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DEEP DIVE 1998: NEUROPSYCHOLOGICAL FINDINGS

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Neuropsychological assessments were conducted during the 1998 1,000 feet of seawater (fsw) dive at the Navy Experimental Diving Unit. Both traditional pencil-and-paper tests and a computerized battery, the Automated Neuropsychological Assessment Metrics (ANAM), were used during the dive. The assessments were administered at the following depths in sequence: surface, 500 fsw, 1,000 fsw, 650 fsw, 200 fsw, and again on the surface. Sample day-related performance decrements were noted during compression and at storage depth in Trails A (traditional battery) and Matching-to-Sample (computerized battery). Attenuation of these performance decrements occurred with decompression.

Traditional batteries were designed to detect gross decrements to cognitive functioning associated with situations such as blunt forehead trauma. Traditional tests function very well in that scenario, but in the diving scenario, they appear to lack the precision to detect more subtle cognitive performance decrements. The answer is to automate the process thus factoring out the human component in data collection and recording. The more times a human has to handle the data, the greater the chance for error. Two distinctive advantages for using the computer platform and removing the human tester from the process are a more controlled testing environment and more precise measurements. In this study, some of the variables present when the traditional battery was administered were possible decrements with the tester, improperly functioning test equipment (the stopwatch), and the complications due to helium speech. All these variables were controlled with the ANAM. The ANAM also proved more beneficial than the traditional battery by automating the data collection, data analysis, and data storage processes, thus providing a near real-time picture of a diver's neurocognitive health.

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INTRODUCTION

Curley[1] summarized neuropsychological assessments for deep saturation dives at the Navy Experimental Diving Unit (NEDU) between 1982 and 1986. During the post-dive debriefs, some diver-subjects reported feeling "different" cognitively at depth and after the dive. Some of the reported effects included having problems remembering things and not feeling as sharp as before the dive. However, post-dive measurements have not supported the subjective reports. Curley concluded that the changes may have been so subtle that detecting them by existing pencil-and-paper methods was not possible.

The European Undersea Biomedical Society and The Norwegian Petroleum Directorate held a workshop entitled "Long Term Neurological Consequences of Deep Diving."[2] The data presented at this workshop suggest that any transient deficits in neuropsychological functioning might be present immediately post-dive and may resolve over a period of weeks. Follow-up assessments of diver-subjects have failed to demonstrate any long-term effects related to deep saturation diving. Again, the measurements may have not been sensitive enough to detect changes in neuropsychological and cognitive functioning.

The Automated Neuropsychological Assessment Metrics (ANAM)[3] is a computer-based assessment battery that may prove to be a valuable tool for screening divers' neuropsychological health. We are currently assessing this automated system in conjunction with various diving situations to determine its usefulness for measuring divers' neuropsychological functioning and cognitive well-being. We hope that the ANAM system will be a useful tool that is quicker to administer and more precise than traditional pencil-and-paper assessments. In the current study, we hoped that the ANAM system would provide the sensitivity of measurement necessary to give us a clear picture of how saturation exposure and depth affect cognitive functioning.

METHODS

GENERAL

One Atmosphere Testing

Approximately one week before each dive, all diver-subjects received a briefing on the entire assessment battery, including the ANAM. Then each subject took the battery, both traditional and ANAM, to determine baseline performance at one atmosphere absolute (atm abs). The assessment battery was administered in the "D" chamber of the Ocean Simulation Facility (OSF) to control for situational confounding. If necessary, additional sessions were scheduled for the ANAM to reestablish stable performance levels for each diver. The entire battery took approximately one hour to administer initially and about 45 minutes during subsequent trials.

At-depth Testing

All at-depth testing took place in the OSF "D" chamber. The traditional testing materials consisted of the test packet and a pencil. The ANAM testing materials consisted of a bunk, computer mouse and a television projector to project the tests onto a white screen in the chamber. For the traditional battery, Logical Memory I and II were administered from outside the chamber and the remainder of the battery was administered by a team member within the chamber. For the ANAM battery, the diver-subject sat on a bunk facing the screen and responded with a mouse as the stimuli were presented on the screen. Each session took approximately 40 minutes.

Two-way communication was conducted on an isolated system that was kept clear at all times during testing; extraneous noise was kept to a minimum.

SUBJECTS

The subjects were nine male U.S. Navy saturation divers.

EQUIPMENT/MATERIALS

The following were evaluated during Deep Dive 98:

1. Trail Making A and B.
2. Symbol Digit Modalities Test (SDMT).
3. Weschler's Memory Scale-Revised Logical Memory I & II (WMS-R LMI & LMII).
4. Automated Neuropsychological Assessment Metrics (ANAM).

PROCEDURE

Each of the following was administered before and after the dive. The battery was also administered on dive-day two during compression at 500 feet of seawater (fsw), on dive-day seven at the storage depth of 1,000 fsw, and on dive-days sixteen and twenty one during decompression at 650 fsw and at 200 fsw, respectively. An additional ANAM-only session was conducted on dive-day ten at 1,000 fsw. Each subject was tested at approximately the same time each day.

Trail Making is a measure of the subject's executive mental functioning. Specifically, this test measures attention, mental shifting, working memory, and to a point, tremors. It relies heavily on frontal lobe functioning. This test requires about five minutes to administer and is given individually. Trail Making forms A and B are given at each session, and scores are derived from the time it takes to complete the forms and the number of errors that are made. These two scores are factored together to yield a standard score on a 10-point scale.[4]

The SDMT is a pencil-and-paper test requiring the subject to match numbers randomly assigned to geometrical symbols. This test assesses sustained attention, visual-spatial motor coordination and response speed, and it requires about three minutes to administer. The SDMT provides a score that reflects successful number-to-symbol matches.[5]

The Logical Memory subscale of the Weschler Memory Scale is a memory examination administered in two parts, the WMS-R LMI and WMS-R LMII, with a delay between the two. The two tests measure immediate and delayed recall as well as verbal memory. Each test takes about two to three minutes to administer and yields both a raw and percentile score.[6]

The ANAM[7,3] is a computer-based standard clinical subset of the Office of Military Performance Assessment Technology's (OMPAT) Tester's Workbench (TWB). The ANAM is a set of TWB tests reconfigured for use in clinical neuropsychological evaluations. Many components of the ANAM were derived from the Unified Tri-service Committee Performance Assessment Battery (UTC-PAB)[8] and the Walter Reed Performance Assessment Battery.[9] The ANAM purports to measure precisely mental efficiency as well as accuracy.[3]

The tests that comprise the current assessment battery are taken from the ANAM battery. They were selected for assessing sustained concentration and attention, mental flexibility, spatial processing, cognitive processing efficiency, mood, arousal/fatigue level, and short-term, long-term, and working memory. The ANAM 2000 battery for this dive included the following subtests:

1. Simple Reaction Time - Measures basic psychomotor speed.
2. Code Substitution (Letter/Symbol Comparison) - Measures visual scanning and learning.
3. Code Substitution (Short and Long Delay) - Measures immediate and delayed recall.
4. Running Memory Continuous Performance Task (CPT) - Measures working memory and executive functions.
5. Mathematical Processing Task - Measures computational speed and working memory.
6. Matching-to-Sample - Measures delayed recall/longer-term memory.

