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A Hands-Free, Visual Search Task Featuring Scalable Cognitive Challenge Based Upon The U.S. Army Trail Making Test

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14. ABSTRACT The U.S. Aeromedical Research Laboratory has developed a hands-free task (USAARL-TMT) designed to induce discrete and measurable levels of cognitive workload. Eye position, gaze location, and pupil dynamics are potential measures to meet this recognized need to measure defined levels of cognitive workload. Inspired by the Trail Making Test, first introduced in the U.S. Army Individual Test Battery in 1944, the USAARL-TMT combined with eye tracking features scalable difficulty, rapid delivery, and the functional flexibility potentially useful in a variety of operational and simulation platforms. Increasing task difficulty involved increasing the incidence of only two mechanisms of task manipulation. Increasing the frequency of changes in the categorical cue and introducing an interrupt cue significantly increased trial completion time and pupil size. These findings confirm both that the USAARL-TMT is able to manipulate cognitive workload, and that it is able to generate the expected physiological responses to the changes in cognitive effort required to successfully navigate the task at each level of difficulty. This instrument may prove a critical tool in the evaluation and validation of future algorithms and metrics designed to measure the cognitive workload of service members in the operational environment.					
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Summary

Introduction

The United States Army Aeromedical Laboratory (USAARL) Warfighter Protection Group (WPG) is developing methods to measure cognitive workload in the aviation operational environment. Evaluating and validating the algorithms needed to measure cognitive workload requires the development of valid, effective, and efficient test-metrics that are compatible with a spectrum of operational and laboratory conditions. Critical to this effort is the development of a task that supports the precise manipulation of the cognitive workload demands. To achieve this goal, USAARL has developed a modified version of the Trail Making Test (USAARL-TMT) that is fast, hands-free, compatible with current eye tracking technologies, and can induce scalable levels of cognitive workload on a wide variety of platforms.

Methods

Visual stimuli are presented on a screen integrated with state-of-the art eye tracking to allow gaze-based user input instead of a manual response in USAARL's Universal Mission Simulator (UMS) that is capable of controlling Shadow and Grey Eagle unmanned aerial vehicles. Volunteers visually locate and fixate target digits as quickly as possible. We present two sets of digits to the subject, each set with a clearly distinguishable stimulus characteristic. The correct target number having the characteristic matching the cue located at the bottom of the screen. An interrupt cue present at the top of the screen indicates when the subject is to break sequence and fixate on an interrupt target located amongst the digits. Presentation frequency of the characteristic cues and interrupt cues occurring within the digit counting sequence sets the cognitive workload demands. Eye position and pupil area were recorded continuously for oculometric analyses.

Results

Introducing the categorical cue changes alone, and then combined with the interrupt cue measurably modulated the USAARL-TMT difficulty. Increasing task difficulty using these interventions significantly increases trial completion time and pupil size. These findings confirm that the USAARL-TMT is compatible with the UMS environment, that the USAARL-TMT is able to manipulate cognitive workload, and that it is able to generate the expected physiological responses to changes in cognitive effort.

Discussion

This task generated controlled levels of cognitive workload without manual or verbal responses from the participant. Further, it provides oculometric data in conditions more akin to a naturalistic viewing environment, where the point of gaze seldom remains fixed to a single point in space. The rapid delivery, reconfigurable nature, and deployment versatility of this task support its continued use in the evaluation and validation of algorithms and metrics designed to assess the physiological indicators of cognitive workload in the operational environment.

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- Ellis Akins and Juan Colon-Cruz for their assistance in the instrumentation and implementation of the task in the UMS Simulator at USAARL.
- Kevin Baugher, Bobby Bowers, Amanda Hayes, and Lana Milam collected all of the data presented within.
- Heath Jones, Jay Murphy, Kevin O'Brian, and Joseph Bleiberg contributed to the development of the task itself.
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Introduction

The U.S. Army Aeromedical Research Laboratory's (USAARL) Warfighter Performance Group (WPG) recognizes the need for technologies to measure cognitive workload in specific operational and near operational environments. In light of this need, WPG staff is developing cognitive workload tasks that allow direct manipulation of cognitive effort required to complete the workload tasks.

