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INVESTIGATING THE IMPACTS OF COCKPIT NOISE EXPOSURE ON HUMAN DECISION-MAKING

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ABSTRACT

A large amount of research focuses on protecting military personnel from over exposure to noise, but little research has focused on the cognitive impacts. As such, Air Force Research Laboratory researchers have conducted a study to explore how cockpit noise influences decision-making. Fifteen participants were placed within a chamber with communication ear plugs (daily attenuation collected) and exposed to noise previously recorded within the cockpit of a fifth-generation fighter jet generated at levels of L_A= 60, 70 and 80 dB under protection. Participants completed a series of auditory working memory and visual search tasks in both single- and dual-task paradigms. Performance changes were observed across individual participants depending on differing noise level and task difficulty; additionally, individual fit variances led to differences in room (full body) sound pressure levels that require further investigating. Overall, the results of this study offer a better understanding of how high-level cockpit noise impacts multitasking and working memory performance involved in decision-making. From this work, recommendations can be made on how to manage cognitive load in these complex military operations.

Keywords: *F-35 cockpit noise, multitask efficiency, decision-making, noise sensitivity, valence-arousal*

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1. INTRODUCTION

Several studies have reliably captured cross-modal demand effects and have found task difficulty modulates the cross-modal impact on performance. More specifically, in a dual-task context, the task load in a primary task of one modality influences the performance on a second task presented in a different modality [1, 2]. However, the literature linking the deleterious effect of prolonged and continuous environmental acoustic noise on intra- or cross-modal attentional resources and cognitive functioning is limited. This is especially true when considering key mechanisms such as working memory (e.g., phonological loop) and higher-order executive functioning (e.g., multitask management). Limited studies have shown that acoustic noise can either enhance or degrade performance. For example, Awada and colleagues demonstrated that incorporation of low levels of white noise improved performance in creative tasks, but increased levels of noise only improved working memory tasks [3]. Overall level of noise influences some aspects of cognitive performance, but some studies have demonstrated that other characteristics (features) of the noise may also be critical indicators [4–6].

In a within-subjects experiment, we systematically investigated the relationship between the level (amplitude) of aircraft noise that F-35 pilots are exposed to and the cognitive processes most relevant for them to achieve mission success. We tested working memory through a standard auditory n-back task and decision-making through a visual multi-object search task. While many environmental stressors exist, this research focused on the impact of acoustic stressors, specifically the level of noise, on cognitive processing and decision-making under various single- and dual-task loads. We factorially manipulated single- (n-back OR decision-task) and dual-tasks, 3 levels of n-back difficulty (n-back), and F-35 cockpit noise recordings presented at 4 A-weighted levels (quiet, L_A = 60, 70, and 80 dB as measured under hearing protection [UHP]). We assessed response times and accuracy to respond to task stimuli, mathematical modeling coefficients (efficiency cost of multitasking [2]), subjective assessments of affect and arousal (HAAS, [7]), and how one's sensitivity to noise (Noise Sensitivity Scale [NSS]; [8]) impacts performance in, and subjective assessments of, different levels of steady-state F-35 cockpit noise.

Unique to our lab task, participants placed hearing protection on before undergoing a measurement of hearing protection fit, which was used to individualize the external level of sound and properly control noise dose UHP. This was completed immediately prior to all three sessions where noise was administered. As such, the variation within- and between-people using communication earplugs (CEPs) will be reported. In addition to our primary research questions described above (and hypotheses below), these data are also useful for evaluating operational guidelines for use of CEPs as a form of hearing protection in the field.

1.1 Hypotheses

We have three hypotheses in regards to research questions of interest.

Hypothesis 1 (H1). Performance and efficiency will decrease when multitasking compared to isolated completion, and higher decrements will be observed with increasing working memory load.

Hypothesis 2 (H2). Performance and efficiency will decrease under noise, compared to quiet, and more decrements will be observed as the level of noise increases.

Hypothesis 3 (H3). Higher noise exposure will result in higher negative affect and lower positive affect in post session affect state assessment, compared to pre session assessment, moderated by the individuals' degree of noise sensitivity.

2. METHOD

2.1 Participants

Participants included 18 (N = 15 after exclusions) US citizens, 60/40 split between female/male, recruited from the Dayton, Ohio area, who received monetary compensation (20 USD/hour) for their time. All participants completed the task in a controlled laboratory setting on Wright-Patterson Air Force Base.