Note: These subtests and the functions they are purported to measure are discussed in more detail in Reeves et. al.[3]

RESULTS

SigmaStat® (SPSS Science, 233 S. Wacker Drive, 11th floor, Chicago, IL 60606-6307) statistical software was used for all analyses. Appendix A shows the results from the Kolmogorov-Smirnov (K-S) test for normality and the Levene test for equality of variance. The following subtests or subtest measures failed the K-S test or the Levene test and were thus analyzed using a Friedman repeated measures (RM) analysis of variance (ANOVA) on ranks:

1) Logical Memory I and II,
2) Continuous performance task mean accuracy measure,
3) Mathematical processing mean reaction time and accuracy measures,
4) Code substitution mean reaction time and throughput measures, and
5) Code substitution short delay accuracy measure.

All other subtests and subtest measures were analyzed using one-way repeated measures ANOVA to determine whether a difference in scores occurred among all test conditions, and a Tukey test was used for pair-wise comparisons if a significant F score resulted.

TRADITIONAL TESTS RESULTS

Appendix D shows the charts for each subtest. Each chart illustrates the scores from each subject and the mean scores at each depth. Appendix B lists the Tukey test results.

Logical Memory I and II each show differences among measurement sessions (LM I: $X^2(5) = 23.567$; $p < .001$; LM II: $X^2(5) = 27.376$; $p < .001$). Scores improved from baseline to later tests.

The SDMT and Trails A and B all showed significant differences among sessions (SDMT: $F(5,40) = 10.913$; $p < .001$; Trails A: $F(5,40) = 15.406$; $p < .001$; Trails B: $F(5,40) = 15.430$; $p < .001$). The number of correct responses in SMDT was greater on day twenty and postdive than at baseline. Trails A took longer on day seven at 1000 fsw than at any other session while Trails B took less time than at baseline on days sixteen, twenty, and postdive.

ANAM RESULTS

Appendix E shows the charts for each subtest. Each chart illustrates the scores from each subject and the mean scores at each depth. Post hoc tests are presented in Appendix C when appropriate.

Continuous Performance Task (CPT)

Mean reaction time (MRT) and the throughput measures differed among testing sessions (MRT: $F(6,48) = 6.846$; $p < .001$; Throughput: $F(6,48) = 10.985$; $p < .001$). MRT was lower and throughput was higher than baseline on day twenty and postdive. Accuracy did not change.

Matching-to-Sample (MSP)

All three measures for MSP differed among testing sessions (MRT: $F(6,48) = 4.325$; $p = .001$; Accuracy: $F(6,48) = 2.977$; $p = .015$; Throughput: $F(6,48) = 6.947$; $p < .001$). MRT was not different from baseline on any day. Accuracy was lower than baseline on day seven, while throughput was lower than baseline on days two and seven.

Mathematical Processing (MATH)

MRT and throughput measures changed with measurement session (MRT: $X^2(6) = 22.190$; $p = .001$; Throughput: $F(6,48) = 6.619$; $p < .001$). The trend as the dive progressed was for MRT to decrease and for throughput to increase with no change in accuracy.

Simple Reaction Time (SMRT)

Both measures of the SMRT showed significant differences among measurements (MRT: $F(6,48) = 4.284$; $p = .002$; Throughput: $F(6,48) = 4.380$; $p = .002$). MRT was not different from baseline at any session but throughput was greater than baseline on days sixteen, twenty, and postdive.

Code Substitution (CDSB)

MRT and throughput measures differed significantly among measurement sessions down and throughput trended up on days sixteen, twenty, and postdive.

Code Substitution Short Delay (CDMI)

MRT showed significant differences across measurement days (MRT: $F(6,48) = 3.742$; $p = .004$). MRT was shorter than baseline on day twenty and postdive.

Code Substitution Long Delay (CDMD)

MRT for long-delayed recall was significantly different across dive days (MRT: $F(6,48) = 2.369$; $p = .044$). However, post-hoc comparisons fail to detect any significant pair-wise difference.

DISCUSSION/CONCLUSIONS

The purpose of the study was to determine the applicability of the ANAM as a cognitive assessment tool for diving medicine. To that end, performance from traditional methods and ANAM performance were assessed.

All scores from the traditional pencil-and-paper test battery showed statistically significant differences among measurement days. WMS-R Logical Memory I and II, Symbol Digit Modality Test, and Trails B showed significant improvements in scores indicating the possible presence of a practice effect. Repeated testing with the same forms could have masked some real depth-related decrements. Trails A yielded a significant performance decrement in functioning at the 1,000 fsw level, indicating possible effects to visual scanning and sequential memory. Because Trails A and Trails B usually are highly correlated,[4] the significant findings seen in Trails A should be interpreted cautiously.

Performance results from all of the ANAM subtests with the exception of Matching-to-Sample demonstrated significant performance improvements across successive test sessions, again suggesting a practice effect. The Matching-to-Sample Subtest demonstrated significant ($p < .05$) performance decrements for throughput on dive day two at 500 fsw, and for accuracy and throughput on dive day seven at 1,000 fsw, followed by a return to baseline with decompression. Matching-to-Sample has been previously shown[10] to be the most sensitive in detecting cognitive changes associated with diving. This relatively simple test taps many cognitive abilities such as pattern recognition, visual scanning, vigilance, working/short-term memory, attention and decision-making. Each of these abilities is vital in maintaining a safe and effective working environment.

Administration of the traditional battery can be problematic in a diving environment. Speech is difficult to understand in the helium atmosphere used for deep dives. This problem in voice communication may have confounded the results of the Logical Memory I and II tests, the only tests that were administered by a person exterior to the chamber. While the helium speech descramblers are helpful, comprehension during the initial reading of the story and during the subsequent recital back to the administrator could have been hampered. Further, the assessor for the Trails tests was a fellow team member, inside the chamber. If this diver-assessor was cognitively impaired by the dive, he may have misrecorded scores or timed tests incorrectly. With the ANAM platform, the facilitator and the timing mechanism are outside the chamber, not subjected to or affected by the high pressure environment. Using the ANAM platform increases the precision of measurement by controlling for the environmental factor.