In 1944, the U.S. Army created The Army Individual Test Battery to assess individual suitability for military service (U.S. Army, 1944). One component of this test battery, the Trail Making Test (TMT), was adapted from Partington's Pathway Test as a measure of visual scanning, complex attention, psychomotor speed, and mental flexibility (No authorship, 2010; Partington & Leiter, 1949). The TMT is used widely in clinical settings for the diagnosis of neurological damage and disorders. Electronic versions of the TMT have been developed using touch-screen technologies to optimize delivery and configurability e.g., (Bracken, Mazur-Mosiewicz, & Glazek, 2019; Fellows, Dahmen, Cook, & Schmitter-Edgecombe, 2017). Furthermore, researchers at Oxford University (Hicks et al., 2013) developed a clinical gaze-position-driven version of the TMT for use in patient populations with significant movement deficits.

Motivated in part by these successes, USAARL's WPG is elaborating the TMT functionality to provide an assessment tool with the potential of improving the granularity or precision of the cognitive effort required to perform the TMT. The USAARL enhanced TMT (USAARL-TMT) currently incorporates two modifications of the traditional TMT. First, the USAARL-TMT has integrated eye-tracking capabilities to expand the objectivity and flexibility of TMT metrics by including saccadic eye movement and gaze position tracking, pupillometry, and eyelid behavior. Second, the TMT display characteristics are computer controlled so they can be made dependent in real-time on the measured eye movement behaviors. This capability enables the TMT performance requirements to be dependent on closed-loop objective measures. These stimulus dependencies on oculometric performance enable the TMT cognitive workload performance requirements to be measured precisely, which in turn, enables the quantification of workload demands based on objective, observable, measurable performance. Here we report the first proof-of-concept demonstration of this emerging technology.

The goals of the USAARL-TMT include the development of objective measures of mental workload derived from oculometrics recorded during the viewing of visual stimuli. Success with this approach will provide a basis for assessing cognitive workload in operational environments. Developing these capabilities will serve as a critical stride toward providing commanders and decision-makers with information regarding the cognitive workload induced by range of conditions, such as boredom, emergency conditions, changes to system designs, etc.

Methods

Participants

The U.S. Army Medical Research and Development Command (HQ USAMRDC) Institutional Review Board reviewed and approved this project under protocol M-10797; and the USAARL Scientific Review Committee reviewed and approved this project under protocol 2018-012.

Ten healthy subjects participated in this research. The volunteers were 7 were men and 3 were women (between the ages of 24 and 56). These volunteers received no financial reimbursement or other compensation for their participation.

Materials

This task utilizes real-time communication with an infrared, video-based, eye-tracking system to provide low latency (< 10 ms) eye-position and pupil-area information (EyeLink[®] 1000+, SR-Research, Ottawa, Canada). The software, developed in MATLAB (MathWorks, Inc.) and Psychtoolbox (Brainard, D. H., 1997) simultaneously measured the subject's point-of-gaze with respect to the targets present on the screen. The faster a subject accurately fixated on the correct target, the faster the task advanced; conversely, the slower a subject fixated on the correct target, the slower the task. This dependency provided metrics of speed and accuracy specific to each subject based on individual performance. This dependency also enabled complete hands-free operation without the need for auditory cues, vocal responses, or gross motor movements of the hands or feet. Further, the eye tracker simultaneously recorded the behavior of the pupil, which is a known indicator of cognitive workload (e.g., Kahneman, D., & Beatty, J., 1966). These data were collected from volunteers seated in USAARL's Universal Mission Simulator (UMS), that is identical to the control stations used for the operation of both Shadow and Grey Eagle unmanned aerial vehicles.

Eye Tracking Calibration

Each subject performed a 9-point gaze-position calibration prior to data collection. If any point registered a mapping accuracy less than 2° , the calibration was repeated. The average (\pm standard deviation) mapping accuracy for all points and all subjects was $1.2^\circ (\pm 0.6^\circ)$. The eye tracker hardware and software collected binocular gaze position and pupil diameter at 1 kHz throughout the experiment. Since all components of the visual display, described below, were luminance matched, none of the various task indications and transitions elicited a pupillary light reflex; thus, the luminance contribution to the size of the pupil remained constant over all conditions.

Visual Display

A 20° horizontal by 15° vertical computer screen at a distance of 57 cm presented the USAARL-TMT visual display. All stimulus elements (Figure 1) were presented simultaneously, and they remained on the screen for the duration of the trial.

