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Effects of Transverse Seat Vibration on Near-Viewing Readability of Alphanumeric Symbology

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Contents

1.0 Executive Summary

We measured the impacts on human visual function of a range of vibration levels (0.15, 0.3, 0.5, and 0.7 g) at the frequency and along the axis of the anticipated Ares thrust oscillation. We found statistically significant and equivalent decrements in performance on a reading and a numeric processing task at tested vibration levels above 0.3 g (0-to-peak), but no evidence of aftereffects. At the smallest font and highest vibration level tested, the average effect was a 50% increase in response time and six-fold increase in errors. Our findings support a preliminary trade space in which currently planned Orion font sizes and text spacing appear to be too small to support accurate and efficient reading at the tested vibration levels above 0.3 g, but not too small to support reading at 0.3 g. This study does not address potential impacts on crew cognitive decision-making or motor control and does not test either the full induced Orion-Ares environment with its sustained Gx-loading or the full complexity of the final Orion seat-helmet-suit interface. A final determination of the Orion-Ares program limit on vibration must take these additional factors into consideration and, thus, may need to be lower than that needed to support effective reading at 1-Gx bias.

2.0 Background and Rationale

During the dynamic flight phases of ascent and entry, the crew of the Orion-Ares vehicle will experience elevated vibration levels (together with sustained accelerations) that may interfere with their ability to read alphanumeric information on cockpit displays, interfering with their ability to monitor vehicle health and status during nominal operations, and severely compromising their ability to perform mission-critical off-nominal operations. While vibration, even well below the health limit imposed by the Human Systems Integration Requirements (HSIR), is known to interfere with visuomotor performance and increase workload (Griffin, 1971), most of the existing non-spaceflight literature addresses vibration along the z-axis (head-to-foot) (O'Briant & Ohlbaum, 1970; O'Hanion & Griffin, 1971). Orion-Ares crews will experience vibration along the transverse or x-axis (chest-to-back). Furthermore, Orion-Ares exposure will be at levels that may exceed the ~0.1 g (0-to-peak) putatively experienced during Gemini-Apollo-Shuttle and perhaps even the 0.25 g limit previously imposed by these programs. Orion-Ares vibration will also be at a different dominant frequency (Gemini POGO at 11 Hz vs. Ares thrust oscillation at 12 Hz). Lastly, Orion's modern displays, interfaces, and operations concepts will be quite different and more complex than Apollo's, with crowded symbology, text, and numbers within interactive displays and controls. Given the potential impacts of the novel and more severe induced vibration environment, the greater complexity of crew operations during ascent and descent, the relatively short contemplated viewing distance (19 in), the relatively small fonts contemplated (10 and 14 pt), and the relatively small, crowded displays, there is a serious risk that the confluence of these many factors will cause unacceptable degradation of human performance, due in part to decrements in visual function.

The rationale of this study is to begin the process of quantifying this risk, and determining acceptable vibration levels in the cockpit, by determining how vibration impacts visual reading performance in a semi-supine position within an Orion-like display/seat layout. Specifically, this study measured the effect on processing alphanumeric material of exposure to a range of vibration levels ranging from those previously experienced (0.1 g), and not expected to significantly impact performance during spaceflight, to those previously shown to adversely impact human performance (0.7 g). We examined the impact for two font sizes (10 and 14 pt). Because of the potential concern of aftereffects, we also examined performance during the time period immediately following exposure to vibration. The primary goal of this study was to determine reading performance trade-offs related to vibration level and font size with a 1-Gx sustained load. A secondary goal was to determine how fast task performance recovers from vibration exposure. A tertiary, future goal will be to compare these results with the results of similar vibration exposures under the sustained Gx-loading of Constellation spaceflight in order to understand the interaction between G-loading and vibration in order to assess the value of vibration-only testing and training.

3.0 Methods

3.1 Vibration Stimuli

The Ames Research Center's Vibration Chair (Figure 1) was used to generate a sinusoidal 12 Hz (single frequency) vibration along the body x-axis (chest-to-back) to simulate the current best estimate of the Orion vehicle response oscillation waveform during the Ares-I rocket first-stage ascent. The sinusoidal vibration was presented at 0, 0.15, 0.30, 0.50, and 0.70 g (0-to-peak) to span the range shown to cause decrements in visual performance during part-task simulations of previous (Gemini) crew operations.