The ANAM provides another distinct advantage over using traditional batteries. It provides a near real-time picture of a diver's neurocognitive functioning. Traditional pencil-and-paper tests require a wait of some time while data is collected, sent to the surface via a medical lockout chamber, scored, analyzed, and interpreted. During this time, a problem may have been resolved or become more detrimental. The ANAM system collects and analyzes the data continuously, and summarizes each subtest, and allows problems to be addressed immediately. Future versions of the system will include a report generator that will provide alarms or flags indicating performance decrements, and will thus ease interpretation.

Traditional batteries were designed to detect gross decrements to cognitive functioning associated with situations such as blunt head trauma. In that scenario, traditional tests do very well. Yet, they lack the precision to detect subtle decrements in cognitive performance. Only by automating the process and eliminating the human component in collecting and recording data can precision be increased. The more times a human handles the data, the greater the chance for error.

The ANAM system did prove beneficial in collecting cognitive performance data. Subtle decrements were detected by the Matching-to-Sample subtest suggesting depth-related impairment. The performance decrements noted with the Matching-to-Sample subtest reveal that depth and the saturation environment may have affected cognition. While these results may have been mirrored by the Trails A in the traditional battery, the results from Trails A could have been a one-time anomaly based on other factors associated with the assessment. The ANAM proved to be useful in this environment, not only for assessing the effects of diving on cognitive performance, but also for the capability to perform real-time assessments. It might be useful to monitor recovery from cognitive impairment caused by diving insults. More research with ANAM is warranted with deep saturation exposures.

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APPENDIX A

RESULTS FROM TEST FOR NORMALITY AND EQUAL VARIANCE

P Values

Subtest	Normality	Equal Variance
Logical Memory I	**<.001**	0.259
Logical Memory II	**<.001**	0.182
SDMT	0.182	0.717
Trails A	0.246	0.416
Trails B	0.258	0.876
Continuous Perf.		
MRT	0.073	0.751
ACC	**0.022**	0.386
THROUGHPUT	0.285	0.956
Matching-to-Sample		
MRT	0.145	0.977
ACC	0.356	0.47
THROUGHPUT	0.142	0.48
Math		
MRT	**0.005**	0.763
ACC	**<.001**	0.763
THROUGHPUT	0.29	0.694
SMRT		
MRT	0.27	0.982
ACC	NA	NA
THROUGHPUT	0.299	0.939
Code Sub		
MRT	**0.025**	**0.027**
ACC	0.078	0.685
THROUGHPUT	0.141	**0.001**
Code Sub Short Delay		
MRT	0.321	0.715
ACC	**0.01**	0.507
THROUGHPUT	0.692	0.82
Code Sub Long Delay		
MRT	0.205	0.827
ACC	0.052	0.424
THROUGHPUT	0.576	0.823

APPENDIX B

POST-HOC RESULTS TRADITIONAL TESTS

SDMT

p <.05 Tukey

	500 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	yes	yes
Day 2 = 500 fsw		no	no	yes	yes
Day 7 = 1,000 fsw			no	no	yes
Day 16 = 650 fsw				no	yes
Day 20 = 200 fsw					no
Postdive					

Note: "no" = p >.05; "yes" = p <.05

Trails A

p <.05 Tukey

	500 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	yes	no	no	no
Day 2 = 500 fsw		yes	no	no	no
Day 7 = 1,000 fsw			yes	yes	yes
Day 16 = 650 fsw				no	no
Day 20 = 200 fsw					no
Postdive					

Note: "no" = p >.05; "yes" = p <.05

Trails B

p <.05 Tukey

	500 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	yes	yes
Day 2 = 500 fsw		no	yes	yes	yes
Day 7 = 1,000 fsw			yes	yes	yes
Day 16 = 650 fsw				no	no
Day 20 = 200 fsw					no
Postdive					

Note: "no" = p >.05; "yes" = p <.05

APPENDIX C

POST-HOC RESULTS ANAM TESTS

Continuous Performance Task Mean Reaction Time

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	no	yes	yes
Day 2 at 500 fsw		no	no	no	yes	yes
Day 7 at 1,000 fsw			no	no	yes	yes
Day 10 at 1,000 fsw				no	no	no
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

Continuous Performance Task Throughput

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	no	yes	yes
Day 2 at 500 fsw		no	no	no	yes	yes
Day 7 at 1,000 fsw			no	no	yes	yes
Day 10 at 1,000 fsw				no	no	yes
Day 16 at 650 fsw					no	yes
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

POST-HOC RESULTS ANAM TESTS
(CONTINUED)

Matching to Sample Mean Reaction Time

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	no	no	no
Day 2 at 500 fsw		no	no	no	no	no
Day 7 at 1,000 fsw			no	yes	no	yes
Day 10 at 1,000 fsw				no	no	yes
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

Matching to Sample Accuracy

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	yes	no	no	no	no
Day 2 at 500 fsw		no	no	no	no	no
Day 7 at 1,000 fsw			no	no	no	no
Day 10 at 1,000 fsw				no	no	no
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

Matching to Sample Throughput

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	yes	yes	no	no	no	no
Day 2 at 500 fsw		no	no	no	no	yes
Day 7 at 1,000 fsw			no	no	no	yes
Day 10 at 1,000 fsw				no	yes	yes
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

POST-HOC RESULTS ANAM TESTS (CONTINUED)

Mathematical Processing Throughput

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	yes	yes	yes
Day 2 at 500 fsw		no	no	no	no	yes
Day 7 at 1,000 fsw			no	no	no	yes
Day 10 at 1,000 fsw				no	no	yes
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

Simple Reaction Time Mean Reaction Time

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	no	no	no
Day 2 at 500 fsw		no	no	no	yes	yes
Day 7 at 1,000 fsw			no	no	yes	yes
Day 10 at 1,000 fsw				no	no	no
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

Simple Reaction Time Throughput

p <.05 Tukey

	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	yes	yes	yes
Day 2 at 500 fsw		no	no	no	no	yes
Day 7 at 1,000 fsw			no	no	no	yes
Day 10 at 1,000 fsw				no	no	yes
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

POST-HOC RESULTS ANAM TESTS (CONTINUED)