One stimulus element was two sets of digits, each set containing the digit sequence from 1 through 5 in black font and of equal size. A blue 1° by 1° square enclosed each digit of one set, while a yellow 1° by 1° square enclosed each digit of the other set. Thus, the two sets of 5 digits

were distinguished by the color of the square surrounding each digit of the set. These 10 single digits were pseudo-randomly distributed over the screen.

The second stimulus element was the Characteristic Cue (CC) that was a 6° horizontal by 2° vertical rectangle centered at the bottom of the screen. The CC was a solid color, either blue or yellow; in this way, the color of the CC identified the target digit set, either blue or yellow.

The third stimulus element was the Interrupt Cue (IC), a gray X enclosed by a 3° horizontal by 4° vertical rectangle centered at the top of the screen. The color of the IC rectangle could be either gray or green. The stimulus screen contained two additional Xs, each enclosed by a 1° by 1° square, one square yellow and the other blue. Thus, the visual display included a pair of Xs among the 10 digits, one X inside a 1° by 1° yellow square and the other X inside a 1° by 1° blue square. Figure 1 displays all these stimulus elements.

Procedure

The subject's task was to fixate the digits in ascending order from 1 through 5 of the target series. The color of the 6° by 2° CC at the bottom of the screen defined the target digit series. When the CC was blue, the target digits were those in blue squares; when the CC was yellow, the target digits were those in yellow squares. The criteria for fixation accuracy was defined as within 2° of the digit for 250 ms.

When the subject adequately fixated the correct target digit, the color of its surrounding square, either blue or yellow, briefly changed to green to signal response accuracy. The square remained green until the next digit in the sequence was fixated. Note that the CC color could change at this time as well.

If the subject failed to fixate adequately on the correct digit within a 3-second search window, the square surrounding the correct digit changed color to red, accompanied by a 2-second time-out period. Following the 2-second time out, the tracking of the subject's eye position resumed allowing them to register fixation on the next number in the sequence.

In this fashion, the frequency of CC blue / yellow color change determined task difficulty. For the easiest condition, the CC was set at the beginning of the trial and did not change over the course of the counting sequence. For the moderately difficult condition, the CC changed between digits in the counting sequence, forcing the subject to switch between blue / yellow digit sets within the counting sequence. The color change could occur as frequently as after every digit, or as infrequently as only once during the trial. Regardless of CC color change frequency, the subject had to monitor the CC color throughout the trial to ensure fast accurate fixations.

The most difficult condition was set with the IC at the top of the display. When the color of the IC rectangle changed from gray to green, the correct target was not a digit but the X in a square of the color of the CC. The IC occurs only once, randomly during a trial. Once the IC was encountered and either successfully or unsuccessfully fixated, the digit counting sequence resumed, requiring the subject to continue, picking up from the digit prior to the IC. Thus, the most difficult condition required the subject to continually monitor both the CC (bottom of the screen) and the IC (top of the screen), modifying as necessary the response strategies as indicated at several points throughout the trial. Since subjects were encouraged to complete the trial as quickly as possible, temporal pressure contributed to the challenge of the task.

