into account in the design of systems in which people work and live. Thus, the human performance aspects of Engineering Psychology have increased in both scope and importance during the past decade (see Alluisi & Morgan, 1976).

The view of the human operator as an information-processing system (Fitts & Posner, 1969) has provided both the conceptual framework and the metrics for a large portion of the research on human performance. This information-theory approach to the study of human performance is based on the notion that human performance depends on the processes involved in (a) receiving inputs from the environment, (b) processing these inputs, and (c) providing outputs in the form of behavior or responses. It has been productive because it provides a methodology for assessing the capabilities of the human operator which are required in the performance of a wide variety of different tasks. Thus, the research findings from this approach have broad implications for the design of operational systems of many and varied types.

The voluminous body of research on human information-processing has significantly advanced our understanding of the general parameters of human performance. However, these investigations have been largely confined to the analysis of information-processing under optimal conditions. Relatively few studies have sought to determine how man's capacity to process information changes under sub-optimal conditions, as during periods of physiological, psychological, or environmental stress, or under the influence of drugs. Some notable exceptions in the literature include studies which have assessed the effects of alcohol (Huntley, 1972; Huntley, 1974; Tharp, Rundell, Lester, & Williams, 1974; Jennings, Wood, & Lawrence, 1976), barbituates (Rundell, Williams, & Lester, 1978), marijuana (Schaefer, Gunn, & Dubowski, 1977), noise (Finkelman & Glass, 1970; Boggs & Simon, 1974), and sleep loss (Williams, Kearney, & Lubin, 1965; Buck & Gibbs, 1972) on information-processing. To the extent that human performance research is largely concerned with performance in the operational setting, and since workers are often required to work under stress of various kinds, studies of this type are of vital importance to human factors specialists.

The present study was designed to investigate how sleep loss, a stressor commonly encountered by workers in military and industrial settings, affects the human operator's already limited capacity to process information. Before this issue is addressed, however, it is necessary to delineate the ways in which the human information-processing system is limited, and how these limitations are measured.

Capacity Limitations of the Human Information-Processing System

The available data suggest that there are some definite limitations on the capacity of the human operator to process information. For example, the classic study by Miller (1956) demonstrated that there are upper limits on the amount of information that can be processed, or transmitted, in an absolute-judgment situation where the stimulus ensemble varies along a single dimension. As the informational content of the stimulus increases, the amount of information transmitted increases to an asymptotic level, beyond which it remains constant or decreases due to the commission of errors. This upper limit on information transmission (viz., 2.3 to 3.2 bits; Miller, 1956) in a given task under optimal conditions has been termed channel capacity. Although this value has been shown to vary with different stimulus or task characteristics (Alluisi, 1957), the important point is that there are limits on the amount of information that can be transmitted by the human information-processing system. Channel capacity can be considered an index of the maximum number of stimulus alternatives to which an individual can respond accurately (e.g., 7 ± 2 in absolute judgment tasks), and defines one source of limitation on processing capacity.

In addition to limitations on the amount of information that can be transmitted, there are also limitations on the speed with which information can be transmitted. The choice-reaction time (CRT) paradigm has been widely used to investigate this type of limitation; choice-reaction tasks are characterized by two or more stimuli mapped onto an equal number of unique responses. On each trial, the subject is presented with one of the stimulus alternatives and is required to make the appropriate response as rapidly as possible. Choice-reaction time, the latency between the presentation of a stimulus and the initiation of a response, has been used as an index of processing time.

A classic study by Hick (1952) demonstrated that choice-reaction time increases as a linear function of the average amount of information transmitted (in bits), which indicates that the rate of gain of information is constant for varying numbers of bits. This relationship has since been termed "Hick's law", and has proven to be one of the most robust effects in information-processing research. Hick employed a choice-reaction task in which subjects were required to make key-press responses to randomly related stimulus lights. In one condition, the number of stimulus-response pairs was varied between one and ten. Few errors were made, so that the amount of information transmitted was virtually equal to the amount of stimulus information, which varied between 0 and 3.3 bits. In a second condition, the number of stimulus-response alternatives was held constant at ten, but the subject was instructed to respond at different speeds. As the emphasis on speed was increased, so did errors. Therefore, the average amount of information transmitted (which takes errors into account) varied between the different speed-emphasis conditions. When reaction times were plotted against the amount of information transmitted for both conditions, Hick obtained essentially the same linear function. Therefore, Hick's law appears to be valid regardless of whether changes in the amount of information transmitted are produced by changes in the number of stimulus alternatives or in the number of errors. In addition, the rate of gain of information (indexed by the slope of the function) for a given stimulus-response ensemble appears to be relatively independent of variations in error rates produced by changes in the subject's criterion for speed versus accuracy of performance. A study by

Pachella and Fisher (1972) provides further evidence supporting this contention.

The generality of Hick's law was expanded by Hyman (1953), who found a linear relationship between the level of stimulus uncertainty (which was equated with the amount of information transmitted, since error rates were low) and reaction time under conditions where stimulus uncertainty was manipulated by varying the number of stimulus alternatives, the relative probabilities of presentation, or the sequential dependencies between successive presentations.

Although the linear relationship between reaction time and the amount of information transmitted has been substantiated by results with a number of different tasks, the slope of this function has been found to vary with different stimulus-response ensembles (Brainard, Irby, Fitts, & Alluisi, 1962; Fitts & Switzer, 1962). This indicates that the rate at which information is transmitted varies between tasks; there is an inverse relationship between the slope and the average rate of information transmission. The slope of the function can therefore be considered an index of the difficulty of the task. Difficult tasks are characterized by steep slopes and low information transmission rates, whereas easier tasks are characterized by relatively flatter slopes and higher information transmission rates. These differential functions indicate that increasing the information load by a constant amount results in a larger increase in reaction time in a difficult task than in a comparatively easier task. Similarly, inducing the subject to reduce reaction time by a constant amount results in a comparatively larger decrease in accuracy (as reflected by a decrease in the amount of information transmitted) in a difficult task. At least two task factors have been shown to influence the slope of the function, and therefore to define the difficulty of a choice-reaction task: stimulus-response compatibility and stimulus similarity.

Stimulus-response (S-R) compatibility can be defined as the degree to which the stimulus-response pairings employed in the task correspond in a direct physical sense or are consistent with population stereotypes (Deininger & Fitts, 1955). Several studies have provided evidence to show that decreases in stimulus-response compatitility produce increases in the slope of the function relating reaction time to the amount of information transmitted. Thus, there is a reduction in the rate of information gain, or the average rate of information transmission (in bits per second) as S-R compatibility is decreased (Fitts & Seeger, 1953; Brainard et al., 1962). A study by Pachella and Fisher (1970) suggests that increasing the similarity of the stimuli has the same effect as decreasing S-R compatibility. This finding is consistent with earlier studies which found reaction time to increase with the degree of stimulus similarity (Crossman, 1955; Thurmond & Alluisi, 1963).

Thus, although increases in stimulus uncertainty produce longer response times in most tasks, this effect is magnified when task difficulty is further increased by reductions in S-R compatibility or increases in stimulus similarity. In a similar fashion, task difficulty magnifies the decrease in accuracy associated with decreased response time. However, when S-R compatibility is high and the stimuli are easily discriminable, increases in stimulus uncertainty do not result in the typical increase in reaction time, and there is little or no decrease in accuracy with moderate decreases in response time. In these cases, the slope of the function declines to near zero, which indicates that there are extremely high rates of information transmission at all levels of stimulus uncertainty. The same effect occurs with high degrees of practice (Mowbray & Rhoades, 1959).

The limitation on the human information-processing system illustrated by these relationships is that it takes time to process information. As the amount of stimulus information increases, there is an attendant increase in the time required to process and respond to it (except in very easy or highly practiced tasks). Task difficulty (defined by the levels of stimulus-response compatibility, stimulus discriminability, and practice) has been shown to influence the magnitude of this effect. Even though subjects may voluntarily reduce reaction times by responding before information has been fully processed (Eriksen & Schultz, 1979), this results in an increase in error rate and a corresponding decline in the average amount of information transmitted. The results of Hick (1952) and Pachella and Fisher (1972) indicate that the trade-off between speed and accuracy results in minimal changes in the relationship between the amount of information transmitted and reaction time, and consequently no substantial change in information transmission rates for a given task. However, the rate at which accuracy is traded for speed is a function of task difficulty. Therefore, the function relating reaction time to the amount of information transmitted describes the effects of stimulus uncertainty on reaction time and the rate at which accuracy is traded for speed, and allows comparisons of these effects between tasks.

The Effects of Sleep Loss on Information-Processing

The previous studies of the effects of sleep deprivation on performance have indicated that tasks differ in their sensitivity to this type of stress. Wilkinson (1969) proposed that the performance effects of a given environmental stressor depend on factors such as (a) the duration of work on the task, (b) the familiarity of the operator with the stress and with the work he has to do under stress, (c) the level of incentive of the operator, (d) the kind of work required, (e) the aspect of performance most involved in the work, and (f) the presence of other stresses in the working situation. Furthermore, there is some evidence to suggest that cognitively complex tasks are more sensitive to performance decrements induced by moderate sleep loss than are tasks in which the cognitive demands are minimal (Wilkinson, 1964; Naitoh & Townsend, 1970; Beatty, Ahern, & Katz, 1977). This implies that the efficiency of information-processing may be reduced by sleep loss, but that this will result in significant performance decrements only when the operator is working at or above his/her processing capacity. As discussed above, three factors which determine the "loading" of processing capacity in choice-reaction tasks are: (a) the levels of stimulus uncertainty, (b) stimulus-response compatibility, and (c) stimulus discriminability. These factors might be expected to influence the degree to which performance deteriorates in choice-reaction tasks during sleep loss.

Stimulus uncertainty.--A study by Buck and Gibbs (1972) suggests that the magnitude of the decrement in performance caused by sleep deprivation is directly related to the level of stimulus uncertainty. These results further indicate that sleep loss produces a decrease in the average rate of information transmission (information transmitted was defined by the amount of stimulus information).

In this study (Buck & Gibbs, 1972), performance was measured every four hours over a 40-hour period of sleep loss. Performance was measured with a step-tracking task in which the subject aligned a pointer, by turning a control wheel, with a target light that could appear in any one of five equally-spaced positions arranged in a semicircle. The relationship between the wheel and the pointer was reversed, such that a clockwise movement of the wheel produced a counter-clockwise movement of the pointer, and vice-versa. The information contained in each signal was defined by the position of the pointer prior to the signal presentation. When the starting position of the pointer was to the extreme left (position 1), any of the four signals which could follow were said to contain 0 bits of information, since all would require a movement of the pointer to the right. Signals presented when the starting position of the pointer was to the extreme right (position 5) were also said to contain no information for a similar reason. Signals presented when the pointer was in positions 2 or 4 were said to have signal uncertainties of .81 bits, since the probability of a signal to one side of the pointer was greater than the probability that the signal would occur on the other side of the pointer. At the center position (position 3), signal uncertainty was designated as 1.0 bits, since the signal could occur to the left or the right with equal probabilities. Mean reaction times were computed at each level of stimulus uncertainty. This provided three pairs of stimulus uncertainty and mean reaction-time values for each session. Although reaction times showed a general tendency to increase over the sleep-loss period, the greatest increases were at the higher levels of stimulus uncertainty. This finding is consistent with earlier studies by Williams, Kearney, and Lubin (1965) and Williams, Lubin, and Goodnow (1959) which found larger performance decrements during sleep loss when signal uncertainty was high than when it was low.

Buck and Gibbs (1972) estimated the mean rate of information transmission from the slope of the regression line relating reaction time to the amount of information transmitted. They found that the average rate of information transmission declined with each session throughout the sleep-loss period, as indicated by a progressive increase in the slope of the regression line. A separate analysis of errors led the investigators to conclude that there was no significant decrease in performance accuracy during sleep loss. These results are consistent with the hypothesis that increased difficulty (in terms of increased stimulus uncertainty) makes an information-processing task more susceptible to the adverse effects of sleep loss.

Stimulus-response compatibility.--Eberhardt (1979) investigated the effects of sleep loss on reaction time as a function of stimulus uncertainty and S-R compatibility. She employed a choice-reaction task in which two stimulus-response ensembles were combined factorially with five levels of stimulus uncertainty in order to produce two levels of S-R compatibility. In the high-compatibility condition, the stimuli were numbers, to which the subject responded verbally by naming the number presented. In the low-compatibility condition, the subject was required to press a different key in response to each number presented. The numeral-finger pairings used were as follows: 2 - left ring, 3 - left middle, 4 - left index, 5 - left thumb, 6 - right thumb, 7 - right index, 8 - right middle, 9 - right ring. The level of stimulus uncertainty was varied by randomly selecting the stimuli from among 2, 3, 4, 6, or 8 possible stimulus alternatives. Performance was tested in the experimental (sleep-loss) group every four hours throughout a 36-hour period of sleep loss, and at a recovery session after one night of sleep (for a total of 10 sessions). The control subjects were tested with the same tasks at approximately the same time of day on ten consecutive days (excluding week-ends).

Eberhardt (1979) found significant differences in the mean reaction times of the experimental group during sleep loss and the control group in corresponding sessions. However, this was not caused by an increase in reaction times for the sleep-loss subjects, but rather by a failure of the experimental subjects to decrease their reaction times across sessions as did the control group. Mean reaction times in the sleep-loss group were maintained at about the same level throughout the sleep-loss period, whereas the control group exhibited a significant decrease in mean reaction times over the ten sessions. In the initial session, the interaction between S-R compatibility and the rate of gain of information was consistent with the findings of previous studies; namely, the numeral-verbal condition was characterized by an essentially flat slope, whereas the numeral-motor condition exhibited a significantly increasing linear trend. However, there was essentially no change in the slopes of either function across sessions in the control or the sleep-loss condition. This suggests that sleep loss had no differential effects on performance in either task over the range in which stimulus uncertainty was varied. This is not consistent with Buck and Gibbs' (1972) finding that sleep loss results in greater increases in reaction times at higher levels of stimulus uncertainty.