Figure 1. Ames' Three Degree-Of-Freedom Vibration Chair illustrating the experimental configuration.

3.2 Visual Stimuli

A sample of the visual display format is shown in Figure 2. As depicted, the display format comprised a fixed six-by-six array of white-frame boxes of various sizes, interconnected by a variety of white lines (paths). All boxes in the display format contained either three rows of three letters or three numbers depending on whether that participant was assigned to the Letter or Number task group. All letters or numbers on the display were presented at the same 10- or 14-pt font size for a particular trial. All three-letter and three-number strings throughout the display format were randomly selected from a pre-computed list. The layout, density, and size of boxes and characters were selected to emulate key features of currently envisioned Orion crew display formats.

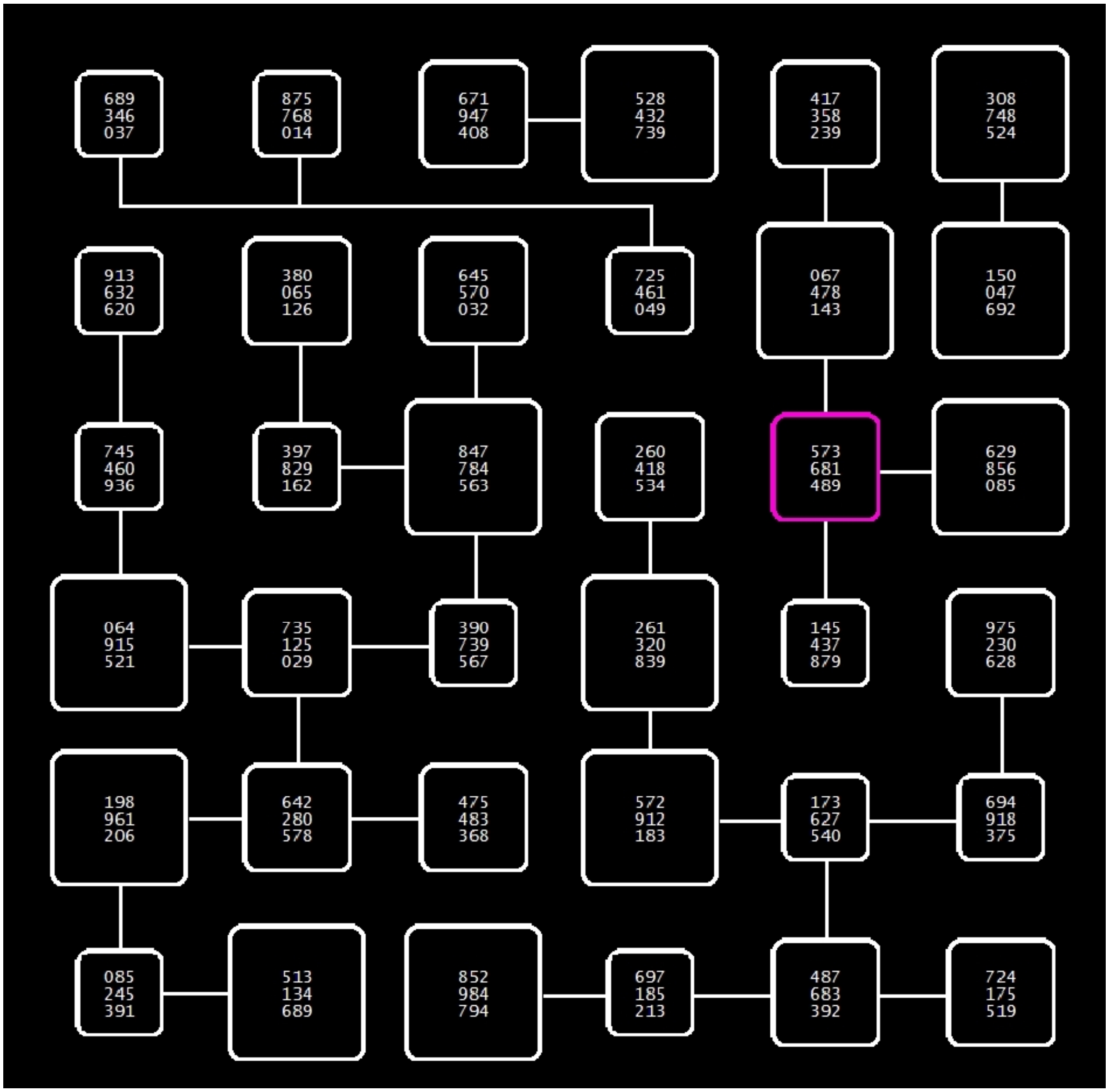


Figure 2. Display format for the numeric task. The displays for the lexical decision task were identical except that the numerical characters were replaced with alphabetic characters.

3.3 Task Descriptions

Each observer was asked to locate the highlighted box, read and process the contents of the middle row, and then make a two-alternative forced-choice (2AFC) based on the row's content. When letter strings were presented, the participant was asked to respond whether the middle string formed a real three-letter American English word (e.g., "BOX"), or not (e.g., "BAX"). When numerical strings were presented, the participant was asked to determine whether the three numbers formed either an unbroken ascending (e.g., "359") or descending (e.g., "953") sequence, or not (e.g., "382"). Letter or number strings assigned to the middle row of the highlighted box were equally likely to require a "yes" or "no" for a correct response. Participants indicated their response manually via a two-button response box. Both the response and its latency from the appearance of the visual stimulus were recorded to compute error rates and response times.

Both the text-based (lexical decision) task and the numeric processing task required observers to process all three characters in the middle row of the highlighted box in order to make a correct response. Thus, these were not mere legibility tasks but also involved rudimentary cognition (word and number identification) processing demands similar to the demands placed on crewmembers when processing such material from real display formats during actual operations. Note, however, that our simple alphanumeric tasks are not meant to capture the full extent of cognitive processing or motor responses required for actual crew operations (see caveats below).