2.2 Surveys

Noise sensitivity is generally defined as "an individual's internal state which increases their degree of reactivity to noise [9]." It is measured using a 6-item noise sensitivity scale (NSS), where participants agree/disagree with each statement [8]. We measured participants' noise sensitivity prior to the experiment.

The Hedonic Arousal Affect Scale (HAAS) is a survey based on the valence-arousal model of affect. Valence is the hedonic tone or (dis)pleasure of the situation, and arousal is the amount of activation associated with their personal state [10]. The abbreviated 12-item HAAS [7] is well-suited for repeated measure designs, such as the experiment described here, and can be summarized to capture overall positive/negative effects of each noise level on one's relative change in valence and arousal. Participants rated each adjective (e.g., Active, Calm, Irritable, Tired) on a scale from 1 (very slight/not at all) to 5 (extremely) before and after each session. For noise sessions (2-4), participants completed the post-session survey after all trials were complete, but prior to terminating the room noise to obtain a reflection of their state in noise.

2.3 Procedure

Participants completed 4 sessions (each 2.5 hours; total time 10 hours) in the Voice Communication Research and Evaluation System (VOCRES) facility, which is a acoustically diffuse room (down to 500 Hz) and capable of continuous 125 dB A-weighted sound pressure level (SPL) w/ bandwidth 20-20k Hz. Session 1 was the quiet day and required participants to complete the informed consent, the NSS, an Ishihara Color Blindness test, and a baseline hearing assessment. Additionally, prior to and post sessions 1-4, the participant completed the HAAS survey. For sessions 2-4, participants completed daily attenuation measurements for their CEPs using the Michael & Associates FitCheck Solo System. Individuals' attenuation results were used to adaptively filter the noise in octave bands to control for any variance in fit across participants and sessions (noise level was randomized after session 1; noise exposure $<$ 2 hrs/session). Next, participants were tasked with completing the visual search (VS), the working memory (WM), or dual-task, depending on the assigned order. All conditions were completed in each session; participants completed practice trials each session.

Participants were given mandatory 30 second breaks approximately every 5 minutes. After the completion of all conditions and surveys, participants completed a post session hearing assessment to check for any threshold shifts (noise sessions) then were thanked and paid for their time (all sessions).

2.4 Tasks

Order of task presentation was pseudo-randomized. Session 1 required participants to complete the VS and WM tasks in isolation prior to completing the dual-task. All other sessions had randomized order of tasks.

2.4.1 Visual Search Task

Participants were asked to complete a visual discrimination task that had two simultaneous 2-alternative-forced-choice (2AFC) responses, where participants had to decide between two response options in each (see Figure 1 for stimuli). The first 2AFC was to determine whether a dog (left arrow key) or lion (right arrow key) was presented on screen; the second was to determine whether a car was present (up arrow key) or not (down arrow key) – each trial demanded two key presses; participants used their right hand to complete this task.

Six fixations were presented in a half-circle (above center), and one in the center for 500 ms at the start of each trial. Following a short, 0-300 ms blank screen, each fixation was replaced with either a target or distractor icon. The center fixation did not remain. Either a dog/lion was present every trial. On car present and absent trials, four and five distractors filled in the remaining locations, respectively. Stimuli were presented for 1000 ms, and participants had 3000 ms (from the onset of stimuli) to make both the animal and car responses.

Each participant completed a minimum of 15 practice trials (dependent on their understanding of the task) before moving onto data collection. Trials lasted 4600 ms for a total of 336 trials across 6 blocks which amounted to 56 trials/block. The task was presented in isolation and a dual-task context, both of which were completed with the participant at a 60 cm viewing distance from the screen.

2.4.2 Auditory Working Memory Task

Participants were also instructed to complete an auditory working memory task, in this case, an n-back task [11, 12] of varying difficulty (1, 2, 3-back). Responses were given in a Go/No-Go format, meaning that participants pressed a key (F; left hand) when the spoken letters matched the letter presented N-ago and withheld a response if the letters did not match, see Figure 2. Letters were prerecorded and took approximately 500 ms to transit aurally via the CEPs; letters C, H, and X were excluded due to idiosyncratic details for this particular experimental design. All letters were presented 6 dB above the level of noise under hearing protection (66, 76, and 86 dB, respectively) to ensure adequate intelligibility (via pilot testing); in the quiet condition, stimuli were presented at 66 dB.