Eberhardt's (1979) comparison of the verbal and motor conditions (collapsed across all levels of stimulus uncertainty) in the sleep-loss group did show results in the expected direction. The mean reaction times in the more difficult motor condition increased, whereas reaction times in the verbal condition showed a tendency to decrease. This may explain why, in the overall comparison of sleep-loss and control conditions, performance in the former appeared to remain stable over the sleep-loss period. The decreases in mean reaction times in the verbal condition offset the increases in mean reaction times in the motor condition. The same comparison within the control group indicated that performance improved over sessions in both the verbal and motor conditions, although the motor condition did not show as much improvement as the verbal. Error rates were analyzed separately, and it was concluded that performance accuracy did not decline significantly during sleep loss.

The finding that reaction times in the more difficult motor condition increased during sleep loss, whereas performance in the verbal condition improved, supports the assertion that increased difficulty (in terms of lowered S-R compatibility) makes a task more sensitive to the deleterious effects of sleep loss. The failure to find any differences in the degree to which performance deteriorated between 1 and 3 bits of stimulus information, whereas Buck and Gibbs (1972) found such differences over a range of 0 to 1 bit of stimulus uncertainty, might be attributed to the relative difficulties of the tasks. It appears that increasing the information load over this range (1 to 3 bits) did not significantly increase the difficulty of the numeral-motor task, although a much smaller increase in information load (0 to 1 bit) did increase the difficulty of the tracking task. The tracking task appears to be more difficult than the numeral-motor condition in at least two ways. First, there seems to be a difference in the perceptual difficulty of signal identification between the two tasks. In the tracking task, signal identification required monitoring the starting position of the pointer, and making a determination as to whether the signal light was to the right or left. This would seem to be more difficult and take longer than the recognition of a number presented at the same location on each trial. A second, and even more obvious, difference in difficulty between the numeral-motor task and the tracking task is in terms of stimulus-response compatibility. The particular numeral-finger mappings used by Eberhardt (1979) appear to be more compatible than the reverse relationship between the turn of the wheel and the direction of pointer movement in the tracking task. As Eberhardt (1979) suggested, the level of stimulus uncertainty might have influenced the degree of performance decrement if either less compatible numeral-finger mappings had been used, or if the information load had been varied over a wider range.

Stimulus similarity.--The studies described above provide empirical evidence to support the hypothesis that the adverse effects of sleep loss on information-processing are more pronounced in difficult tasks, as reflected by interactions between sleep loss and (a) stimulus uncertainty (Buck & Gibbs, 1972) and (b) stimulus-response compatibility (Eberhardt, 1979). Although stimulus similarity (discriminability) influences the difficulty of an information-processing task, there have been no studies conducted to assess a possible interaction between this factor and sleep loss. Based on the above evidence, such an interaction would appear probable.

Purposes of the Study

The present study was designed to assess the effects of 36 hours of sleep loss on information-processing in an absolute judgment task at four levels of stimulus similarity, or discrimination difficulty. Specifically, this study seeks to answer the following questions:

(1) Does sleep loss have adverse effects on information-processing in absolute judgment tasks?

(2) Are the adverse effects of sleep loss on information-processing reflected in measures of speed or accuracy of information-processing, or in both?

(3) Are the adverse effects of sleep loss on information-processing more pronounced when stimulus discriminability is low rather than high?

Method

In the present experiment, three major independent variables were investigated: (1) Condition (two levels; sleep loss and control), (2) Discrimination Difficulty (four levels), and (3) Session (ten levels). Both Discrimination Difficulty and Session were within-subject factors; Condition was a between-subject factor. Thus, all subjects were tested at all four levels of discrimination difficulty in each of ten test sessions. In the sleep-loss condition, subjects were tested at four-hour intervals across a 36-hour sleep-loss period, and at a recovery session after approximately 12 hours of rest and recovery. The ten test sessions for control subjects were given on ten consecutive days (excluding week-ends).

In each test session, subjects were required to make absolute judgments of the size of two small circles of light. Each subject worked with four different pairs of circles in each session, which defined the four levels of difficulty of the absolute judgment required of the subject. A model of the experimental design is presented in Table 1.

Subjects

The subjects were 24 Old Dominion University students, ranging in age from 18 to 30 years with a median age of 20 years. All subjects were required to have normal (20/20) visual acuity, corrected or uncorrected. Of the 24 subjects, 12 (six males and six females) served in the sleep-loss and control conditions, respectively. The sleep-loss subjects were paid $50.00 for their participation; the control subjects received extra credit awarded for participation in experiments in their General Psychology class.

Table 1

The Experimental Design

Sleep-loss Condition

Discrimination Difficulty (in SD-scale units)	Session 1	2	3	4	5	6	7	8	9	10
1	S_1-S_{12}*	.	.	.	.	.	.	.	.	.
2	.									
3	.									
12	.									

Control Condition

Discrimination Difficulty (in SD-scale units)	Session 1	2	3	4	5	6	7	8	9	10
1	S_{13}-S_{24}**		.	.	.	.	.	.	.	.
2	.									
3	.									
12	.									

*Subjects 1-12
**Subjects 13-24

Apparatus

The stimuli were displayed at the center of an 8-cm diameter circular display area made of plexiglass, located at the center of a 68 x 85-cm plywood surface. A 1.3-cm diameter green jewel indicator light, which served as a warning signal, was located 9 cm below the center of the plexiglass display area.

The stimuli were formed by projecting light onto the plexiglass display surface through holes drilled in opague plexiglass slides. The light source was a 1.5-volt bulb located approximately 10 cm from the back of the display area. The bulb was placed in a light-proof tube which extended to the back of the display area. The beam of light was reduced by a lens stop, which consisted of a metal disk with a .5-cm hole in the center.

The stimulus was presented when the bulb was illuminated, two seconds after the illumination of the warning light. The presentation of the stimulus started a Hunter digital timer (model 1521) and extinguished the warning light. The subject was provided with a response key for each hand; when either key was depressed the timer stopped, the stimulus was terminated, and an indicator light was illuminated on the experimenter's side of the display to indicate which key had been pressed.

All subjects were tested in a 3.41 x 3.51 m room, darkened except for a 40-watt bulb in a high intensity lamp at the experimenter's station. The stimuli were well above threshold, with a surface luminance of 2.4 ft.L. and a background luminance of .01 ft.L. Broad-band noise was broadcast in the room from a General Radio random-noise generator (model 274) at a level of approximately 70 dB (SPL) to mask equipment sounds and other extraneous noises.

Stimuli

The stimuli were five circular spots of light selected from an equal-discriminability (ED) scale developed by Alluisi and Sidorsky (1958). The stimuli selected were the same as those used by Morgan & Alluisi (1967), and formed a subset of those used by Thurmond & Alluisi (1963). The diameter in inches, and the corresponding ED-scale value are indicated in the first two columns of Table 2. These five stimuli were arranged into four pairs, by combining the smallest spot of light (which served as the standard stimulus) with each of the remaining four. Subjects were required to judge which of the two stimuli was displayed on each presentation (each subject worked with all four pairs). Therefore, presentation of either stimulus within a pair provided one bit of stimulus information, at one of four difficulty values (defined in terms of dissimilarity values).

The stimulus-dissimilarity (SD) scale values (shown in the last column of Table 2) represent the difference between the ED-scale value of the smaller, standard stimulus in a pair (viz., 3.0) and the ED-scale value of the larger. The SD-scale values define an interval scale of stimulus dissimilarity, since equal differences in SD-scale values correspond to equal differences in discriminability. Discrimination difficulty varies inversely with the SD-scale values; an increase in scale value denotes a decrease in the difficulty of discrimination.

Procedure

Subjects in both the sleep-loss and control conditions were tested at all four levels of discrimination difficulty in each of ten test sessions. Sleep-loss subjects were tested every four hours over a

Table 2

ED-Scale Values, Diameters of Stimuli, and

Dissimilarity Values of Stimulus Pairs

ED-Scale Value	Diameter (in inches)	Dissimilarity (SD-Scale Value)
3.0	0.0470	Standard
4.0	0.0540	1.0
5.0	0.0594	2.0
6.0	0.0680	3.0
15.0	0.2383	12.0

36-hour sleep-loss period, on one of four alternate week-ends (three subjects of the same sex were tested during each of the four sleep-loss periods), and at a recovery session following one night of sleep. Potential subjects for the sleep-loss condition were fully informed as to the procedures of the experiment and the duration of the sleep deprivation period upon initial contact by the experimenter. Those who agreed to participate were instructed to maintain a normal regimen of sleep and to refrain from the use of drugs for one week prior to the experiment. Subjects reported to the laboratory at 0800, approximately four hours prior to the first test session. The mean test times on the first day of the sleep-loss period were at 1200, 1600, 2000, and 2400 hours, and on the second day at 0400, 0800, 1200, 1600, and 2000 hours. The final test session was scheduled for the following day after one night of rest and recovery. Each test session was completed in approximately 30 minutes. In the remaining 3.5 hours before the next session, subjects were given a 45-minute test regimen consisting of tests of visual acuity, depth perception, time estimation, and choice-reaction time; none of these tasks were analyzed as part of the current study. Television, video games, and reading material were also provided to occupy the subjects for the remaining time in which they were not being tested. Meals were served at regular hours. Subjects who agreed to serve in the control condition were informed as to the procedures of the experiment, and were instructed to maintain a normal regimen of sleep and to refrain from the use of drugs during the week prior to testing. Control subjects were tested with the same task at the same time of day, insofar as possible, for ten consecutive days excluding week-ends. The additional tests given the experimental subjects between test sessions were not given to the control subjects.

All subjects were tested individually. Each was seated at a viewing distance of approximately 72 cm from the display surface. The experimenter read task instructions aloud before the experimental trials began (see Appendix A). Subjects were instructed to respond to the smaller stimulus by pressing the key placed under their preferred hand, and to the larger stimulus by pressing the key under their non-preferred hand. Response speed and accuracy were stressed as performance criteria of equal importance. The subjects were shown both stimuli within the pair with which they were to work, and were given four practice trials before the experimental trials began. The subjects were given 30 trials with each pair in each session, at a rate of approximately one every ten seconds. The order of presentation was randomized, with the constraint that each was presented an equal number of times. Each trial consisted of the two-second warning signal, followed by presentation of one of the two stimuli in a pair and the key-press response. Following the response, the subjects were given immediate knowledge of results by the experimenter. If the response was correct, the experimenter said "right": if the response was incorrect, the experimenter named the correct identification. The stimulus presented, the response made, and the subject's reaction time (to the nearest millisecond) were recorded for each trial.

Results

The primary dependent measures in this study were median reaction times, errors, and rates of information transmission. The third measure was used to analyze the potential trade-off of speed for accuracy, as previously discussed. Rate of information transmission is a more global index of performance, because it is sensitive to effects that might be evidenced in decrements of either speed or accuracy of performance. These dependent measures were also used in previous information-processing studies which employed the same absolute judgment task (Thurmond & Alluisi, 1963; Morgan & Alluisi, 1967). Each of these dependent measures was analyzed by a 2 x 4 x 10 (Condition x Discrimination Difficulty x Session) analysis of variance, with subjects nested in the first factor.

Change scores for each of the measures delineated above were also analyzed. These scores reflect the magnitude and direction of changes from the subjects' initial (session 1) performances in each of the nine subsequent sessions. These measures were computed and analyzed in order to control for between-subject differences (experimental, or sleep-loss, vs. control) in initial-session performances. A 2 x 4 x 9 (Condition x Discrimination Difficulty x Session) analysis of variance, with subjects nested in the first factor, was computed for each of the change score measures.

As suggested by the hypotheses under consideration in the study, the Condition x Discrimination Difficulty and the Condition x Discrimination Difficulty x Session interactions were of primary interest. Since the effect of Condition and an interaction between Condition and Discrimination Difficulty were only predicted to occur in those sessions given during the latter portion of the sleep-deprivation period, when the effects of sleep loss become prominent, it was anticipated that the overall Condition x Discrimination Difficulty and the Condition x Discrimination Difficulty x Session interactions might not reach statistically significant levels. Therefore, Duncan-range pairwise comparisons between cell means in the control and sleep-loss conditions at each level of difficulty in corresponding sessions were planned *a priori* for all dependent measures.

Reaction Times

Median reaction times were computed for each subject for the 30 test trials given in each condition; medians rather than means were computed because the distribution of reaction times is known to be positively skewed. Although reaction time measures are frequently transformed in order to meet the statistical assumptions underlying the analysis of variance (viz., normality and homogeneity of within-cell variances), Box (1954) has shown that the analysis of variance is robust despite moderate departures from these assumptions. Therefore, these data were not transformed, but conservative alpha levels ($p < .01$) were set for the F-tests performed on the reaction-time data before data collection. The summary of the analysis of variance of these data is presented in Table 3. Figure 1 shows the means of the median reaction times for experimental and control conditions across sessions at each of the four levels of discrimination difficulty, SD 1, 2, 3, and 12 (difficulty varies inversely with SD-value).