The study employed a mixed-group three-factor design, with vibration (5 levels) and font size as within-subject factors, and task type (letter or number sequences) as a between-subject factor. Trials were blocked by font size, then by vibration level (with the baseline zero-vibration block completed first), resulting in a total of 10 blocks per participant. Each block comprised 40 self-paced trials, with the observers pressing a button to advance to the next trial following feedback. For each trial, the display had a maximum presentation time of 4 s. On the non-baseline blocks, the vibration started, the observer advanced through the 40 trials, and then the vibration ceased. The block continued without pause for an additional 20 vibration-free trials to assess whether there were vibration aftereffects. Thus, each non-baseline block consisted of 60 trials: 40 vibration trials and 20 aftereffect trials.

3.4 Observers

One group of eight observers performed the Letter task; a second group of eight performed the Number task. Other than the differentiation between letter and number stimuli, the details of the experimental task such as vibration levels, font sizes, stimulus and rest durations, and order balancing were identical.

3.5 Post-Test Subjective Responses

Following each block, observers were asked to respond to three questions on task readability, difficulty, and effort using the 7-point Likert scales shown in Table 1.

TABLE 1. POST-RUN QUESTIONS

Q1: How difficult was it to clearly identify the individual numbers/letters?						
1 easily readable; 100% confident	2	3	4	5	6	7 unable to read; guessing
Q2: How difficult was the task?						
1 easy	2	3	4	5	6	7 impossible
Q3: How much effort did the task require?						
1 little effort; could do other things concurrently	2	3	4	5	6	7 all my effort; no spare capacity

4.0 Results

4.1 Response Times

On average, observers responded in 1.288 s (SEM = 0.038 s) for the lexical decision task and in 1.857 s (SEM = 0.088 s) for the numeric task in the vibration-free condition. The main effect of task was highly significant, $F(1,14) = 20.51, p < 0.0005$). To better isolate vibration effects from inter-task and inter-subject effects, we normalized observer response time to with respect to their individual baseline levels. The normalized data are plotted in Figure 3.