Code Substitution Short Delay Mean Reaction Time

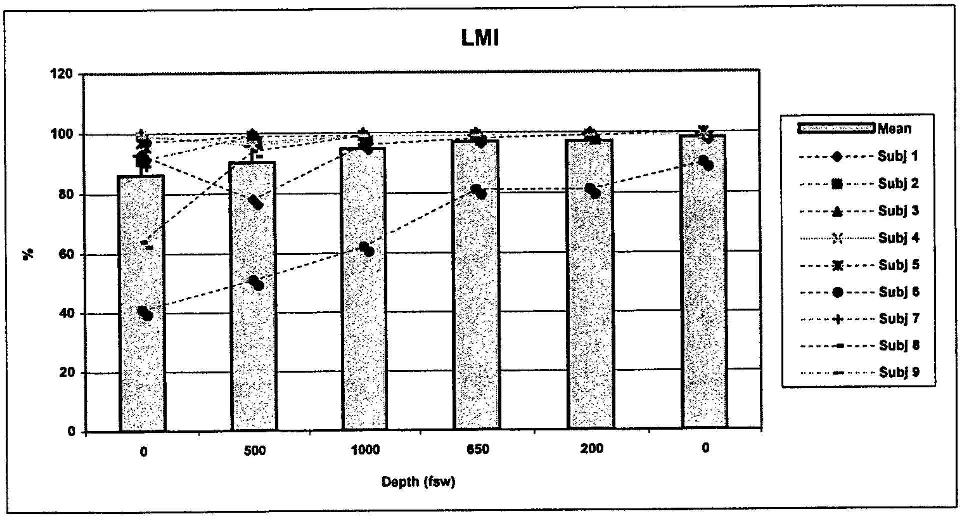
p <.05 Tukey

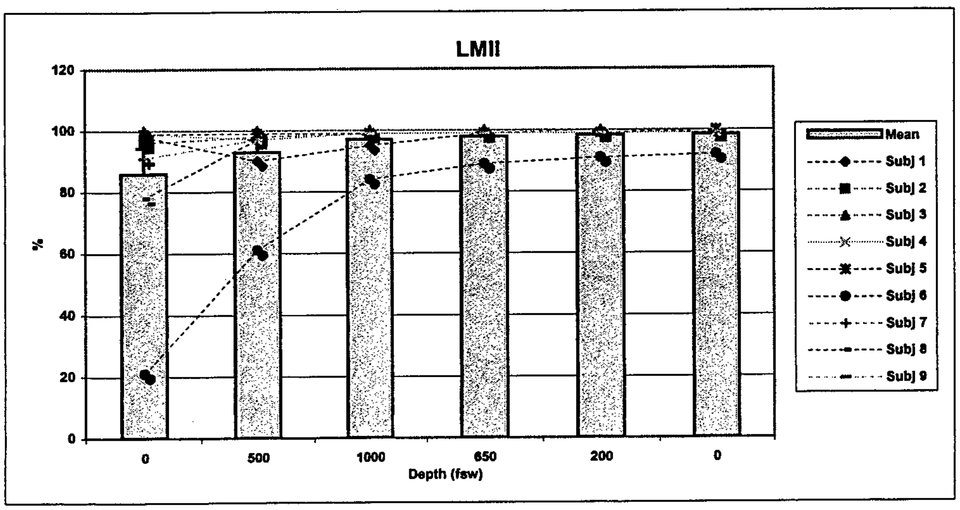
	500 fsw	1,000 fsw	1,000 fsw	650 fsw	200 fsw	postdive
Baseline	no	no	no	no	yes	yes
Day 2 at 500 fsw		no	no	no	no	no
Day 7 at 1,000 fsw			no	no	no	no
Day 10 at 1,000 fsw				no	no	no
Day 16 at 650 fsw					no	no
Day 20 at 200 fsw						no
Postdive						

Note: "no" = p >.05; "yes" = p <.05

APPENDIX D

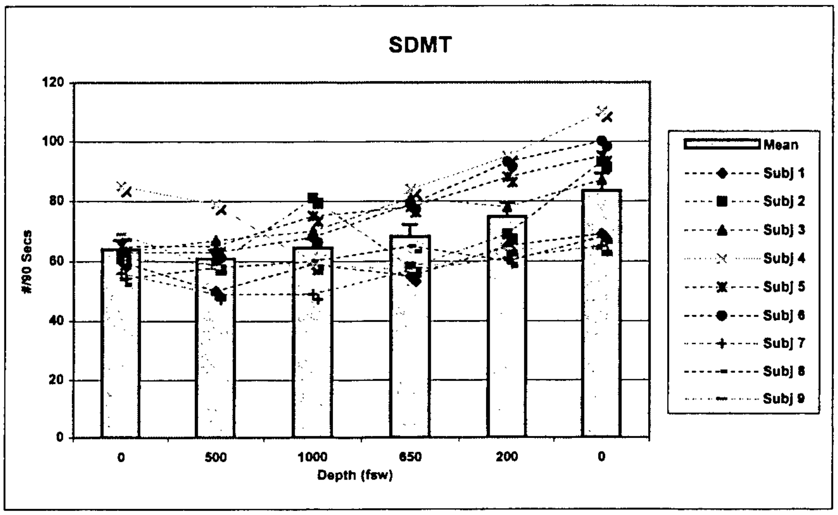
INDIVIDUAL AND MEAN SCORES FOR TRADITIONAL ASSESSMENTS





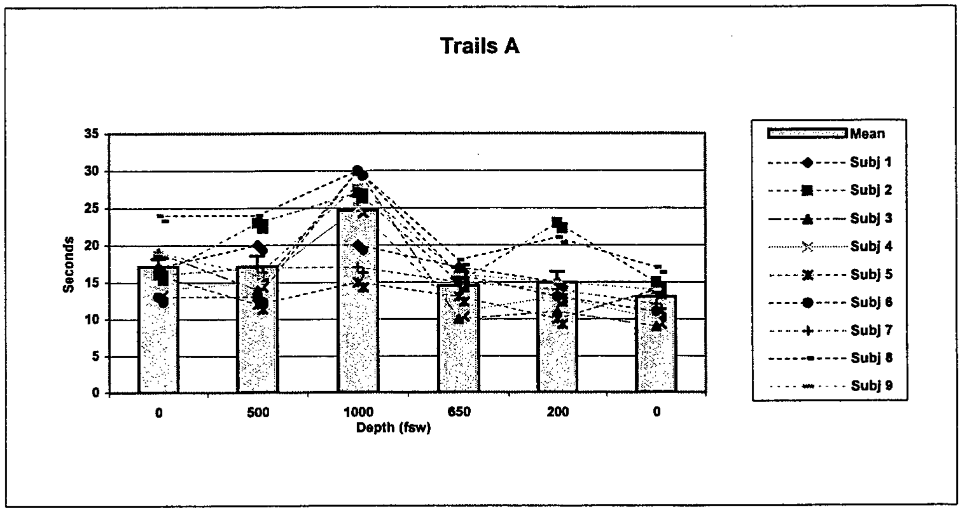
LMI - Logical Memory I
LMII - Logical Memory II
% - Percentile Score
fsw - feet of seawater