Table 3

Summary of Analysis of Variance

of Median Reaction Times

Source of Variation	dF	Mean Square	F
Condition (C)	1	2.64170	11.52748**
error - Subjects within Condition (Ss(C))	22	.22917	
Discrimination Difficulty (D)	3	2.49323	106.78153***
DC	3	.18599	7.96580***
error - DSs(C)	66	.02335	
Session (S)	9	.03769	3.09144**
SC	9	.11083	9.08944***
error - SSs(C)	198	.01219	
DS	27	.00492	1.40670
CDS	27	.00866	2.47527***
error - DSSs(C)	594	.00350	

**p < .01
***p < .001.

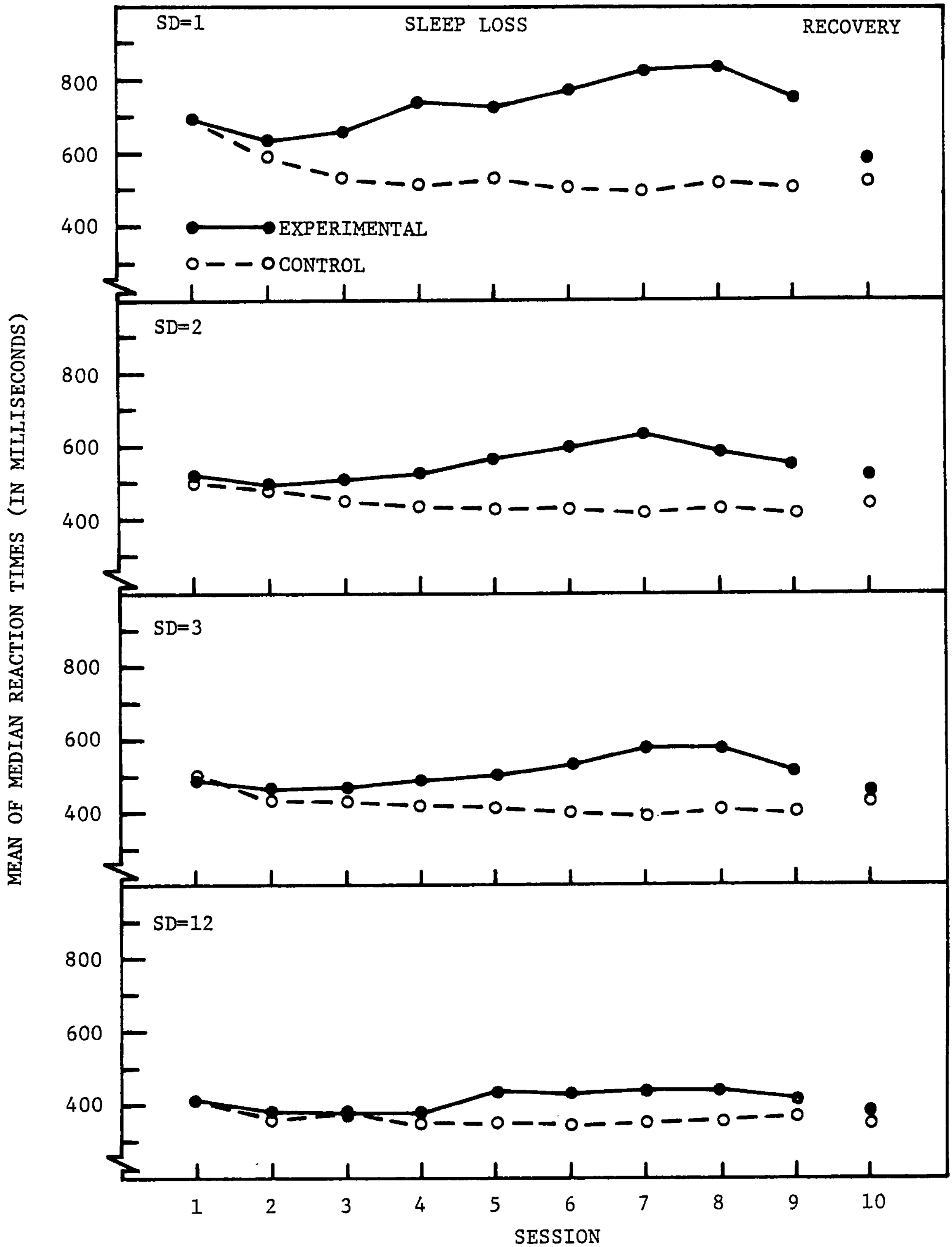

Figure 1. Mean of median reaction times as a function of condition and session at each level of task difficulty.

The effects of sleep loss on the average of the median reaction times are apparent in the divergence of the experimental and control functions shown in Figure 1, particularly during the latter half of the sleep-loss period (sessions 5-9). As indicated in Figure 1, there were small improvements in the performances of the control group while the experimental group was experiencing corresponding decrements in performance. The magnitude of this divergence between functions increased monotonically with task difficulty. The overall divergence of the experimental and control functions was reflected in the significant main effect of Condition and the significant Condition x Session interaction (see Table 3).

The effects of sleep loss on performance are probably more accurately reflected in the divergence of the experimental and control functions rather than in the magnitude of performance decrements in the experimental group alone; the effects of sleep loss are superimposed on the effects of practice, and, therefore, can best be assessed by comparing performance levels during sleep loss with levels attained with comparable amounts of practice in the absence of sleep loss.

There was no apparent difference in reaction times between the experimental and control groups in session 1 (indeed, Duncan-range tests to be discussed later show that during sesson 1 the experimental and control groups did not differ significantly at any level of discrimination difficulty). This finding indicates that the results of the analysis of reaction-time change scores (see the next section) should not differ markedly from those described in this section (as will be seen, the results are essentially identical to those discussed here).

In sessions 2 and 3, reaction times in both the experimental and control groups tended to decrease as a function of practice. These reductions in reaction time were slightly larger in the control group than in the experimental group at SD 1, 2, and 3, but were of about the same magnitude in both groups at SD 12. The relatively larger effects of practice in the control group may be attributable to differences in experimental procedures between groups (i.e., experimental subjects were tested at four-hour intervals and remained in the laboratory between test sessions; control subjects were tested on consecutive days and were only in the laboratory during the test sessions).

A major divergence of the experimental and control functions was apparent in session 4 (which occurred at 12:00 midnight for the experimental group, after approximately 16 hours of sleep deprivation), and this clear separation in the functions was maintained through session 9. Response times in the control group decreased maximally in session 4, and were maintained at approximately this level across subsequent sessions; this effect was apparent at all levels of difficulty. Conversely, reaction times in the experimental group increased from minimum values in session 2 to maximum values (longest reaction times) by session 7 or 8. At SD 1, reaction times increased to reach maximal levels in session 8, and decreased slightly from this level in session 9 (the last session of the sleep-loss period); reaction times at SD 2 and SD 3 peaked in session 7, and decreased slightly in sessions 8 and 9. This "end-spurt" improvement in performance toward the end of the sleep-loss period often occurs in sleep-deprivation studies. Although the magnitude of the increases were quite small, experimental-group reaction times also increased at SD 12; reaction times reached their maximal values in session 5 and were maintained at this level throughout the remainder of the sleep-loss period.

Performance in the experimental group during the recovery session (session 10), following approximately 12 hours of rest and recovery, showed marked improvement; reaction times at SD 1 were faster than in any of the previous sessions, and at SD 2, 3, and 12 were approximately equal to the reduced levels attained in sessions 2 and 3. Reaction times in the control group in session 10 were maintained at approximately the same levels evidenced in sessions 4-9. Therefore, the differences in reaction times between the experimental and control groups were substantially reduced in session 10, primarily as a function of the reductions in reaction times in the experimental group.

Of primary interest with respect to the performance of the experimental group was whether the magnitude of their performance decrements across sleep loss increased as a function of task difficulty. This effect was assessed by comparing the relative magnitudes of the divergence of the experimental and control functions across sleep-loss sessions for the four difficulty levels. As previously noted, the magnitude of this divergence increased monotonically with task difficulty, which indicates that the detrimental effects of sleep loss on performance increased with task difficulty; the divergence of the functions was largest at SD 1, intermediate (but equivalent) at SD 2 and SD 3, and smallest at SD 12. These effects were further reflected in the significant _Condition_ x _Discrimination Difficulty_ and _Condition_ x _Discrimination Difficulty_ x _Session_ interactions (see Table 3).

Duncan-range pairwise comparisons of all cell means provided further evidence that sleep loss had detrimental effects on performance, and furthermore, that these effects increased in magnitude with task difficulty (see Appendix B for a numerical presentation of cell means). Reaction times were significantly longer in the experimental condition than in the control condition in sessions 4-9 at SD 1, in sessions 5-9 at SD 2, and in sessions 6-9 at SD 3 ($p < .01$). Differences between groups in other sessions were not statistically significant. At SD 12, none of the differences between group means in corresponding sessions were significant ($p > .01$).

Consistent with previous studies (Thurmond & Alluisi, 1963; Morgan & Alluisi, 1967), the overall means of median reaction times increased as discrimination difficulty increased. This effect was reflected in the significant main effect of Discrimination Difficulty (see Table 3), and is apparent in the differences in the levels of the four sets of functions shown in Figure 1. In order to show this effect more clearly, median reaction times in the first session were averaged across the experimental and control groups, for each discriminability condition. The obtained function is shown in Figure 2. As is apparent, median reaction times increased with increases in discrimination difficulty. The shape of the function is quite similar to those obtained by Thurmond and Alluisi (1963, Figure 2, page 332) and Morgan and Alluisi (1967, Figure 2, page 56).

Reaction-Time Change Scores

The change scores were computed for each subject in each condition by subtracting the median reaction times obtained in sessions 2-10, respectively, from those obtained in session 1. Positive scores indicate an improvement in performance over initial levels (faster reaction times), whereas negative scores indicate a decrement in performance (slower

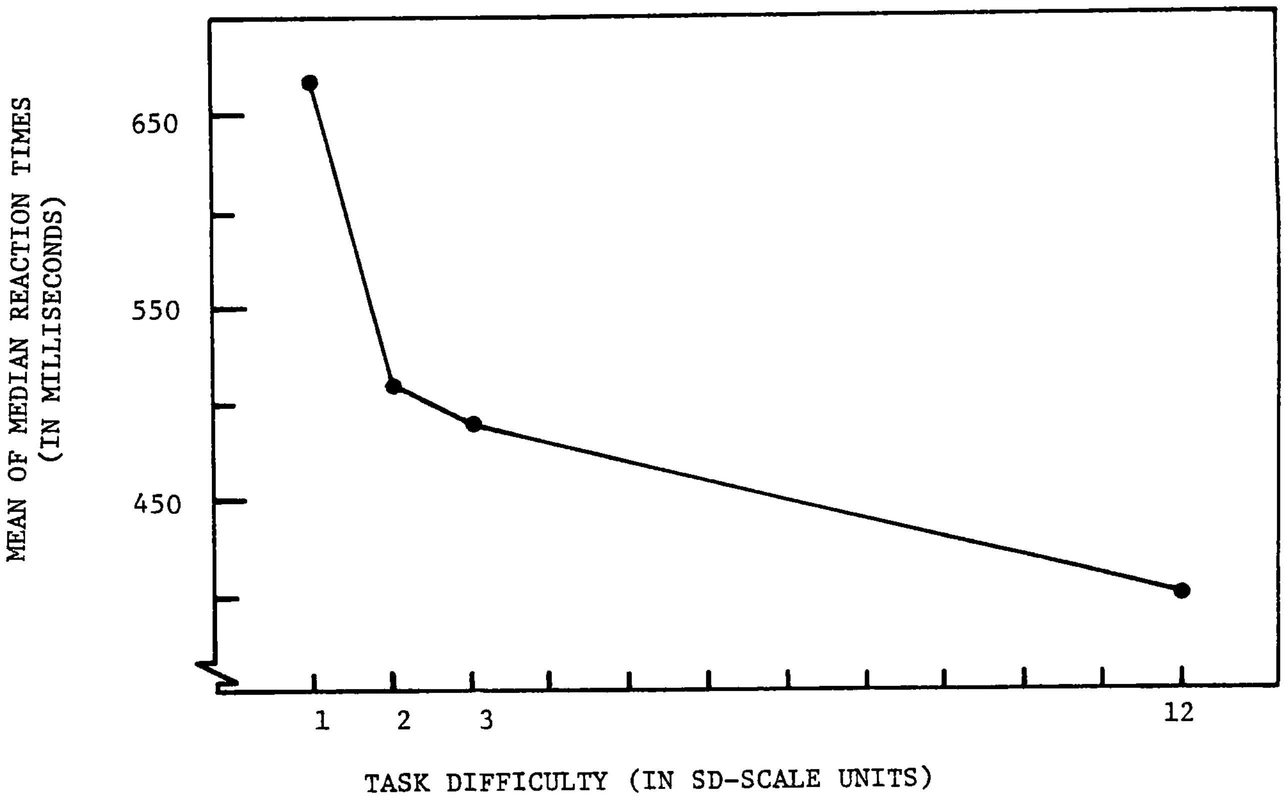

Figure 2. Mean of median reaction times of all subjects in session one as a function of task difficulty.

reaction times). The summary of the analysis of variance of these data is presented in Table 4. As in the previous section, conservative alpha levels ($p < .01$) were set for all F-tests. Figure 3 shows the mean change scores in the experimental and control conditions in each session and at each level of difficulty.

The change-score functions were similar in pattern to the reaction-time functions shown in Figure 1. There was a consistent divergence of the experimental and control functions which increased in magnitude with task difficulty. The divergence of the experimental and control functions was reflected in the significant main effect of Condition and the significant Condition x Session interaction. The differences in the magnitude of this divergence between difficulty levels was reflected in the significant Condition x Discrimination Difficulty and Condition x Discrimination Difficulty x Session interactions (see Table 4). These results are consistent with the analysis of median reaction times in the preceding section.

As indicated by the positive change scores, performance at SD 1 improved during sessions 2 and 3 in both the experimental and control groups. However, the magnitude of the reduction in response times across this period was smaller in the experimental group than in the control group. At SD 2, the performance of the control group improved slightly during sessions 2 and 3, whereas the performance of the experimental subjects exhibited only slight variations around their session-1 level of performance. At SD 3 and SD 12, neither the experimental nor the control subjects experienced any systematic change in performance during sessions 2 and 3.