For both tasks, there was an increase in normalized response time with increased vibration, $F(3,42) = 42.12, p < 0.0001$. In addition, response times were lengthened for the smaller compared to the larger font, $F(1,14) = 24.67, p < 0.0002$. The two variables also interacted, $F(3,42) = 10.35, p < 0.0001$, reflecting the fact that vibration effects appeared at smaller vibrations levels for the 10-pt font than for the 14-pt font (note the statistics reported here do not include the follow-up, vibration aftereffect periods). There were no significant differences between the effects of vibration on normalized response times for the lexical decision and Numeric tasks.

Post-hoc t-tests (pairwise for each participant with respect to their normalized, i.e., unity, baseline response time) of the data combined across the two tasks reveal significant increases at 0.5 g, $t(15) = 3.23, p < 0.003$, and 0.7 g, $t(15) = 6.21, p < 0.0001$ for the 10-pt font, but only at 0.7 g for the 14-pt font, $t(15) = 4.15, p < 0.0006$. For the smallest font and highest vibration level, responses were ~50% slower than baseline.

For both tasks and fonts, there was no discernible aftereffect, with performance returning to baseline after exposures as high as 0.7 g. Further analysis indicates that even in the first 5 trials immediately following the vibration exposure, response times returned to (i.e., were not significantly different from) pre-exposure levels.

4.2 Error Rates

As depicted in Figure 4, both tasks showed an increase in error rate above a baseline rate of ~5% with increased vibration, $F(4{,}56) = 29.61$, $p < 0.0001$, and a larger effect of vibration for the smaller font, $F(1{,}14) = 12.84$, $p < 0.003$. As with the analyses of response times, there was also a significant interaction between these variables, $F(4{,}56) = 19.20$, $p < 0.0001$, reflecting the fact that accuracy was compromised for the smaller (10 pt) font at smaller levels of vibration than the larger (14 pt) font. (An ANOVA performed on error rate data transformed by the arcsine-square-root function used for proportional data supported the main effect for vibration as well as the vibration interaction with font size, but not the main effect for font size.) There were no significant differences between the effects of vibration on response accuracy in the lexical decision and numeric tasks.

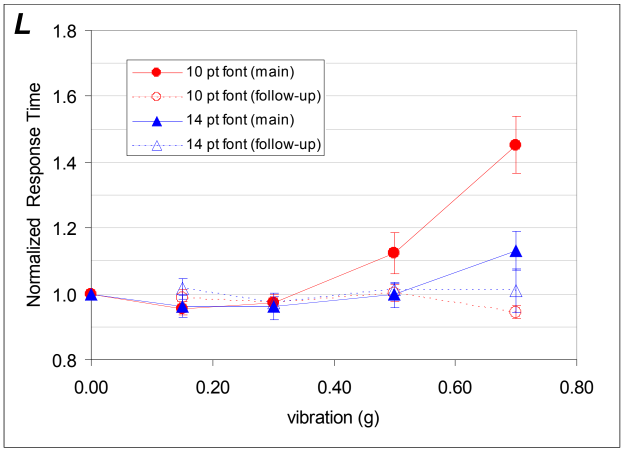
Post-hoc t-tests (pairwise for each participant with respect to their baseline zero-vibration error rate) of the data combined across the two tasks revealed significant increases at 0.5 g, $t(15) = 4.16$, $p < 0.0005$, and 0.7 g, $t(15) = 7.84$, $p < 0.0001$ for the 10 pt font, but only at 0.7 g for the 14 pt font, $t(15) = 2.96$, $p < 0.005$. Arcsine-square-root transforms of the error rate data support the same significant contrasts. For the smallest font and highest vibration level, errors rates are ~30% (i.e., about 6 times higher than baseline).

Note also that, for both tasks and fonts, there was no discernible aftereffect, with performance returning to baseline after exposures as high as 0.7 g. Further inspection indicates that response times even for the first 5 trials immediately following the vibration exposure had returned to (i.e., were not significantly different than) pre-exposure levels.

4.3 Subjective Ratings

Post-run self-assessments of perceptual, cognitive, and workload impacts revealed an effect of vibration as shown in Figure 5 (Friedman nonparametric ANOVAs separately for each subjective rating at each font size: cr2(4) > 40, $p < 0.0001$). The three subjective rating measures are highly correlated (Spearman correlation for the three possible pairings: $0.77 < rs < 0.82$, $df = 158$, $p < 0.0001$).