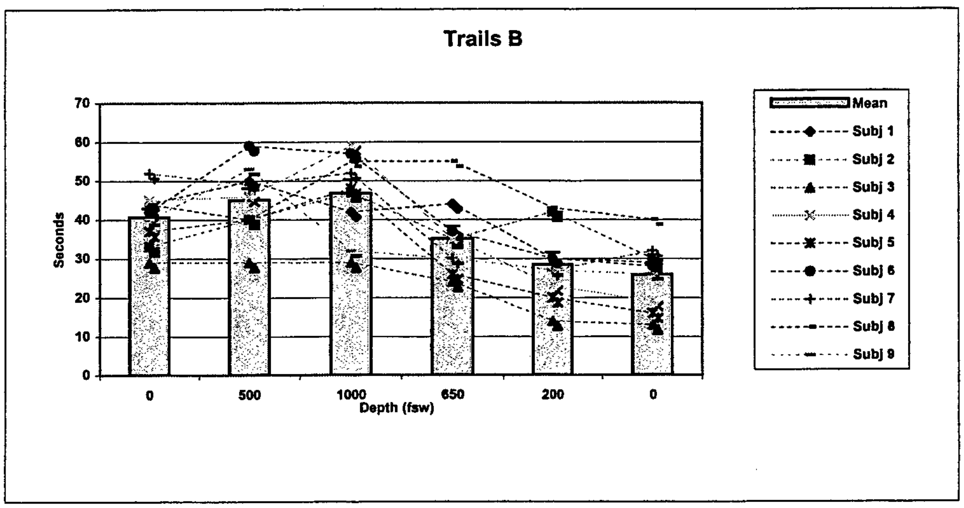
INDIVIDUAL AND MEAN SCORES FOR TRADITIONAL ASSESSMENTS (CONTINUED)



SDMT - Symbol Digit Modalities Test
#/90 Secs - Number of correct responses in alloted 90 seconds
fsw - feet of seawater

INDIVIDUAL AND MEAN SCORES FOR TRADITIONAL ASSESSMENTS (CONTINUED)

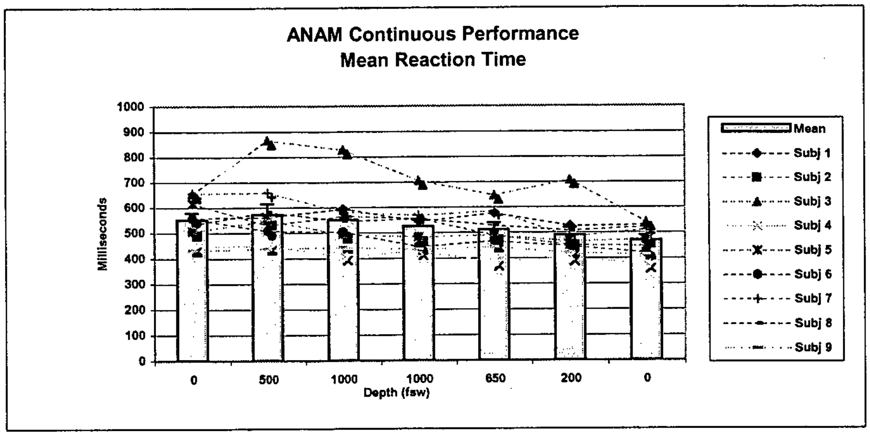


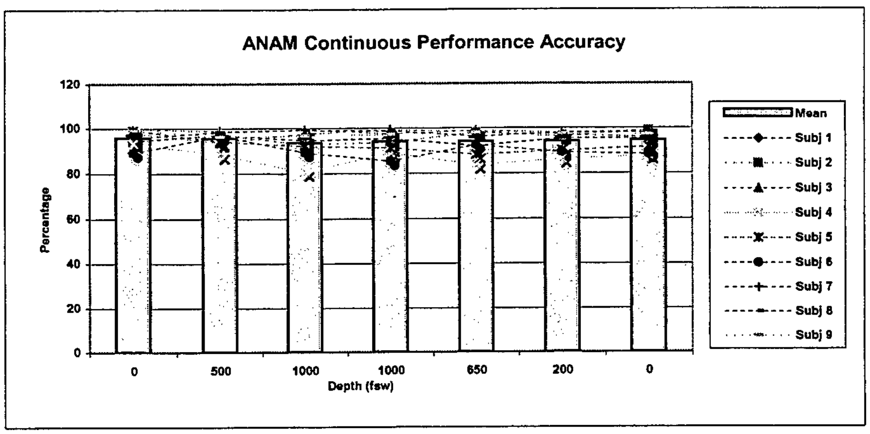


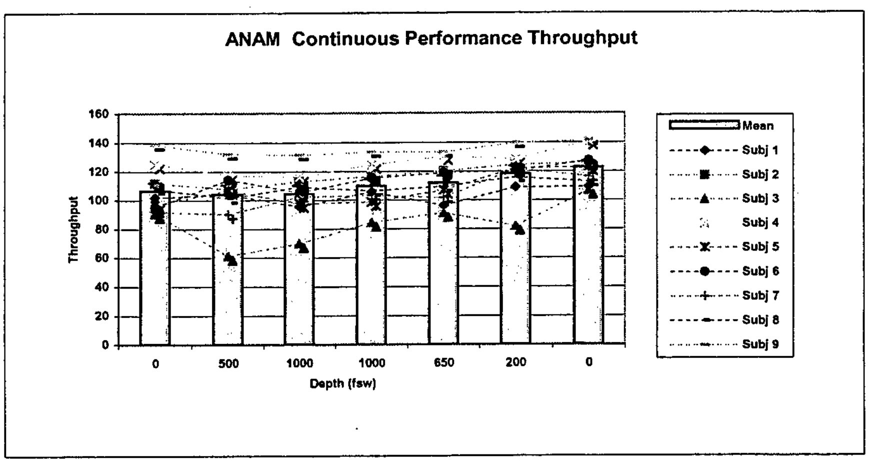
Trails A - Simple form of this task
Trails B - Complex form of this task
fsw - feet of seawater

APPENDIX E

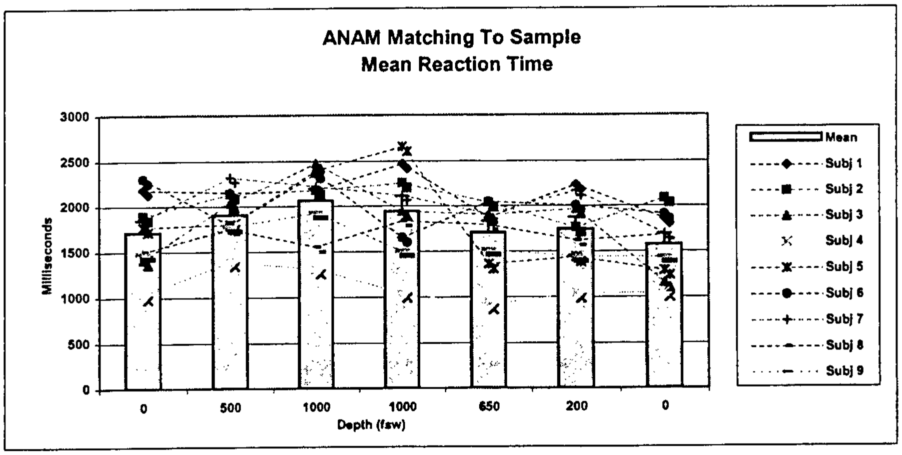
INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS

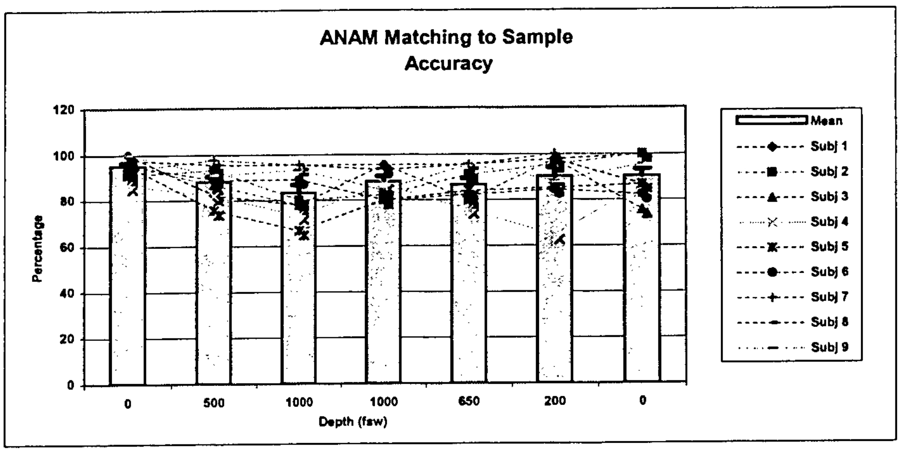


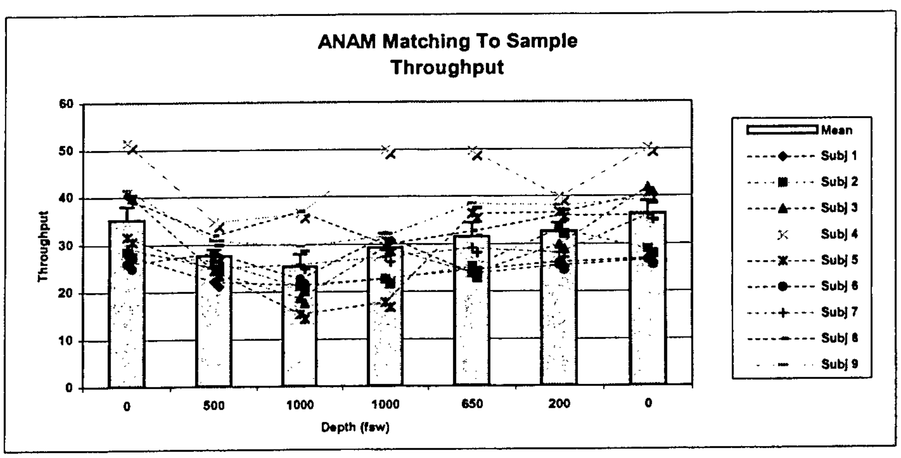




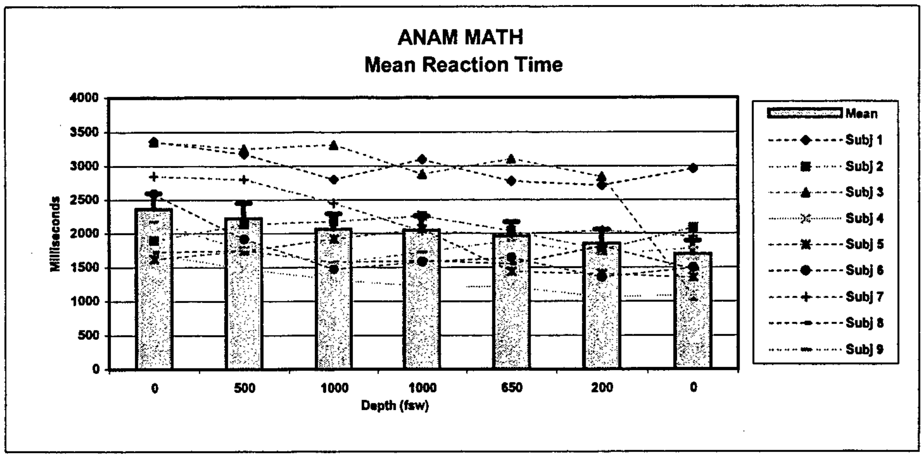
INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS (CONTINUED)