Table 4

Summary of Analysis of Variance of Median

Reaction-Time Change Scores

Source of Variation	dF	Mean Square	F
Condition (C)	1	2.78563	23.91288***
error - Subjects within Condition (Ss(C))	22	.11649	
Discrimination Difficulty (D)	3	.02393	.64144
DC	3	.18560	4.97530**
error - DSs(C)	66	.03730	
Session (S)	8	.03261	2.65965**
SC	8	.08986	7.32901***
error - SSs(C)	176	.01226	
DS	24	.00524	1.50957
CDS	24	.00742	2.13919***
error - DSSs(C)	528	.00347	

** $p < .01$.
*** $p < .001$.

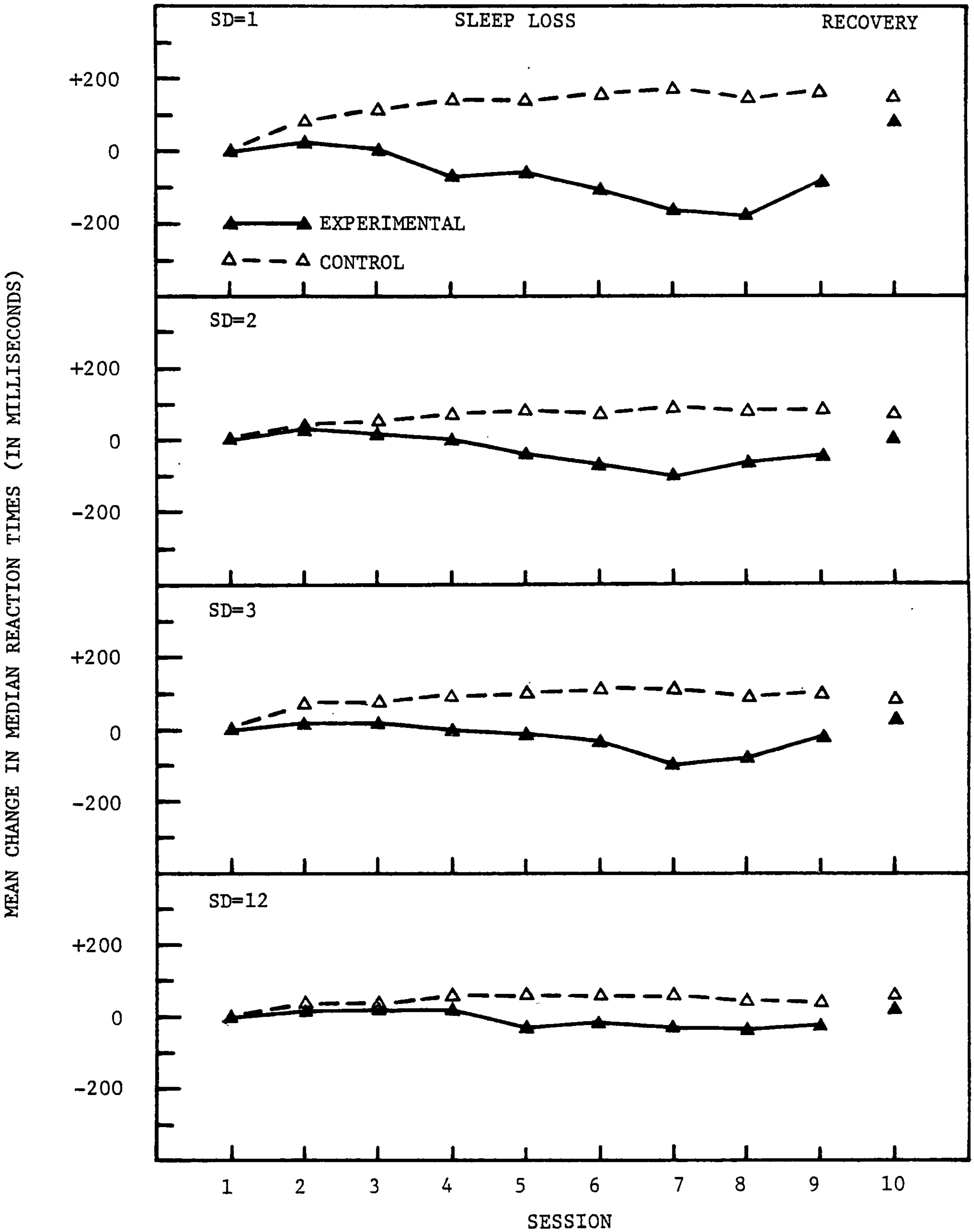

Figure 3. Mean change (from session one) in median reaction times as a function of condition and session at each level of task difficulty.

The effects of sleep loss are apparent in the divergence of the experimental and control functions across sessions 4-9. Change scores in the experimental group shifted from positive (in initial sessions) to negative in session 4 at SD 1 and in session 5 at SD 2, 3, and 12, and remained negative for the duration of the sleep-loss period. The magnitude of the increases in reaction time increased with task difficulty, hence were largest at SD 1, intermediate (but equivalent) at SD 2 and 3, and smallest at SD 12. An "end-spurt" improvement in performance was apparent in sessions 8 and 9 at SD 1, 2, and 3; reaction times decreased from previous levels, but were longer than in the initial session, as well as longer than in the control group in the corresponding session. This effect did not occur at SD 12. Change scores in the control group across sessions 4-9 were all positive, which indicates that reaction times were consistently longer in the initial session than in later sessions. The magnitude of these reductions in response times increased as task difficulty increased. At all difficulty levels, maximal reductions in response times were attained by session 5, and remained stable at about this level across subsequent sessions.

Recovery-session (session 10) performance in the experimental group showed marked improvements. At all levels of difficulty, response times were reduced to session-1 levels or lower. The largest improvement occurred at SD 1; reaction times in the recovery session were shorter than in any of the previous sessions. Reaction times in the control group in session 10 remained at about the same level as in sessions 4-9. The differences between reaction times in the control and experimental groups in session 10 were markedly reduced in magnitude from sessions 4-9, which is largely attributable to the reductions in response times in the experimental group.

The results of Duncan-range pairwise comparisons of all cell means (see Appendix B) were consistent with the effects previously discussed. Comparisons of the mean change scores in the experimental and control groups in the corresponding sessions indicated that the differences were significant in sessions 4-9 at SD 1, in sessions 5-9 at SD 2, and in sessions 6-9 at SD 3 ($p < .01$). None of the differences between group means were significant at SD 12 ($p > .01$).

Errors

The number of incorrect responses was computed for the 30 test trials given each subject in each condition. The summary of the analysis of variance of these data is presented in Table 5. It should be noted that an alpha level of $p < .05$ was set for all F-tests before data collection rather than the more conservative level set for the reaction-time measures. The mean number of errors in the experimental and control conditions across sessions and at each level of difficulty are shown in Figure 4.

The differences in the mean number of errors in session 1 between the experimental and control groups were minimal at SD 2, 3, and 12, but were relatively larger at SD 1 (see Figure 4). This indicates that there might have been a confound between the effects of Condition and systematic differences between the experimental and control groups attributable to extraneous factors (such as random differences among subjects or incidental differences in experimental procedures between groups which only affected performance in the most difficult task condition). If it can be assumed that these effects remained constant across subsequent sessions, the analysis of change scores (see the next section) should control for this confound. Therefore, the effects of

Table 5

Summary of Analysis of Variance of Errors

Source of Variation	dF	Mean Square	F
Condition (C)	1	204.42605	5.52714*
error - Subjects within Condition (Ss(C))	22	36.98589	
Discrimination Difficulty (D)	3	520.78439	134.84303***
DC	3	63.45660	16.43037***
error - DSs(C)	66	3.86215	
Sessions (S)	9	1.94549	1.22386
SC	9	2.26863	1.42714
error - SSs(C)	198	1.58964	
DS	27	1.85382	1.47331
CDS	27	1.37635	1.09385
error - DSSs(C)	594	1.25827	

*$p < .05$.
**$p < .01$.
***$p < .001$.

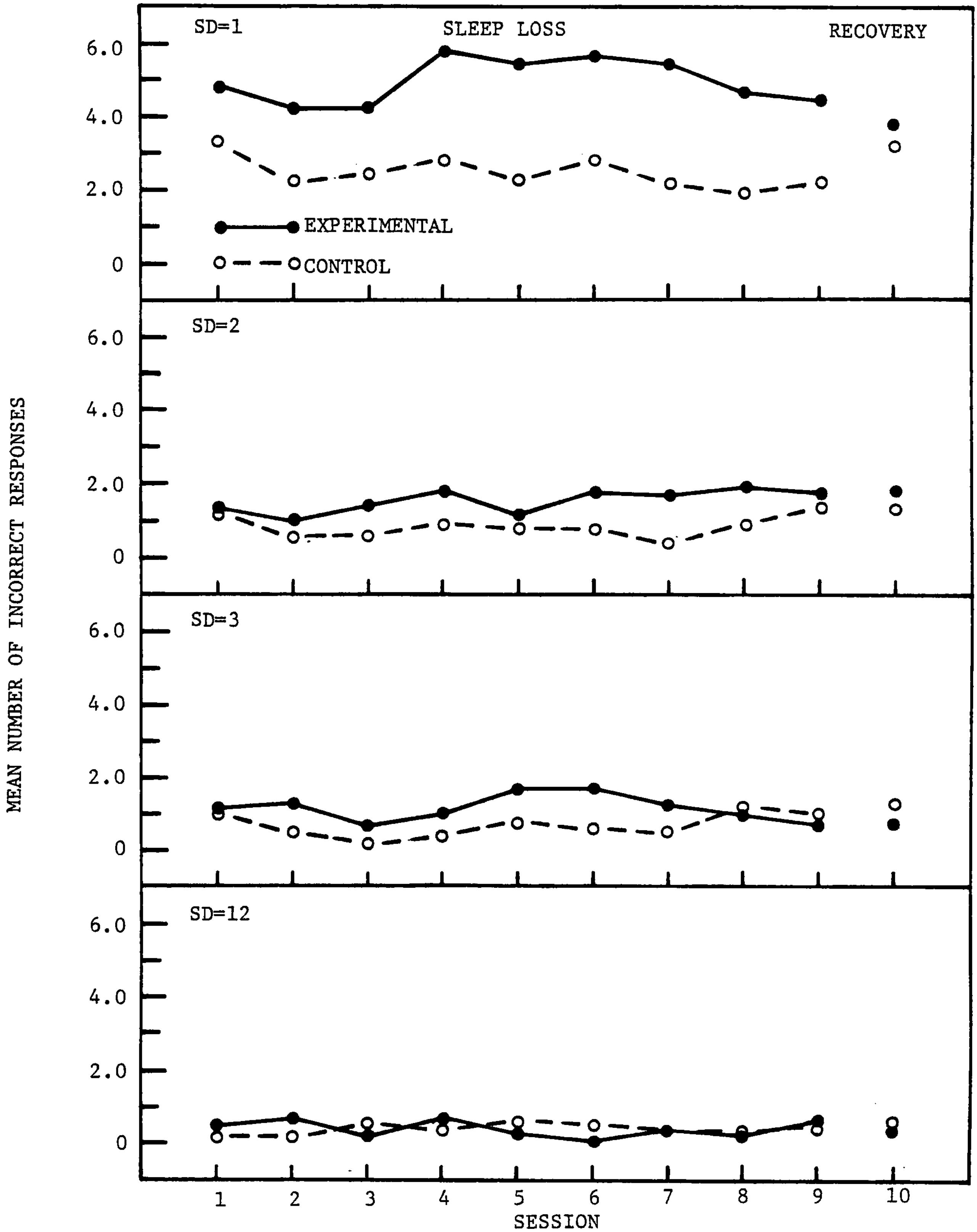

Figure 4. Mean number of incorrect responses as a function of condition and session at each level of task difficulty.

Condition and the interaction of Condition with other factors are probably more accurately assessed by the analysis of change scores.

At SD 1, the effects of practice were evidenced in sessions 2 and 3 by the reduction in errors from initial levels in both the experimental and control groups. At SD 2 and 3, practice effects were only apparent in the control group; errors in the experimental group remained at approximately session-1 levels. Errors in both groups at SD 12 were maintained at the same low levels obtained in session 1.

The experimental and control functions diverged across sessions (beginning in session 2, but becoming more prominent in sessions 4-9) at all difficulty levels except SD 12. At SD 1, the mean number of errors for the experimental group increased across sessions 4-9, whereas errors remained lower than the session-1 level across corresponding sessions in the control group; this divergence of the functions was exaggerated, perhaps because of the initial performance differences between groups. An "end-spurt" improvement in performance (reduction in errors) occurred in sessions 8 and 9 in the experimental group. At SD 2 and 3, slight increases in errors were apparent across sessions 4-9 in the experimental group. Performance in the control group was maintained at about the same level obtained in sessions 2 and 3, except that errors increased slightly in sessions 8 and 9. There was no apparent difference between accuracy in the experimental and control groups at SD 12; in both groups, errors were maintained at approximately the same low levels obtained in session 1.

In the recovery session, the mean number of errors in the experimental group at SD 1 was reduced below those obtained in all previous sessions. In the control condition at SD 1, and in both conditions at SD 2, 3, and 12, errors were maintained at approximately the same levels as in the immediately preceding sessions. The number of errors in the experimental group remained consistently lower than in the control group, though these differences were minimal. The main effect of Condition and the Condition x Discrimination Difficulty interaction were both significant (see Table 5), which was probably due to the relatively larger divergence of the experimental and control functions at SD 1. As previously discussed, these effects are probably confounded with the effects of spurious differences between the experimental and control groups (reflected in initial differences in accuracy between groups at SD 1). No inferences regarding the effects of sleep loss on performance accuracy, or the impact of task difficulty on these effects, are warranted based on this analysis.

The results of Duncan-range comparisons of the mean number of errors in the experimental and control conditions in corresponding sessions (see Appendix B) indicated that the only significant differences were at SD 1; the experimental group made significantly more errors than the control group in sessions 1-9 ($p < .05$). Session-10 differences were not significant ($p > .05$).