A. Lexical Decision Task Performance: Response Time



B. Numeric Task Performance: Response Time

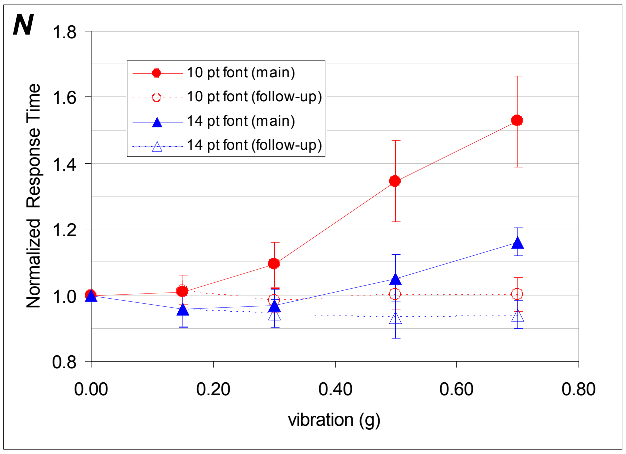
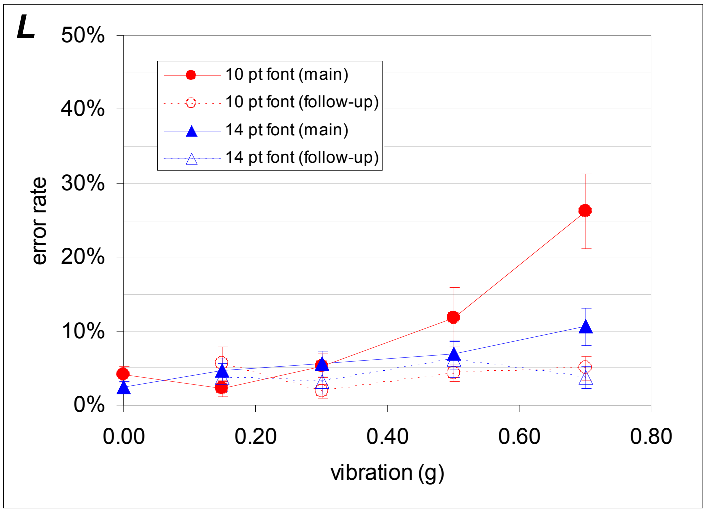


Figure 3. Normalized response time. These two panels plot response time as a function of vibration level (normalized with respect to the baseline "no-vibration" block) averaged over 8 observers (±1 SEM) in the Lexical Decision (A) and Numeric (B) tasks. Solid symbols and lines represent performance during vibration and dashed lines represent performance during the recovery period.

A. Lexical Decision Task Performance: Accuracy



B. Numeric Task Performance: Accuracy

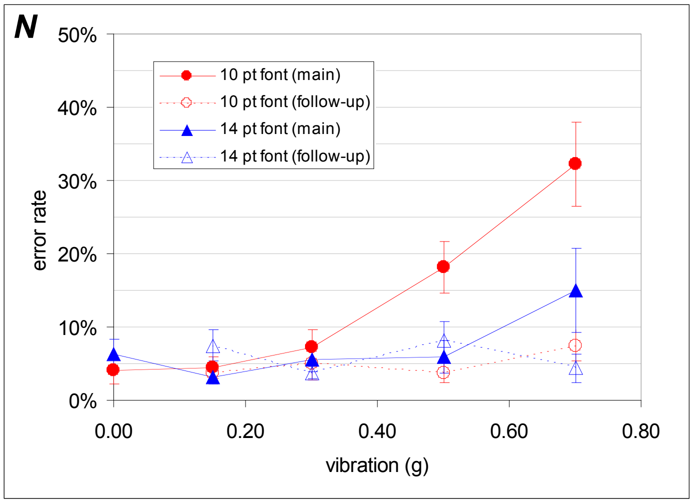


Figure 4. Response accuracy. Error rate (% incorrect) as a function of vibration level averaged over 8 observers (±1 SEM) in the Lexical Decision (A) and Numeric (B) tasks. Solid symbols and lines represent performance during vibration and dashed lines represent performance during the recovery period.