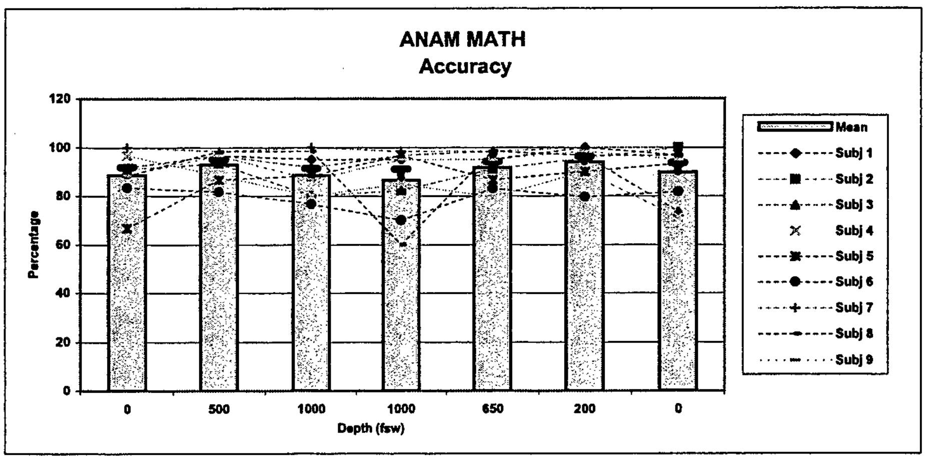


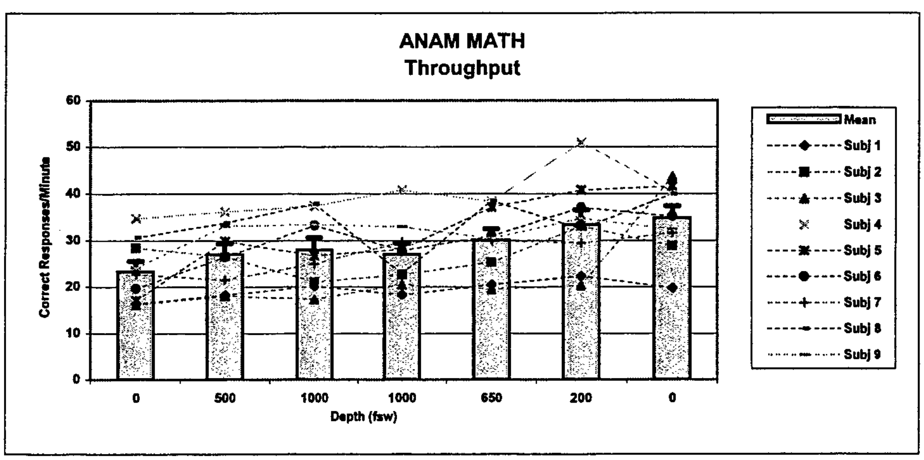




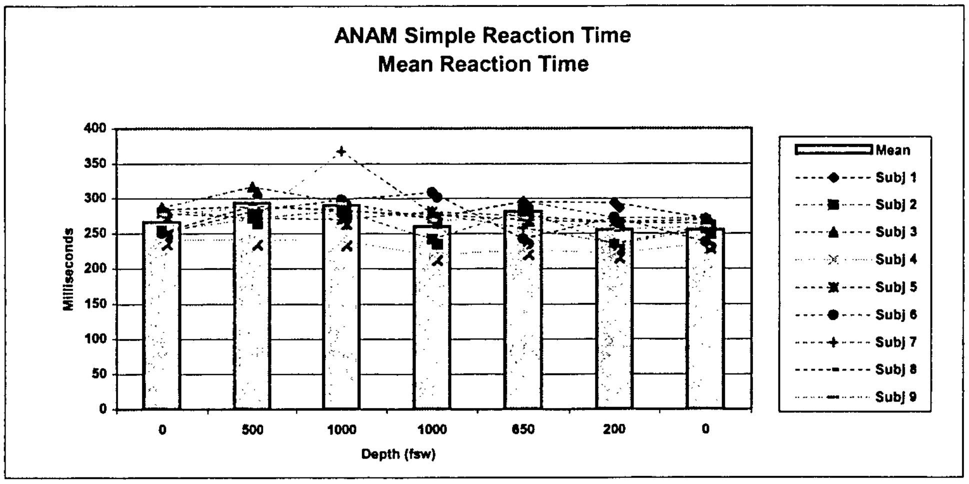
INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS (CONTINUED)





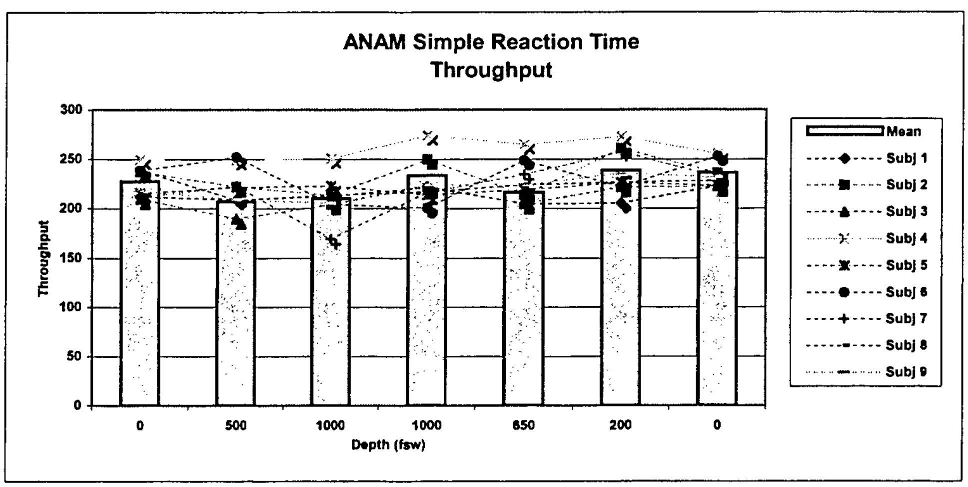


INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS (CONTINUED)