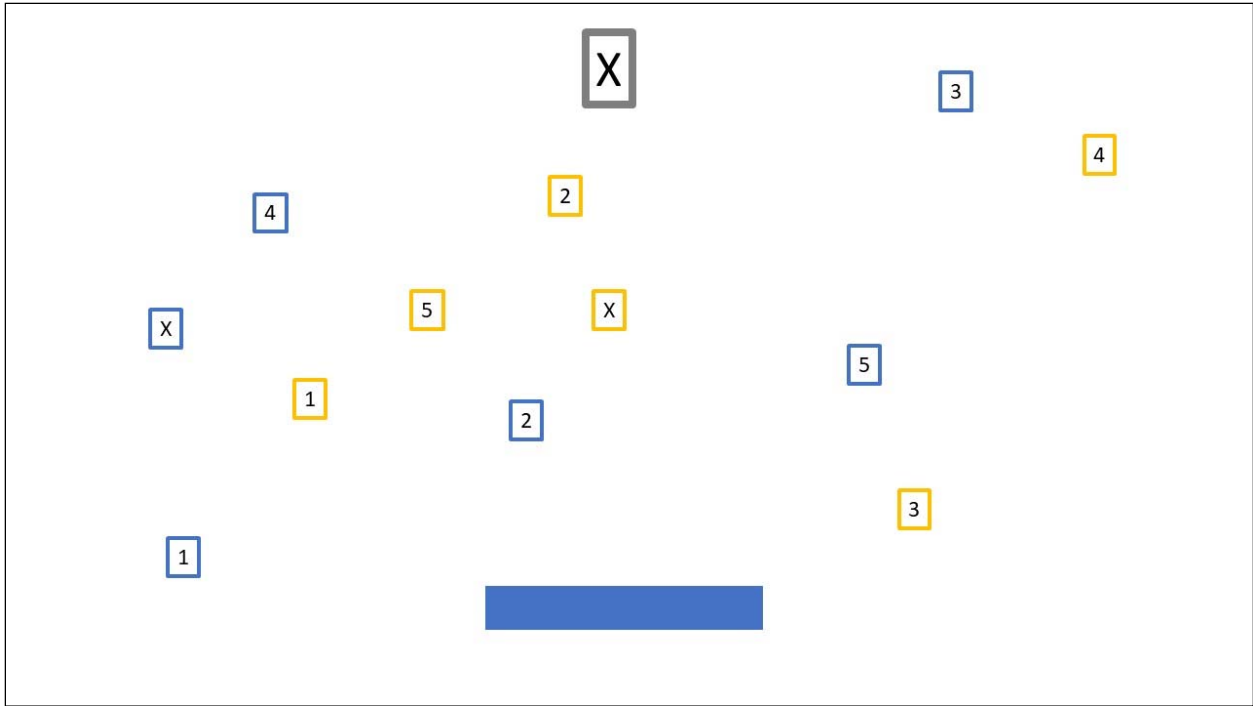


Figure 1. Example layout of the USAARL-TMT. The Characteristic Cue, shown here in blue, indicates that the subject is to identify all of the numbers outlined by blue in ascending order. The Interrupt Cue, shown here as present, indicates that the subject must identify the target X outlined in blue. Target locations remain unchanged during a trial but change with each new trial. Difficulty is manipulated by changes in both the Characteristic and Interrupt Cues.

Results

Figure 2 presents the average completion time for the three USAARL-TMT difficulties. As the challenge of the task increases, the completion time significantly increases, demonstrating altering the CC and IC manipulated task difficulty. The average completed time for the difficult conditions was about 13 sec. with no trial taking longer than 17 sec. to complete. These data included 20 trials at each difficulty, with each subject completing the entire assessment, including the initial gaze-position calibration, in roughly 10 minutes.