The absolute levels of the functions shown in the four panels of Figure 4, and the significant main effect of Discrimination Difficulty (see Table 5), indicate that the mean number of incorrect responses (collapsed across Condition and Session) increased with task difficulty. Figure 5, which shows the mean number of incorrect responses (averaged across the experimental and control groups) in the first session as a function of discrimination difficulty, more clearly illustrates the deleterious effects of increased discrimination difficulty on response accuracy. It is clear from Figure 5 that the greatest improvement in

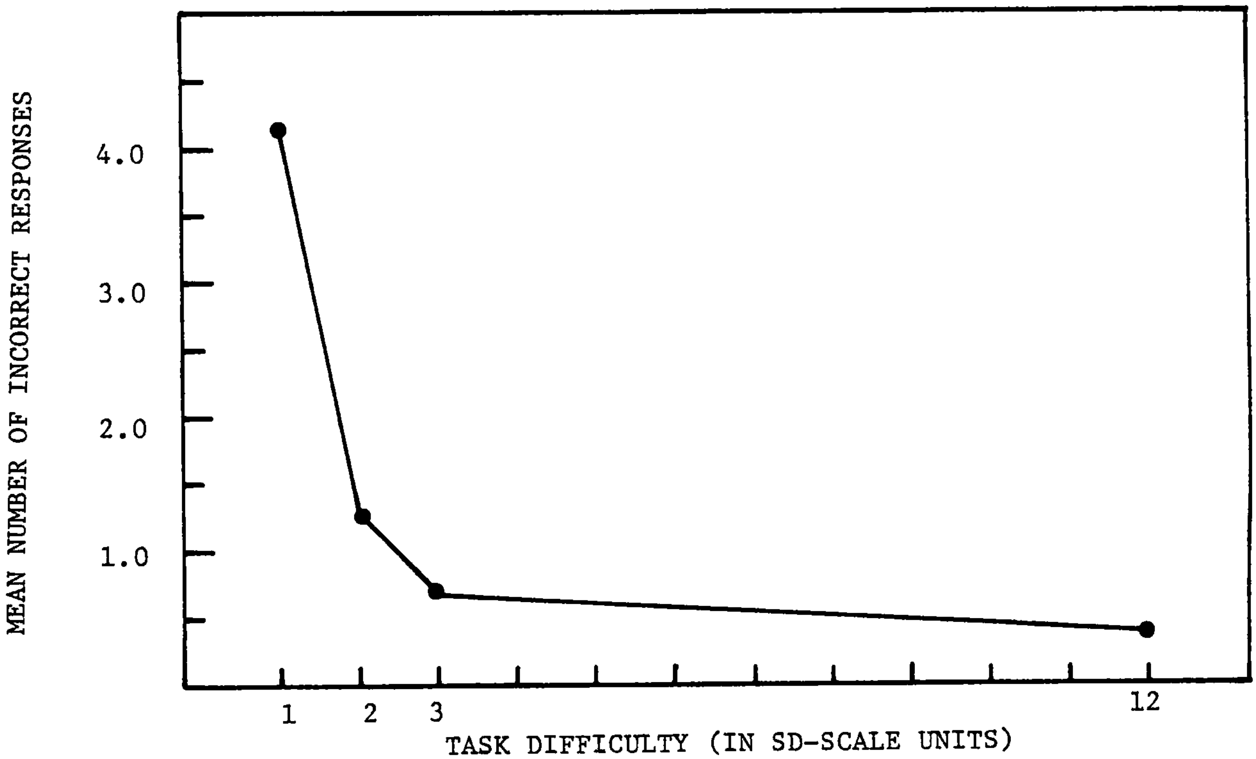

Figure 5. Mean number of incorrect responses of all subjects in session one as a function of task difficulty.

performance accuracy occurred between SD 1 and SD 2; however, it must be noted that this effect was exaggerated somewhat by the significantly higher number of errors in the experimental condition across all sessions at SD 1. The shape of the function is comparable to those obtained by Thurmond and Alluisi (1963, Figure 1, page 330) and Morgan and Alluisi (1967, Figure 1, page 56).

Error Change Scores

Change scores were computed for each subject in each condition by subtracting numbers of incorrect responses in sessions 2-10, respectively, from those obtained in session 1. Positive change scores indicate a decrease in the number of errors (an improvement in performance), whereas negative scores indicate an increase (a decrement in performance). The summary of the analysis of variance of these data is presented in Table 6; the alpha level for F-tests was set a $p < .05$. The mean change scores for the experimental and control groups across sessions at each level of difficulty are shown in Figure 6. It should be noted that none of the mean changes exceed ±1; therefore, the magnitude of the effects discussed are, in an absolute sense, quite small.

Accuracy improved slightly from initial levels in sessions 2 and 3 at SD 1 (as indicated by positive change scores), in both the experimental and control groups. At SD 2 and SD 3, small improvements were apparent in the control group, but not the experimental group. During sessions 2 and 3, there were no systematic changes in the accuracy of either group at SD 12.

The experimental and control functions diverged (particularly across sessions 4-9) at all difficulty levels, but the magnitude of these divergences were small. At SD 1, accuracy of performance decreased

Table 6

Summary of Analysis of Variance of

Error Change Scores

Source of Variation	dF	Mean Square	F
Condition (C)	1	34.64055	1.32168
error - Subjects within Condition (Ss(C))	22	26.20907	
Discrimination Difficulty (D)	3	15.53202	1.20499
DC	3	10.93943	.84869
error - DSs(C)	66	12.88977	
Sessions (S)	8	2.18229	1.49398
SC	8	2.11921	1.45079
error - SSs(C)	176	1.46073	
DS	24	1.89140	1.50778
CDS	24	1.41165	1.12533
error - DSSs(C)	528	1.25443	

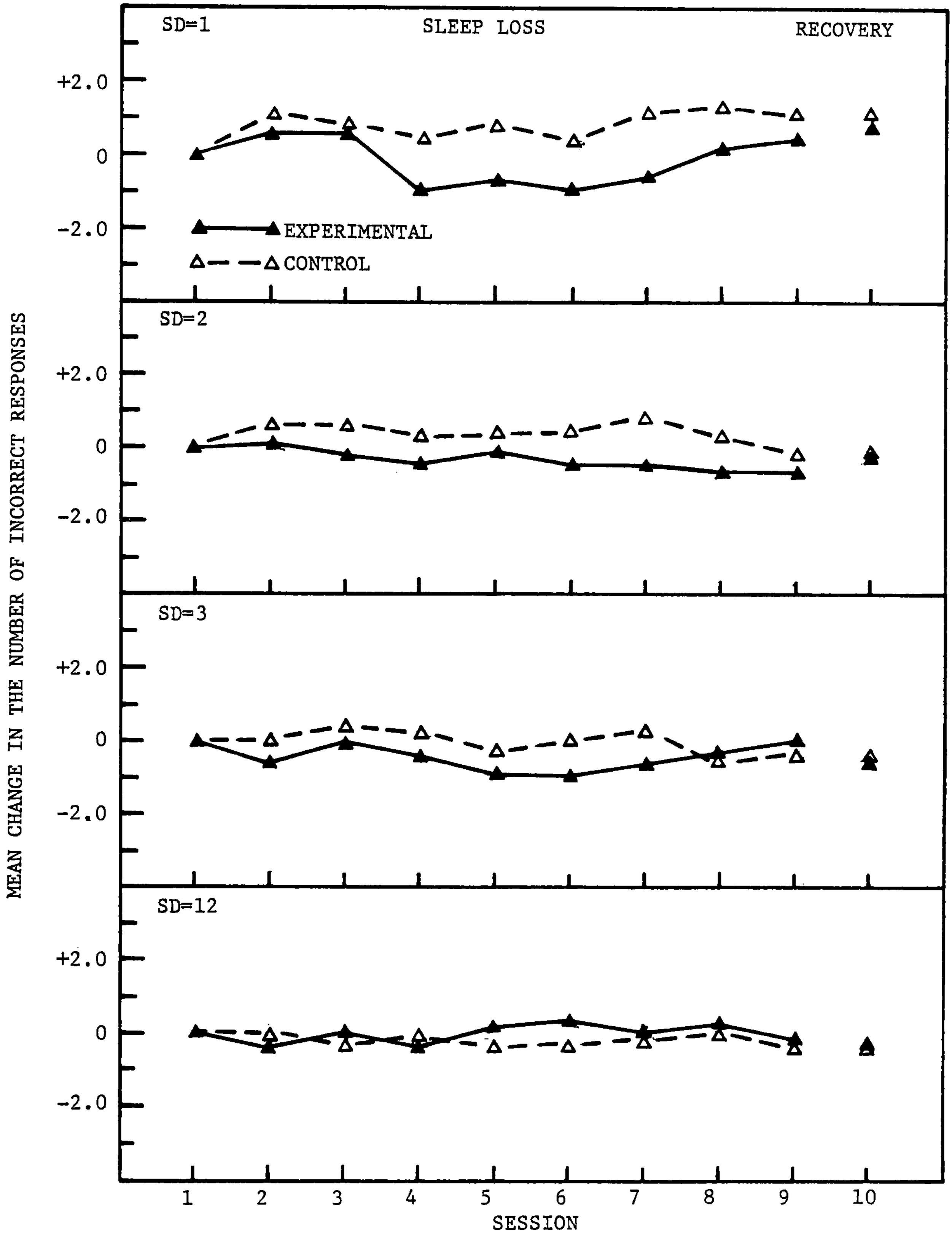

Figure 6. Mean change (from session one) in the number of incorrect responses as a function of condition and session at each level of task difficulty.

from initial levels in sessions 4-7, as indicated by a shift from positive to negative change scores; an "end-spurt" improvement in performance occurred in sessions 8 and 9. Errors in the control group remained at about the same reduced levels obtained in sessions 2 and 3 throughout all subsequent sessions. At SD 2 and SD 3, the accuracy of performance in sessions 4-9 was below that of initial sessions in the experimental group, but remained slightly higher than initial levels across corresponding sessions in the control group. The differences between functions at SD 12 were minimal. In session 10 (the recovery session in the experimental group), the differences in mean change scores were minimal, at all difficulty levels.

To summarize, Figure 6 suggests that sleep loss resulted in slight reductions in response accuracy at SD 1, as indexed by the divergence of the experimental and control functions. Only a slight divergence in the functions was apparent at SD 2 and SD 3 across the sleep-loss period, and no real differences occurred at SD 12. Thus, the overall effects of sleep loss on accuracy appear negligible, and only under the most difficult condition, if at all.

As indicated in Table 6, none of the effects analyzed by the analysis of variance were significant. In addition, the results of Duncan-range comparisons of mean change scores (see Appendix B) indicated that none of the differences between the experimental and control groups in corresponding sessions were statistically significant ($p > .05$). Therefore, the results of this analysis indicate that sleep loss did not affect performance accuracy to a significant extent, irrespective of task difficulty.

Rate of Information Transmission

Rate of information transmission incorporates both aspects of performance discussed in the previous sections (i.e., speed and accuracy) into a single measure. As suggested by the previous discussion of potential trade-offs between speed and accuracy of performance, performance decrements may be reflected in only one of these aspects of performance. Therefore, rate of information transmission is a more sensitive indicator of the performance effects of sleep loss, since it is independent of the subject's strategy to maintain speed at the cost of accuracy, or, conversely, to maintain accuracy at the cost of speed.

The rate of information transmission, in bits per second, was estimated for each subject in each condition by dividing the amount of information transmitted by the median reaction time (Ht/RT). The amount of information transmitted was computed from response information and equivocation according to the procedures outlined by Garner and Hake (1951); this measure reflects accuracy of performance because it varies as a function of error rate. Computational procedures are presented in more detail in Appendix C. The summary of the analysis of variance of these data is presented in Table 7; alpha levels were set at $p < .05$. Figure 7 shows the means of the rates of information transmission in the experimental and control conditions across sessions at each of the four levels of discrimination difficulty.

The effects of sleep loss are apparent in the divergence of the experimental and control functions, particularly across the last six sleep-loss sessions (sessions 4-9). As indicated in Figure 7, the divergence was consistently obtained across all levels of difficulty.

Table 7

Summary of Analysis of Variance of Rates

of Information Transmission

Source of Variation	dF	Mean Square	F
Condition (C)	1	55.72822	31.87307***
error - Subjects within Condition (Ss(C))	22	1.74844	
Discrimination Difficulty (D)	3	96.94880	386.95682***
DC	3	.94059	3.75423**
error - DSs(C)	66	.25054	
Sessions (S)	9	.27525	1.77102
SC	9	.99073	6.37468***
error - SSs(C)	198	.15542	
DS	27	.10392	1.02594
CDS	27	.09445	.93247
error - DSSs(C)	594	.10129	