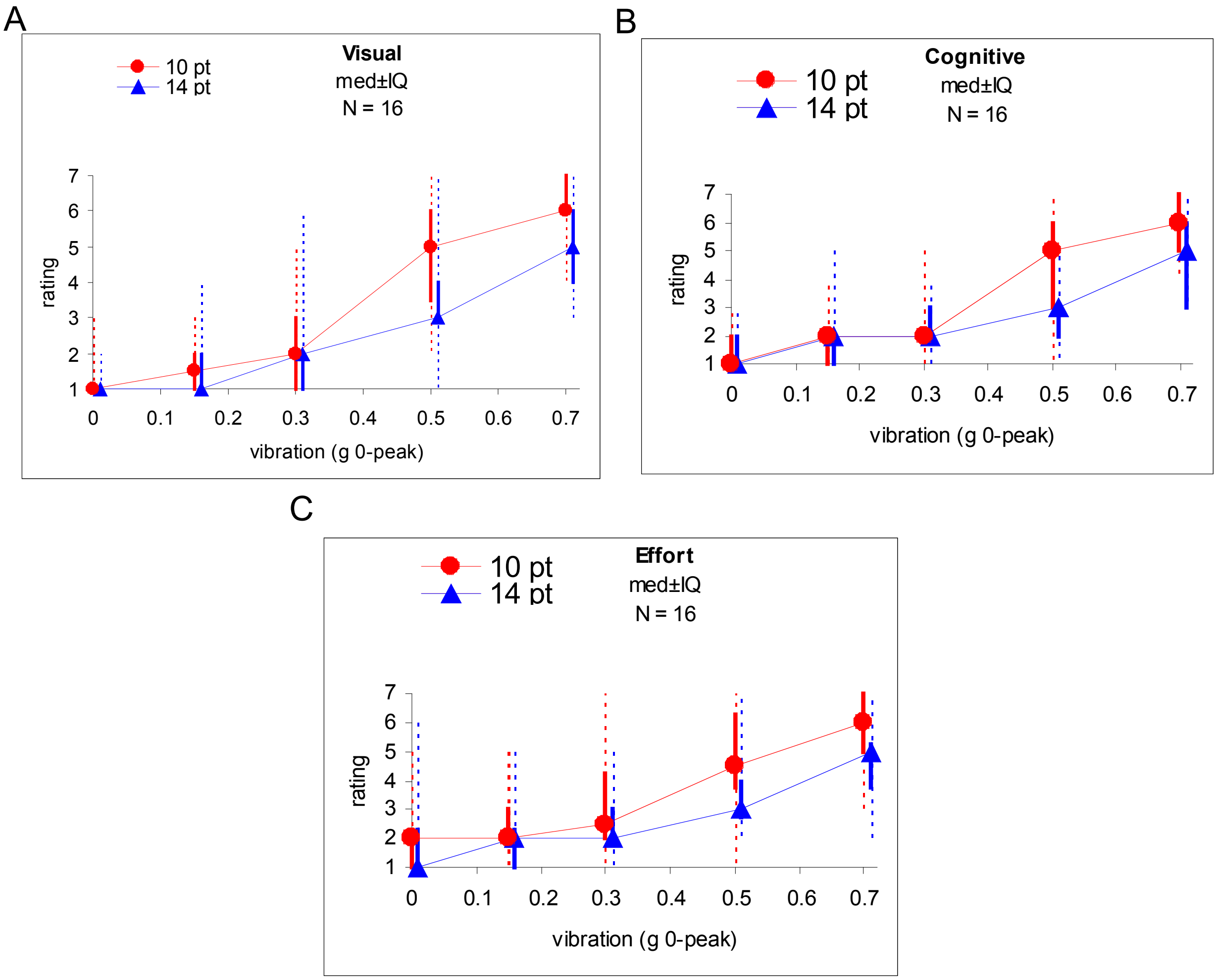


Figure 5. Subjective perceptual (A), cognitive (B), and workload (C) ratings as a function of vibration level and font. Symbols indicate medians. Solid bars indicate interquartiles and the dashed lines max-min.