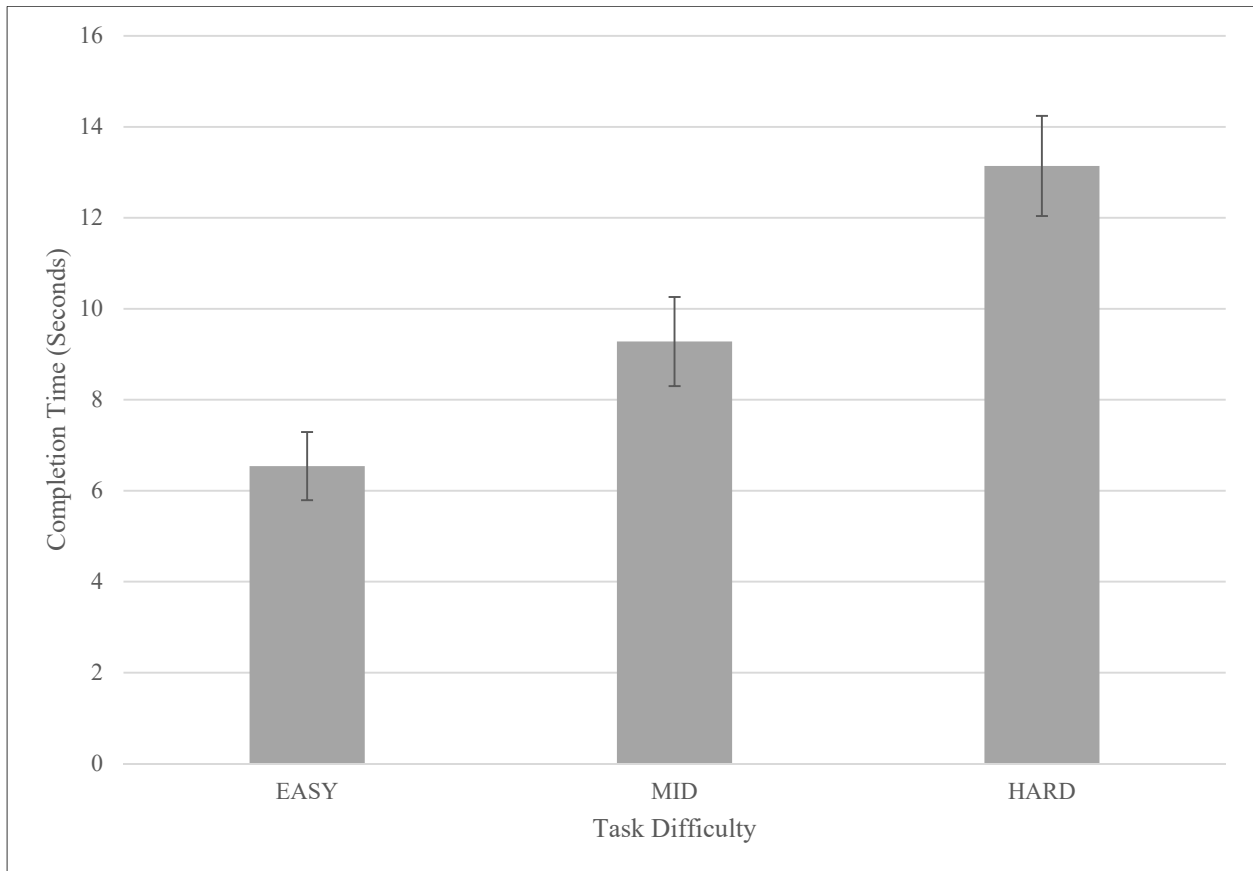


Figure 2. Average single-trial completion time, in seconds, for all subjects ($n = 10$) at each tier of task difficulty. Error bars are SEM, all differences are statistically significant ($p < 0.05$).

Figure 3 shows the relationship between average pupil area and the difficulty of the task. Average pupil size increased significantly with task difficulty and reflects the cognitive workload of the participant. This supports the conclusion that the USAARL-TMT is also effective at eliciting the physiological responses that indicate cognitive workload.