**$p < .01$.
***$p < .001$.

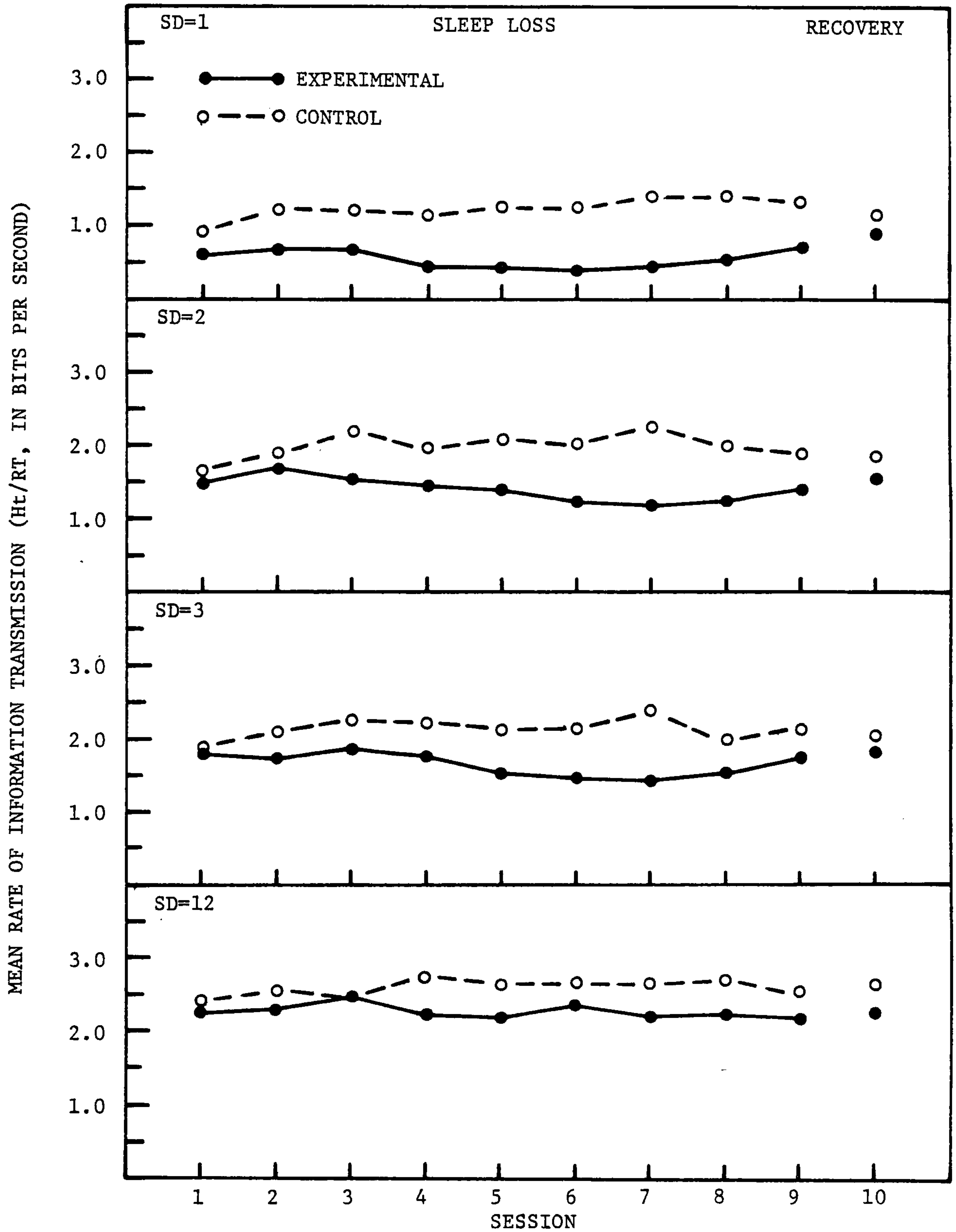

Figure 7. Mean rate of information transmission as a function of condition and session at each level of task difficulty.

The differences between the performances of the experimental and control groups was smaller in session 1 than in any of the subsequent sessions, although performance was consistently poorer for the experimental group. At SD 2, 3, and 12, these differences were minimal; the relatively larger differences at SD 1 can be attributed to the significant initial differences in error rates between the experimental and control groups. Even though these differences were not extensive, the analysis of rates of information transmission change scores (see the next section) controlled for the possible confound between the effects of Condition and systematic differences between the experimental and control groups in initial performance levels.

The effects of practice were apparent in sessions 2 and 3. Mean rates of information transmission increased across these sessions for both the experimental group and the control group. The magnitude of these increases was relatively larger for the control group (except at SD 12). However, the fact that both groups exhibited the same trends in performance across this period (viz., increases in rates of information transmission) is of primary importance.

The major divergence between the experimental and control functions occurred in session 4 and was maintained through session 9; while performance in the control group tended to improve, a decline in performance was apparent in the experimental group. Information transmission rates declined below session-1 levels in session 4 at SD 1 and SD 2, and in session 5 at SD 3, and remained relatively stable at this level through session 8; the familiar "end-spurt" improvement in performance occurred in session 9. However, performance only improved to about session-1 levels, and remained lower than the performance levels of the control group. At SD 12, the decline in performance was smaller than in the more difficult conditions; information transmission rates declined to approximately session-1 levels in session 4, and remained relatively stable at this level through session 9 (no "end-spurt" improvement was apparent).

Information transmission rates in the control group increased from initial levels across sessions 4-9. At SD 1, 2, and 3, information transmission rates improved to maximum levels in session 7; a slight decrement from this level was apparent in subsequent sessions at SD 2 and SD 3, but transmission rates remained higher than initial levels, as well as superior to rates in the experimental group in corresponding sessions. At SD 12, information transmission rates reached the maximum level in session 4, and remained at approximately this level across all subsequent sessions. However, the magnitude of the improvement in performance was markedly smaller than in the more difficult conditions, which can probably be attributed to the ease of the task and the relatively high initial rates of information transmission.

The detrimental effects of sleep loss on performance were reflected in the divergence of the experimental and control functions across sessions 4-9. The magnitude of the divergence was smaller at SD 12, compared to the more difficult conditions, because of the relatively smaller decrements in performance in the experimental condition and the smaller improvements in performance in the control condition. There were no apparent differences in the magnitude of the divergence between functions when task difficulty was varied over the range corresponding to SD 1, 2, and 3. The divergence of the experimental and control functions, particularly in sessions 4-9, was reflected in the significant main effect of _Condition_ and the significant _Condition_ x _Session_ interaction (see Table 7).

Recovery session (session 10) performance in the experimental group provided evidence regarding the effects of 12 hours of rest and recovery following 36 hours of sleep loss. Recovery performance evidenced the largest improvement at SD 1, to the extent that the mean rate of information transmission was higher than in any of the previous sessions. At SD 2 and SD 3, information transmission rates in the recovery session were higher than in sessions 4-8, but were approximately equivalent to the improved levels attained in session 9. As previously noted, performance in the control group at SD 1, 2, and 3 declined somewhat (from maximum levels) in session 10. The magnitude of the differences in rates of information transmission between the experimental and control groups were smaller in session 10 than in sessions 4-9, because of the slight decrements in control-group performance and the concomitant improvements in experimental-group performance. At SD 12, rates of information transmission in both groups were maintained at about the same levels as in the immediately preceding sessions. Therefore, not only did performance in the control group remain superior, but the magnitude of the differences in performance between groups remained about the same as in sessions 4-9.

Of primary interest in the present study is whether the magnitude of the performance decrements across sleep loss is a function of task difficulty. It has already been noted that the divergence of the experimental and control functions was smaller at SD 12 than at SD 1, 2, or 3; there were no apparent differences among SD 1, 2, and 3. It might be surmised that the effects of sleep loss were more deleterious at SD 1, 2, and 3 than at SD, in that potentially large practice effects (illustrated by control group performance) were abolished by decrements to levels below session-1 performance. Practice effects were negated at SD 12 as well, but these effects were much smaller than in the more difficult conditions.

The results of the analysis of variance indicated that the interaction between Condition and Discrimination Difficulty was significant, probably because of the smaller divergence between the experimental and control functions at SD 12 compared to the more difficult conditions. The three-factor interaction (Condition x Discrimination Difficulty x Session) was not significant (see Table 7).

As indicated in Figure 7, mean rates of information transmission in the experimental group were consistently lower than in the control group in the corresponding sessions. These differences were extant at all difficulty levels. Planned comparisons were made to determine which of these differences were statistically significant. The results of Duncan-range pairwise comparisons of all cell means (see Appendix B) revealed that the mean rates of information transmission in the control and experimental groups were not significantly different in session 1, in any of the four difficulty conditions ($p > .05$). Similarly, there were no significant differences between experimental and control group performance in session 10 ($p > .05$). Performance levels in the experimental group were significantly lower than in the control group in sessions 2-9 at SD 1, in sessions 3-9 at SD 2, and in sessions 4-8 at SD 3 and SD 12 ($p < .05$).

Consistent with the findings of earlier studies (Thurmond & Alluisi, 1963; Morgan & Alluisi, 1967), mean rates of information transmission decreased as discrimination difficulty increased. This effect was reflected in the significant main effect of Discrimination Difficulty (see Table 7), and is apparent in the differences in the absolute levels of the functions across difficulty conditions (see Figure 7). The rates of information transmission in session 1, averaged across all subjects, are shown in Figure 8 as a function of discrimination difficulty. As indicated, information transmission rates are inversely related to task difficulty. The obtained function is similar in form to those obtained by Thurmond and Alluisi (1963, Figure 4, page 335) and Morgan and Alluisi (1967, Figure 3, page 57).

Rate-of-Information-Transmission Change Scores

These measures were computed and analyzed to control for session-1 differences in rates of information transmission between the experimental and control groups. As indicated in the previous section, these differences were not statistically significant, although the rates of information transmission in the experimental group were consistently lower than those of the control group.

The change scores were computed for each subject in each condition by subtracting the rate of information transmission obtained in the first session from the rate of information transmission obtained in each subsequent session. Thus, the change scores represent both the magnitude and direction of changes from initial-session performance levels; a positive score indicates an improvement in performance (a higher rate of information transmission), whereas a negative score represents a decrement in performance (a lower rate of information transmission). The summary of the analysis of variance of these data is presented in Table 8; the alpha level was set at $p < .05$ for all F-tests. Figure 9

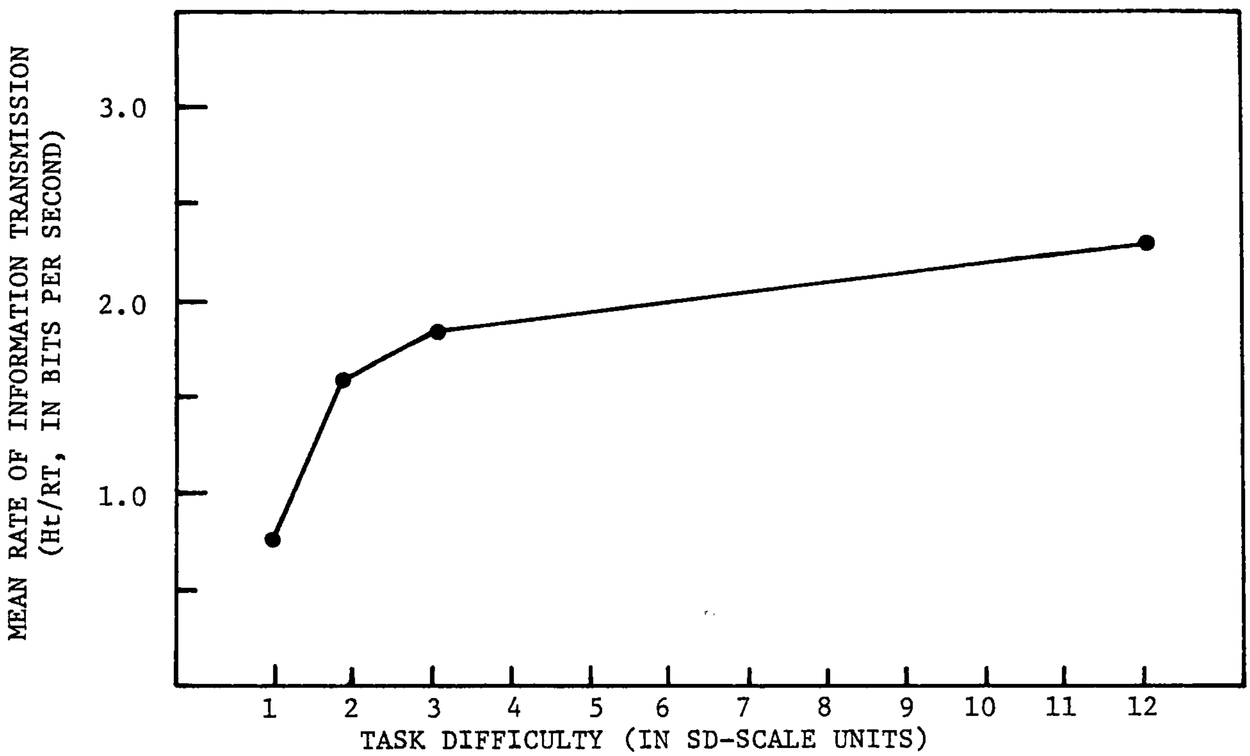

Figure 8. Mean rate of information transmission of all subjects in session one as a function of task difficulty.