5.0 Caveats

5.1 Visual Function is Only One Performance Factor

Visual function is only the first component of the visuo-cognitive-motor process underlying crew performance in any vehicle-health monitoring or flight control task. Nonetheless, reading will be the limiting factor in many tasks, i.e., astronauts cannot properly perform a task requiring encoding and processing of alphanumeric information on cockpit display formats if they cannot read the display. Thus, any exposure-induced limitation on readability measured in this study represents an upper limit because it does not address the next two performance steps: 1) cognitive integration of alphanumeric information into a operationally relevant task (such as using numeric data to proceed through an off-nominal checklist), and 2) effecting accurate and precise motor responses with interactive displays via a hand controller. In other words, even if the crew can read the display for a particular vibration-font combination, they still may not be able to perform the full task properly. Thus, future follow-on studies should include an examination of vibration effects on expert cognitive function by collecting, in conjunction with objective performance measurements, astronauts' subjective ratings of impacts on performance and on manual control responses for interactive displays and (flight) controls.

5.2 G-Force interactions

Sustained accelerations and their associated G-forces alter the biomechanical impedance of humans. Thus, the vulnerability to vibration will change and will do so in a complex manner that cannot be predicted with any confidence. The current results therefore only apply to the +1 Gx sustained load of a semi-supine position. The Orion-Ares vehicle anticipates a load around +3.8 Gx concurrent with the maximum vibration condition of ascent. Thus, this study should be repeated under that elevated G-load in order to validate the trade-off space for actual Orion-Ares conditions. However, given the fact the current vibration, font-size, and vibration and font-size interaction results were indistinguishable between the Lexical Decision and Numeric tasks, one need not use both reading tasks.

5.3 Detailed Seat-Helmet-Suit Configuration

The effect of vibration on performance will necessarily depend on the exact seat-helmet-suit configuration because these factors affect the transfer of motion from vehicle to crew as well as the extent to which a predominantly x-direction motion stimulus is transferred into the other five degrees-of-freedom (in particular, into head pitch movements). At this time, however, the Orion seat-helmet-suit design and its interfacing have not as yet been finalized.

6.0 Summary and Conclusions

Our data show:

- For the viewing distance currently planned for Orion, reading performance for displays directly in the forward field of view is not significantly degraded at vibration levels less than or equal to 0.3 g (0-to-peak) for even 10 pt font.
- For both number and letter processing, performance is meaningfully worse at both 0.5 g and 0.7 g for 10 pt font and at 0.7 g for 14 pt font.
- Because both alphabetic and numeric character processing was affected in similar ways by vibration, the same font size can be chosen for both.
- Alphanumeric processing performance recovers immediately following cessation of vibration, even after 2–3 minutes of exposure to vibration levels as high as 0.7 g.

We conclude that the tested vibration levels above 0.3 g (0-to-peak) will meaningfully compromise the processing of alphanumeric symbology in the currently anticipated Orion display viewing conditions. However, this conclusion must be tempered by the following caveats:

- Performance impacts may differ when combined with sustained elevated Gx-loading.
- Mission task performance may be more severely impacted as there may be additional cognitive and motor performance decrements associated with vibration.
- The final seat-helmet-suit configuration may mitigate or exacerbate the risk.

Finally, we note that the ultimate goal of this domain research is to develop robust models of human performance in the presence of vibration. Ultimately, such models could accurately predict the performance impact of vibration across a wide range of operational scenarios in order to shape and evaluate the design trade space.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study examined the impacts on human visual function of a range of vibration levels at the frequency of the anticipated Ares thrust oscillation. We found decrements in performance on a reading and a numeric processing task at tested vibration levels above 0.3 g (0-to-peak), but no evidence of aftereffects. Our findings support a preliminary trade space in which currently planned Orion font sizes and text spacing appear to be too small to support accurate and efficient reading at the tested vibration levels above 0.3 g, but not too small to support reading at 0.3 g. This study does not address potential impacts on crew cognitive decision-making or motor control and does not test either the full induced Orion-Ares environment with its sustained Gx-loading or the full complexity of the final Orion seat-helmet-suit interface.

15. SUBJECT TERMS

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