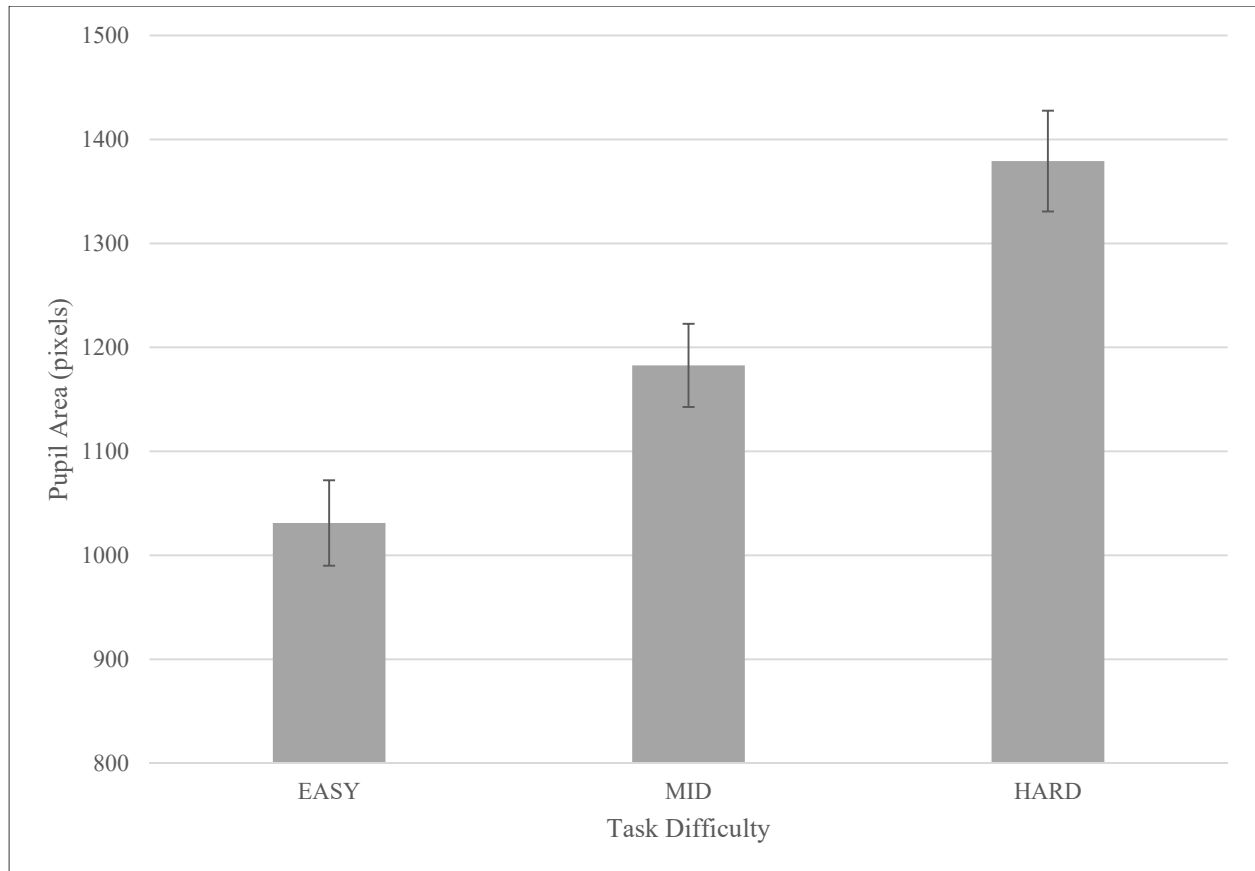


Figure 3. Mean pupil area for $n = 10$ subjects performing the USAARL-TMT at 3 levels of difficulty. Area is in camera pixels at a fixed distance. Error bars are SEM, all differences are statistically significant ($p < 0.05$).

Discussion

The theoretical maximum possible trial time can be estimated at 25 seconds with a 3 sec window within which to fixate, a 2-sec time out for each failed fixation, and 5 digit presentations. The longest trial was 17 seconds, well short of the possible 25 seconds. This suggests that the subjects remained engaged with the USAARL-TMT, which implies that the USAARL-TMT provides a sufficiently engaging challenge without being overly difficult. The close parallelism between the task completion times and the pupil diameters for the three levels of task difficulty further supports this conclusion.

The hands-free, sound-free characteristics of the USAARL-TMT provide the flexibility needed for deployment to the near-operational environment, and potentially the operational environment with the development of field-ready eye-tracking solutions. The present study, executed in USAARL's UMS, demonstrates that all the hardware and software components supporting the USAARL-TMT are compatible with the Unmanned Aerial Vehicle footprint. Currently, work is ongoing to expand the granularity of the USAARL-TMT to scale cognitive workload with greater resolution. The USAARL-TMT permits the measurement of the cognitive workload using techniques borrowed from standard sensory psychophysics to develop multi-dimensional cognitive workload measures to be integrated with physiological monitoring systems. Current and projected research includes implementing the USAARL-TMT metric on additional platforms, including the many simulators available at USAARL.

Conclusions

The USAARL-TMT provides a metric for hands-free cognitive workload calibration capability. It features expanded task-cuing modalities that allow for the fine-tuning of cognitive workload, while reducing interaction time and streamlining test administration. Further, this workload metric is deployable in a wider variety of near-operational settings to provide testing and calibration functionality. Proven and calibrated metrics for inducing cognitive workload are critical to the development and testing of real-time cognitive workload measures that will be incorporated into future aviation platforms and operator monitoring systems.

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Appendix A: Acronyms and Abbreviations

CC	Characteristic Cue
DTIC	Defense Technical Information Center
HQ USAMRDC	U.S. Army Medical Research and Development Command
IC	Interrupt Cue
IRB	Institutional Review Board
SEM	Standard error of the mean
TMT	Trail Making Test
UMS	Universal Mission Simulator
USAARL	U.S. Army Aeromedical Research Laboratory
USAARL-TMT	U.S. Army Aeromedical Research Laboratory Trail Making Task
WPG	Warfighter Performance Group



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