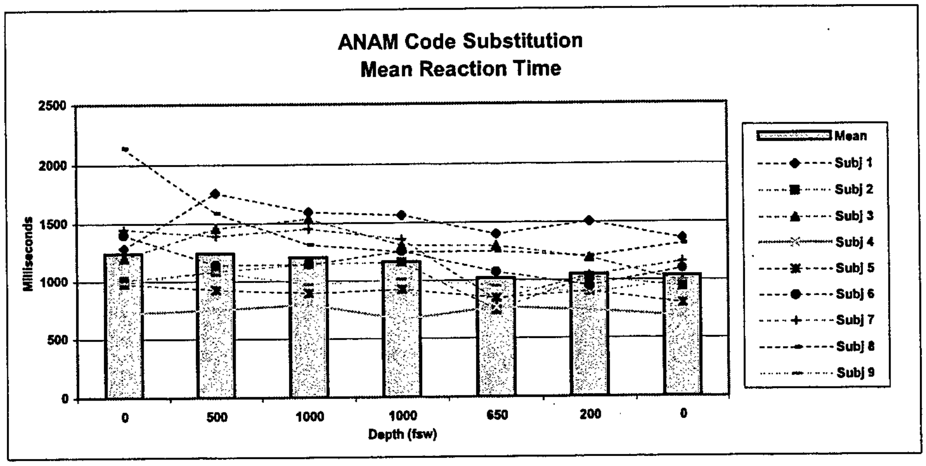


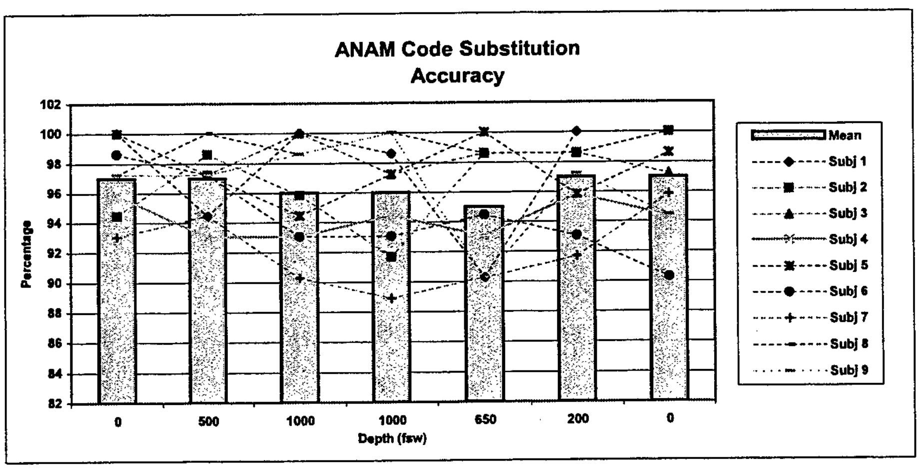
ANAM Simple Reaction Time
Accuracy

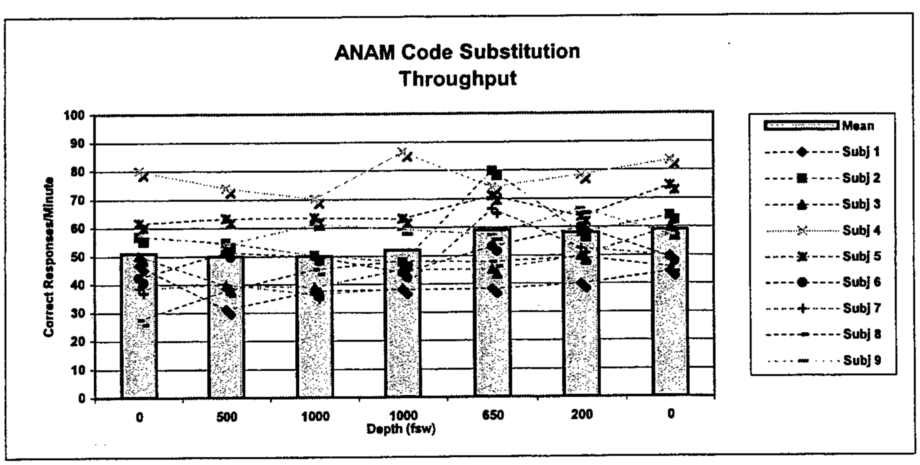
Accuracy rate is always 100 % because the subject responds to the presence of a stimulus. There is no right or wrong answer.



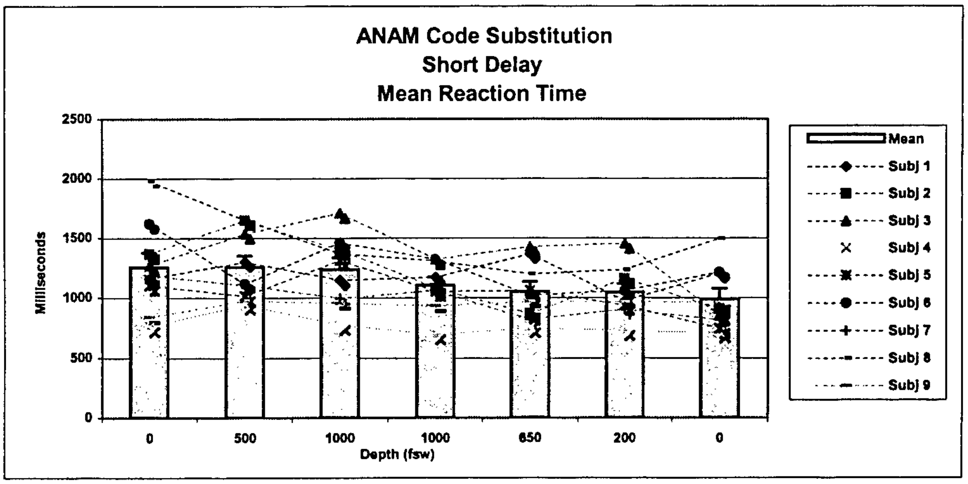
INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS (CONTINUED)

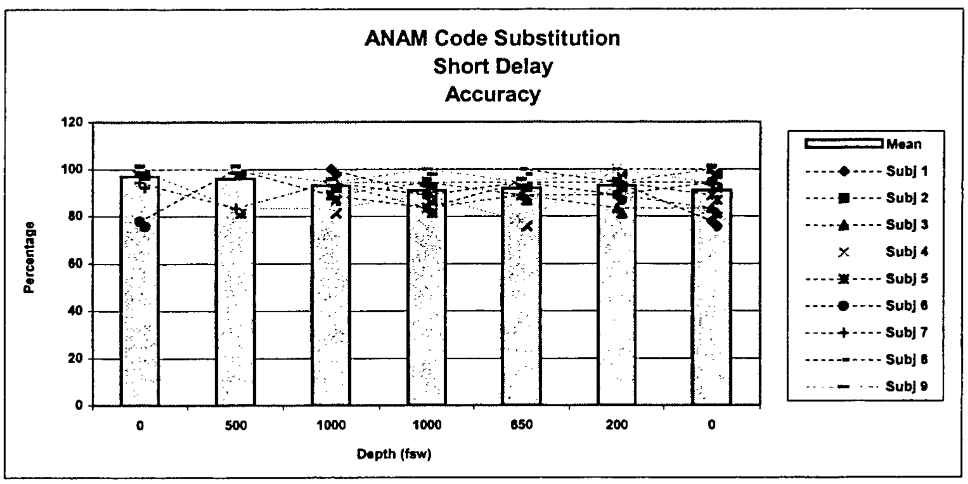


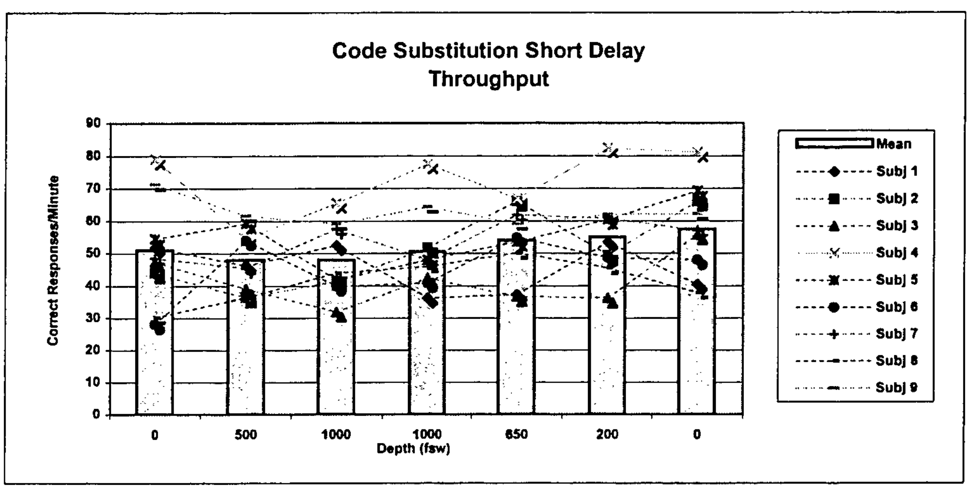




INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS (CONTINUED)







INDIVIDUAL AND MEAN SCORES FOR ANAM SUBTESTS (CONTINUED)