Table 8

Summary of Analysis of Variance of Rate-of-Information-Transmission Change Scores

Source of Variation	dF	Mean Square	F
Condition (C)	1	30.24902	15.89122***
error - Subjects within Condition (Ss(C))	22	1.90350	
Discrimination Difficulty (D)	3	.29766	.38038
DC	3	.51213	.65447
error - DSs(C)	66	.78252	
Session (S)	8	.09764	.64643
SC	8	.73646	4.87562***
error - SSs(C)	176	.15105	
DS	24	.11319	1.08655
CDS	24	.09986	.95857
error - DSSs(C)	528	.10417	

***$p < .001$.

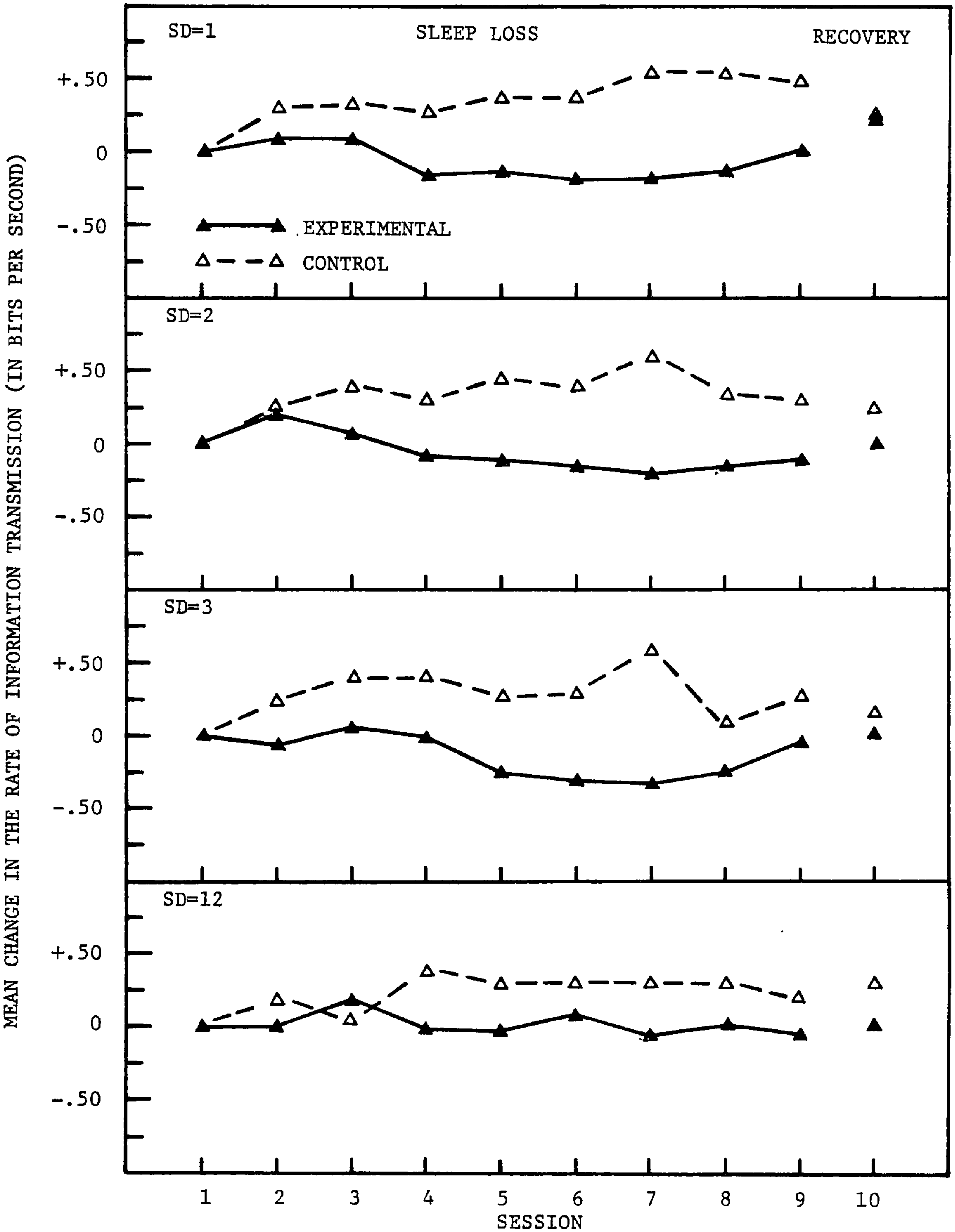

Figure 9. Mean Change (from session one) in rates of information transmission as a function of condition and session at each level of task difficulty.

shows the mean change scores in the experimental and control conditions in each session at each level of difficulty.

The change score functions were quite similar to the functions showing absolute rates of information transmission (see Figure 7). The general pattern of the functions was similar at all levels of difficulty; there was a consistent divergence between the experimental and control functions, although the magnitude of this divergence was smaller at SD 12 than at SD 1, 2, and 3.

The effects of sleep loss are apparent in the differences in performance between the experimental and control groups in sessions 4-9. At SD 1, 2, and 3, information transmission rates in the experimental group showed a general tendency to decrease from initial levels across the sleep-loss period (as indicated by negative change scores), and to increase across corresponding sessions in the control group (as indicated by positive change scores). The rates of information transmission in the experimental group declined below session-1 levels in session 4 at SD 1 and SD 2 and in session 5 at SD 3, and remained relatively stable at this level through session 8. An "end-spurt" improvement in performance was apparent in session 9 in the experimental group, though performance levels remained markedly lower than for their control counterparts. At SD 12, the rates of information transmission in the experimental group declined from the maximum level attained in session 3, but only to approximately session-1 levels. In the control group, information transmission rates increased from initial levels across sessions 4-9 at all difficulty levels; however, the increases at SD 12 were smaller than in the more difficult conditions. The divergence of the experimental and control functions was of smaller magnitude at SD 12 than at SD 1, 2, or 3, since both performance improvements in the control group and performance decrements in the experimental group were of smaller magnitude.

Recovery (session 10) performance in the experimental group at SD 1, 2, and 3 showed a general improvement over the lowest levels obtained during the sleep-loss period. The largest improvement was apparent at SD 1; the rate of information transmission attained in the recovery session was higher than in any of the nine previous sessions. At SD 2 and SD 3, performance in the recovery session was approximately equal to the improved levels evidenced in session 9. Session-10 performance in the control group at SD 1, 2, and 3 showed slight decrements from the peak levels obtained in session 7. At SD 12, performance in both the experimental and control groups was maintained at approximately the same level as in the immediately preceding sessions.

The consistent divergence of the experimental and control functions, particularly across the latter half of the sleep-loss period, was reflected in the significant main effect of Condition and the significant Condition x Session interaction (see Table 8). These results parallel those obtained in the earlier analysis of rates of information transmission.

The hypothesis that the magnitude of sleep-loss effects would increase as a function of task difficulty was not supported by the analysis of variance. The Condition x Discrimination Difficulty interaction was not significant (in contrast to the analysis of rates of information transmission), nor was the Condition x Discrimination Difficulty x Session interaction (see Table 8).

Although the results of the analysis of variance indicate that there was no significant difference between difficulty levels in the magnitude of the divergence of the experimental and control functions, a trend in the correct direction is apparent in Figure 9, particularly between SD 12 and the more difficult conditions. As described previously, the divergence of the functions at SD 12 was markedly smaller than at SD 1, 2, or 3, where the magnitude of the divergence appeared equivalent.

Duncan-range pairwise comparisons of all cell means (see Appendix B) provided further evidence to support not only the contention that sleep loss had detrimental effects on performance, but that these effects were less marked at SD 12. Experimental group performance was consistently lower than control group performance, at all difficulty levels. However, comparisons of mean change scores between corresponding sessions in the experimental and control groups revealed that these differences were only significant in sessions 5-8 at SD 1 and SD 2, and in sessions 5-7 at SD 3 ($p < .05$). In contrast, none of the differences between means in the experimental and control groups at SD 12 were significant ($p > .05$).

Discussion

The performance effects of sleep deprivation are highly variable, ranging from essentially no effect to an almost complete breakdown in performance (Woodward & Nelson, 1974). Numerous task (and non-task) factors have been shown to influence the extent to which performance deteriorates during sleep loss (see Wilkinson, 1965; Naitoh & Townsend, 1970; Johnson & Naitoh, 1974; Woodward & Nelson, 1974). One of the critical task variables appears to be the extent to which the task in question requires sustained attention and steady performance over relatively long periods of time (Woodward & Nelson, 1974). This type of performance demand is imposed by vigilance or monitoring tasks. Accordingly, sleep loss has been shown to produce significant performance decrements in auditory vigilance (Hord, 1976), visual vigilance (Williams, Kearney, & Lubin, 1964), and radar-monitoring tasks (Bergstrom, Gillberg, & Arnberg, 1973). Similarly, sleep loss has been shown to produce performance decrements in psychomotor tasks which require sustained attention and continuous motor performance, as in serial choice reaction (Wilkinson, 1964) and continuous tracking tasks (Pasnau, Naitoh, Stier, & Kollar, 1972; Collins, 1976).

Another important variable is the extent to which the task "loads" the information-processing capabilities of the subject. It appears that subjects can compensate for the adverse effects of sleep loss by increasing their level of effort in tasks which impose minimal demands, but such compensation may be impossible in tasks which require the subject to work at or near capacity. Complex cognitive tasks, which impose stringent demands on central processing mechanisms, are particularly vulnerable to the adverse effects of sleep loss (Naitoh & Townsend, 1970). Although Williams and Lubin (1967) found processing time to increase significantly after one night of sleep loss in a mental computation task (subjects were required to mentally add pairs of two-digit numbers presented aurally), performance decrements were relatively larger in the more complex two-step addition task (subjects were required to add eight to each sum obtained). In the same study, Williams and Lubin (1967) found mental addition at the rate of one per 1.25 seconds deteriorated more rapidly and to a greater extent than when one addition per two seconds was required.

Although sleep loss has been consistently shown to produce performance decrements in certain tasks (e.g., those which require sustained attention or which impose heavy demands on information-processing mechanisms), different explanations have been offered as to how these effects are mediated. Performance decrements obtained during sleep loss (particularly on vigilance tasks) have often been attributed to the occurrence of brief, intermittent lapses, or periods of microsleep (Bills, 1931; Warren & Clark, 1937; Williams, Lubin, & Goodnow, 1959; Cannon, Drucker, & Kessler, 1964). Indeed, there is physiological evidence (from electroencephalographic recordings) that such lapses do occur during sleep loss (Williams, Granda, Jones, Lubin, & Armington, 1962; Jovanovic, 1971). The occurrence of lapses may account for performance decrements in some situations (e.g., those requiring sustained attention). However, the results of other studies (e.g., Williams & Lubin, 1967) suggest that sleep loss also results in a more general reduction in information-processing capabilities, which induce progressively larger performance decrements as the information-processing demands of the task increase;

this reduction in processing capabilities may result from the general reduction in arousal which occurs as a consequence of sleep deprivation (Wilkinson, 1963).

Choice-reaction time tasks, which are frequently employed to investigate human information-processing capabilities, have been used in recent studies to determine how information-processing capabilities are influenced by sleep loss. The results of two such studies indicate that the efficiency with which information is processed is degraded by sleep loss, to an extent determined by the difficulty of the task (Buck & Gibbs, 1972; Eberhardt, 1979). In both these studies, the adverse effects of sleep loss were reflected in increased response times, and consequently, decreased rates of information transmission; accuracy remained relatively unaffected. However, both tasks were subject-paced; even though subjects were instructed to balance their efforts to reduce response times and errors, respectively, there were no limits placed on response time. Given that rates of information transmission decrease during sleep loss, it seems reasonable to conclude that if subjects were induced to respond rapidly (as when subjects are instructed to emphasize speed rather than accuracy, or when tasks are speeded through experimenter control), accuracy would be negatively affected. Buck and Gibbs (1972) found that the reduction in processing efficiency during sleep loss (reflected in increased reaction times and decreased rates of information transmission) increased in magnitude as stimulus uncertainty increased. Similarly, Eberhardt (1979) found that increasing task difficulty by reducing stimulus-response compatibility had the same effect. The difficulty of a choice-reaction task can also be manipulated by varying the discriminability of the stimuli employed.

Based on the results of previous studies, it was hypothesized in the current study that sleep loss would result in relatively larger decrements in performance as discrimination difficulty increased. This study was designed to determine (1) whether sleep loss reduces the efficiency of information-processing, (2) whether this reduction in processing efficiency is reflected in speed or accuracy of response, or both, and (3) whether the magnitude of these effects is a function of task difficulty, when task difficulty is manipulated by stimulus discriminability.

The results indicated, as consistent with the findings of Buck and Gibbs (1972) and Eberhardt (1979), that processing efficiency was reduced by sleep loss, and that these reductions in efficiency resulted in increased processing time (reaction time) rather than decreased accuracy. In the experimental group, reaction times increased markedly from initial levels across the sleep-loss period; conversely, reaction times in the control group were reduced from initial levels across the corresponding sessions.

More errors were made by the experimental group than the control group. However, these differences were apparent in the first session, and therefore were probably the result of systematic differences between the experimental and control groups. When initial differences between groups were controlled (i.e., in the change-score analysis), there was no significant difference in performance accuracy for the experimental and control groups in any session.

The rate of information transmission combines both the speed and accuracy measure into a single, more global index of performance. Since decrements in performance were evidenced in measures of speed, such decrements were also reflected in rates of information transmission.

Rates of information transmission in the experimental group declined from initial levels across the sleep-loss period, whereas increases in rates of information transmission were apparent in the control group across corresponding sessions.

Of primary interest was whether the magnitude of the deleterious effects of sleep loss would increase as a function of task difficulty. The influence of task difficulty was most apparent in the reaction time measure. As task difficulty increased, there was a monotonic increase in the magnitude by which response times increased during sleep loss. In the easiest task condition (SD 12), only minimal slowing of response times was apparent during sleep loss. These effects were not as pronounced in the rate of information transmission measure. The change-score analysis indicated that the differences in the effects of sleep loss between difficulty conditions were not statistically significant. However, there were indications that these effects did occur (in the trends of the functions plotted and in comparisons of cell means), although they were not of sufficient magnitude to reach levels of statistical significance. Specifically, the more difficult task conditions (SD 1, 2, and 3) appeared to be more detrimentally affected (in terms of rates of information transmission) by sleep loss than the least difficult task condition (SD 12).

The increase in the magnitude of sleep-loss effects (as reflected in reaction times and rates of information transmission) with increasing task difficulty is consistent with the findings of Buck and Gibbs (1972) and Eberhardt (1979). Thus, the current study provides additional evidence concerning the characteristics that make an information-processing task more susceptible to the deleterious effects of sleep loss.

The studies of Buck and Gibbs (1972), Eberhardt (1979), and the present study indicate that sleep-loss stress increases the time required to process information, make accurate decisions, and respond accordingly, especially when the task is relatively difficult. The practical implication of this finding is that in jobs (particularly complex jobs) where rapid and accurate responses are critical, work schedules should be designed to reduce the possibility of workers being subjected to sleep-loss stress.

Knowledge concerning specific factors which make a task susceptible to performance decrements during sleep loss not only provides evidence regarding the types of work that will deteriorate, but how tasks might be engineered to reduce these effects. It has often been suggested that as work becomes more complex or difficult, it is more likely to deteriorate during sleep loss. However, the studies of Buck and Gibbs (1972), Eberhardt (1979), and the present study provide evidence concerning the specific task characteristics that make it susceptible to performance decrements during sleep loss. Stimulus uncertainty, stimulus-response compatibility, and stimulus discriminability have now been shown to influence the degree to which information-processing performance deteriorates during sleep loss. Thus, particularly in systems where sleep loss is expected, displays should be designed so as to reduce stimulus uncertainty and increase stimulus discriminability, and displays and controls should be maximally compatible. Although these are design features which should always be incorporated in the design of man-machine systems, workers are known to be able to compensate for deficiencies in design and perform at adequate levels despite them. However, the evidence indicates that in work situations where sleep-loss stress is likely to occur, good design is even more critical, since operators do not have the performance reserves necessary to compensate for these deficiencies.

Suggestions for Future Research

The relatively few studies that have examined information-processing performance during sleep loss suggest that this line of research will improve man's understanding of the effects of sleep loss (as well as other stressors) on performance. In light of the extensive literature on information-processing and the variables that influence it, the current findings suggest a wide variety of research paradigms and topics for future research. Future research projects might assess changes in processing capabilities during sleep loss in other types of information-processing tasks (e.g., memory scanning, visual search), or examine possible interactions between sleep loss and other variables known to influence information-processing.

Given the proposition that the adverse effects of sleep loss are more pronounced in difficult tasks, these effects might be reduced to some extent by overtraining the subject before the sleep-loss period. Specifically, future research might compare effects of various amounts of pre-stress training to determine whether and to what extent training effectively reduces the magnitude of performance decrements during sleep loss.

Task duration has been shown to influence the magnitude of performance decrements during sleep loss (Donnell, 1969). Although sleep loss clearly produced performance decrements in the current study, particularly in the more difficult task conditions, these effects might have been more pronounced had test sessions been longer and/or more closely spaced. Future research might assess the effects of task duration on the interaction between sleep loss and task difficulty.

A number of investigators have observed that increased task difficulty increases performance decrements during sleep loss, but only if there is not a concurrent increase in the "interest value" of the task (e.g., Wilkinson, 1964). Even simple tasks, if they are boring and monotonous, deteriorate markedly during sleep loss. The task used in the present study, as corroborated by the subjects, was both boring and monotonous. However, the obtained decrements in performance appeared to result from both decreased motivation (because the subjects disliked the task and considered it uninteresting) and decreased information-processing efficiency. If only the monotony of the task was responsible for decrements in performance in successive sessions, it is difficult to account for the differential decrements in performance between difficulty conditions. However, the noted improvements in performance in the final sessions of the sleep-loss period suggest that motivational factors may have accounted for at least part of the performance decrement. Future research might be designed to assess more clearly the relative effects of motivational factors and reduced processing efficiency, by independently manipulating task interest and task difficulty.

Another avenue of research would be to assess the effects of sleep loss on the speed-accuracy trade-off. The speed-accuracy trade-off function can be delineated by inducing the subject to respond at various speeds. The rate at which accuracy is traded for speed (and vice-versa) is an index of the efficiency of information-processing; therefore, it provides another way to assess the degradation in processing efficiency induced by sleep loss, as well as how these effects are impacted by task difficulty.

Finally, research efforts might be directed toward the development of a taxonomy of information-processing tasks and abilities degraded by sleep loss (and other stressors). This would be an effective way to systematize research efforts and results.

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APPENDIX A

TASK INSTRUCTIONS

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In this experiment you will be required to make discriminations between the sizes of two small circles of light. Although you will work with four different pairs of circles in each test session, you will work with only one pair at a time. First you will be shown both circles in the pair with which you will be working. Then you will be given a series of 30 trials in which only one of the pair is presented. Your task is to judge which was presented on each trial, the larger or the smaller one. You will indicate your decision by pressing one of the two keys placed on the desk in front of you. Press the right (left)[1] key if you think the circle presented was the smaller one; press the left (right)[2] key if you think it was the larger one.

On each trial, the green light on the board in front of you will come on as a warning signal to indicate that the stimulus is about to be presented. After two seconds, the warning light will go off and the stimulus will be presented in the center of the round screen on the display board. After your response, I will indicate whether you were correct or incorrect. You should try to minimize both your reaction time and the number of errors you make. That is, you should try to maintain a balance between speed and accuracy, since they are equally important. Please remember that the order of presentation of the larger or the smaller stimulus is completely random. Do not try to anticipate which will be presented. After you are shown the pair of circles with which you will be working, you will be given five practice trials before the experimental trials begin.

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[1]Right if the subject is right-handed; left if the subject is left-handed.

[2]Left if the subject is right-handed; right if the subject is left-handed.

APPENDIX B

CELL MEANS

APPENDIX B

CELL MEANS

1. Median Reaction Times (in milliseconds)

	Session	Experimental	Control
SD1	1	.671	.666
	2	.638	.587
	3	.662	.553
	4	.743	.524
	5	.725	.531
	6	.767	.506
	7	.825	.497
	8	.842	.519
	9	.748	.510
	10	.588	.517
SD2	1	.524	.503
	2	.493	.480
	3	.506	.455
	4	.520	.436
	5	.568	.426
	6	.592	.431
	7	.627	.417
	8	.585	.429
	9	.549	.415
	10	.518	.438
SD3	1	.494	.503
	2	.464	.434
	3	.473	.434
	4	.488	.416
	5	.500	.405
	6	.527	.397
	7	.589	.394
	8	.576	.409
	9	.515	.401
	10	.468	.426
SD12	1	.405	.409
	2	.381	.370
	3	.384	.380
	4	.387	.348
	5	.438	.351
	6	.426	.346
	7	.435	.353
	8	.436	.357
	9	.422	.370
	10	.385	.345

2. Median Reaction-Time Change Scores

	Session	Experimental	Control
SD1	1	0	0
	2	+.032	+.079
	3	+.008	+.113
	4	-.073	+.142
	5	-.055	+.136
	6	-.096	+.160
	7	-.155	+.170
	8	-.171	+.147
	9	-.078	+.156
	10	+.082	+.149
SD2	1	0	0
	2	+.030	+.024
	3	+.018	_.049
	4	+.003	+.068
	5	-.044	+.077
	6	-.068	+.073
	7	-.103	+.087
	8	-.061	+.075
	9	-.025	+.089
	10	+.006	+.065
SD3	1	0	0
	2	+.029	+.070
	3	+.020	+.070
	4	+.006	+.087
	5	-.007	+.099
	6	-.034	+.106
	7	-.096	+.109
	8	-.082	+.094
	9	-.022	+.103
	10	+.026	+.077
SD12	1	0	0
	2	+.023	+.039
	3	+.021	+.028
	4	+.018	+.060
	5	-.033	+.057
	6	-.021	+.063
	7	-.031	+.056
	8	-.031	+.052
	9	-.017	+.038
	10	+.019	+.063

3. Errors

	Session	Experimental	Control
SD1	1	4.917	3.250
	2	4.333	2.167
	3	4.333	2.417
	4	5.833	2.833
	5	5.500	2.333
	6	5.833	2.833
	7	5.500	2.167
	8	4.750	1.917
	9	4.500	2.167
	10	3.833	3.167
SD2	1	1.333	1.167
	2	1.083	.583
	3	1.417	.583
	4	1.750	.917
	5	1.417	.750
	6	1.750	.750
	7	1.667	.417
	8	1.917	.917
	9	1.833	1.417
	10	1.677	1.250
SD3	1	.750	.583
	2	1.250	.500
	3	.750	.167
	4	1.000	.417
	5	1.667	.833
	6	1.667	.583
	7	1.333	.250
	8	1.000	1.167
	9	.750	.833
	10	1.250	.833
SD12	1	.500	.250
	2	.750	.333
	3	.417	.500
	4	.750	.417
	5	.333	.500
	6	.083	.500
	7	.417	.417
	8	.167	.333
	9	.583	.500
	10	.750	.500

4. Error Change Scores

	Session	Experimental	Control
SD1	1	0	0
	2	+.583	+1.083
	3	+.583	+ .833
	4	-.917	+ .417
	5	-.583	+ .917
	6	-.917	+ .417
	7	-.583	+1.083
	8	+.167	+1.333
	9	+.417	+1.083
	10	+1.080	+ .083
SD2	1	0	0
	2	+.250	+.583
	3	-.083	+.583
	4	-.417	+.250
	5	-.083	+.417
	6	-.417	+.417
	7	-.333	+.750
	8	-.583	+.250
	9	-.500	-.250
	10	-.333	-.083
SD3	1	0	0
	2	-.500	+.083
	3	0	+.417
	4	-.250	+.167
	5	-.917	-.250
	6	-.971	0
	7	-.583	+.333
	8	-.250	-.583
	9	0	-.250
	10	-.500	-.250
SD12	1	0	0
	2	-.250	-.083
	3	+.083	-.250
	4	-.250	-.167
	5	+.167	-.250
	6	+.417	-.250
	7	+.083	-.167
	8	+.333	-.083
	9	-.083	-.250
	10	-.250	-.250

5. Rates of Information Transmission (in bits/second)

	Session	Experimental	Control
SD1	1	.625	.877
	2	.709	1.170
	3	.725	1.201
	4	.460	1.151
	5	.494	1.248
	6	.431	1.243
	7	.454	1.423
	8	.515	1.419
	9	.649	1.365
	10	.865	1.140
SD1	1	1.499	1.630
	2	1.723	1.880
	3	1.568	2.017
	4	1.440	1.941
	5	1.397	2.077
	6	1.352	2.051
	7	1.307	2.244
	8	1.343	1.988
	9	1.398	1.918
	10	1.506	1.877
SD2	1	1.797	1.871
	2	1.741	2.129
	3	1.870	2.255
	4	1.794	2.239
	5	1.538	2.142
	6	1.496	2.184
	7	1.474	2.442
	8	1.548	1.994
	9	1.777	2.154
	10	1.818	2.036
SD12	1	2.255	2.378
	2	2.286	2.560
	3	2.442	2.440
	4	2.240	2.744
	5	2.222	2.651
	6	2.359	2.664
	7	2.196	2.649
	8	2.265	2.687
	9	2.198	2.585
	10	2.283	2.672

6. Rate-of-Information-Transmission Change Scores

	Session	Experimental	Control
SD1	1	0	0
	2	+.084	+.293
	3	+.101	+.325
	4	-.164	+.275
	5	-.131	+.372
	6	-.194	+.366
	7	-.171	+.546
	8	-.109	+.543
	9	+.025	+.488
	10	+.241	+.263
SD2	1	0	0
	2	+.224	+.250
	3	+.069	+.388
	4	-.059	+.311
	5	-.102	+.447
	6	-.147	+.421
	7	-.192	+.615
	8	-.155	+.359
	9	-.101	+.288
	10	+.007	+.248
SD3	1	0	0
	2	-.056	+.258
	3	+.073	+.384
	4	-.002	+.368
	5	-.259	+.271
	6	-.301	+.313
	7	-.323	+.571
	8	-.249	+.123
	9	-.019	+.283
	10	+.021	+.165
SD12	1	0	0
	2	+.031	+.182
	3	+.187	+.062
	4	-.015	+.366
	5	-.033	+.273
	6	+.104	+.286
	7	-.059	+.271
	8	+.010	+.309
	9	-.057	+.207
	10	+.028	+.294

APPENDIX C

COMPUTATION OF INFORMATION MEASURES

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COMPUTATION OF INFORMATION MEASURES

The primary information measure analyzed was rate of information transmission (Ht/RT). The rate of information transmission was computed from the 30 test trials given each subject in each session and at each level of discrimination difficulty. Rate of information transmission, expressed in bits per second, was computed by dividing the amount of information transmitted (Ht) by the median value of the reaction times obtained across the 30 test trials. The amount of information transmitted, expressed in bits, was computed according to the following procedures outlined by Garner and Hake (1951, pages 447-449).

A data matrix was constructed for each subject in each session and at each level of difficulty.

		Stimulus category (k) 1	2	
Response Category (j)	1	N_{jk}	N_{jk}	$N_{j\cdot}$
	2	N_{jk}	N_{jk}	$N_{j\cdot}$
		$N_{\cdot k}$	$N_{\cdot k}$	$\Sigma N_{\cdot k} = \Sigma N_{j\cdot} = N$

The cell entries, N_{jk}, indicated the number of joint occurrences of each stimulus category, k, with each response category, j. The row totals, $N_{j\cdot}$, represent the number of occurrences of each response category; the column totals, $N_{\cdot k}$, represent the number of occurrences of each stimulus category; the sum of the row (or column) totals, N, indicates the total number of trials. For the task employed in the present study, N was 30, since there were 30 trials, and the column totals, $N_{\cdot k}$, were 15, respectively, since each stimulus was presented on exactly half of the trials.

From the frequency matrix just described, a probability matrix was constructed, in which the following probabilities were represented.

$p(j) = \frac{N_{j\cdot}}{N}$: Probability of the occurrence of a given response category, j.

$p(k) = \frac{N_{\cdot k}}{N}$: Probability of the occurrence of a given stimulus category, k.

$p_k(j) = \frac{N_{jk}}{N_{\cdot k}}$: Conditional probability of the occurrence of a particular response category (j), given that a particular stimulus category (k) has occurred.

$$\begin{array}{cc|c|c|c} & & \multicolumn{2}{c}{k} & \\ & & 1 & 2 & \\ \hline j & 1 & p_k(j) & p_k(j) & p(j) \\ \cline{3-4} & 2 & p_k(j) & p_k(j) & p(j) \\ \hline & & p(k) & p(k) & \end{array}$$

The cell entries, $p_k(j)$, were derived from the previous frequency matrix by dividing the corresponding entry, N_{jk}, by the total of the column in which it occurred, $N_{\cdot k}$. The entries in the last column, p(j), were derived by dividing the corresponding row totals in the frequency matrix, $N_{j\cdot}$, by N. Similarly, the entries in the last row of the matrix, p(k), were derived by dividing the corresponding column totals, $N_{\cdot k}$, by N.

Two values, response information (I_r) and response equivocation (E_r), were computed directly from the probability matrix. Response information was defined as

$$I_r = - \sum_{j=1}^{2} p(j) \log_2 p(j).$$

Response equivocation was defined as

$$E_r = - \sum_{k=1}^{2} p(k) \sum_{j-1}^{2} p(j) \log_2 p_k(j).$$

The amount of information transmitted, Ht, was defined as the difference between response information and response equivocation. Thus,

$$Ht = I_r - E_r.$$