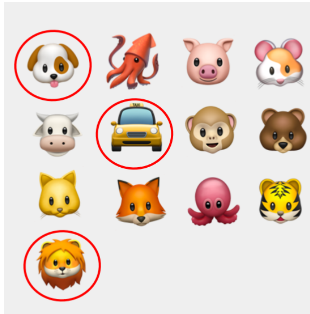

Figure 1. All possible visual stimuli. The red circle represents the target stimuli; all others served as distractors.

Each participant completed a minimum of 16 practice trials at each difficulty level (dependent on task understanding) before moving onto data collection. Trials lasted 2300 ms with a 1500 ms response window for a total of 672 trials across 6 blocks, which amounted to 112 trials/block. The task was presented in isolation prior to a dual-task context in the first session.

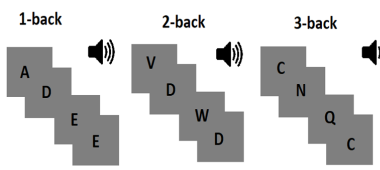

Figure 2. Example of how the n-back task was presented to participants. For these examples, the participant should press the 'F' key following the most recent letter (E, D, C, respectively).

2.4.3 *Dual-Task*

The dual-task consisted of all combinations of n-back paired with the search task. To maintain pacing, there were 2 auditory trials (2300 ms/trial) per 1 visual trial (4600 ms/trial). Each participant completed a minimum of 16 practice trials at each working memory difficulty before moving onto data collection.

2.5 Equipment

Participants used a desktop computer and the Michael & Associates FitCheck Solo System to collect attenuation data; the experimenter used the same computer to administer aircraft noise at the desired level for the duration of the experiment. Participants used a 10.5in Microsoft Surface Go 3 to complete the experiment (fixed location). Participants used CEP 508-SR w/ comply tips (Memory Foam P-Series) to both hear the audio stimuli and as hearing protection in the experiment, see Figure 3. Hearing threshold measurements were conducted using an AudioStar Pro.

Figure 3. Example of CEPs used by participants for noise protection and presentation of audio task.

3. RESULTS

3.1 Data Cleaning

For the visual search task, reaction times (RTs) quicker than 100 ms were removed to eliminate anticipatory responses. Three participants were removed due to any of the following: lack of responses within an isolated task, less than 60% accuracy when completing the visual task, or willingly excluding themselves from the experiment. Two auditory blocks, each in different sessions, were removed from one participant due to a lack of responses. Block one of the visual search task in isolation was removed due to training effects for all participants.

3.2 Auditory Health

Auditory thresholds, noted as hearing level (dB HL), were measured across nine frequencies in each ear (e.g., 125, 250, 500, 1k, 2k, 3k, 4k, 6k, 8k Hz). Baseline thresholds were taken during session 1 and any participant that had $>=$ 25 dB HL in two+ frequencies in one ear were excluded, $M = 2.98$ dB HL, $Max = 25$ dB HL. No participants presented with greater than a 10 dB HL threshold shift averaging across 2-4k Hz after noise exposure (Threshold shift: $M = 1.05$ dB HL, $Max = 10$ dB HL) collected less than 5 minutes post-noise exposure.

Due to individual differences in inserting the CEPs, participants had changes in personal attenuation rating (PAR) each session. Nonetheless, due to the adaptive filtering used, the UHP levels remained balanced across participants. However, this necessitated different external room levels based on the individual fit differences, see Table 1.

Table 1. A table summarizing auditory differences among participants across noise levels.

	Desired Noise Exposure	$M(SD)$
CEP Fit	60	30.66 (3.88)
	70	31.85 (4.95)
	80	31.64 (4.08)
Room Levels	60	94.86 (3.86)
	70	107.24 (3.48)
	80	114.34 (3.28)
UHP Levels	60	58.35 (0.53)
	70	68.72 (0.59)
	80	78.15 (0.99)

3.3 Performance

To test H1 and H2, we assessed how VS and WM (n-back) task accuracy and efficiency changed as a function of WM task load and single- v. dual-task (H1), and as a function of noise (H2). We applied z-score and t-tests to assess post hoc differences between conditions for accuracy and Cost, respectively. We applied a Bonferroni p-value correction for all post hoc analyses.

3.3.1 *Accuracy*

First, we used two repeated-measured ANOVAs to assess the accuracy of the VS and WM tasks across single- and dual-task conditions, and various WM loads and noise levels. z-score statistics are presented for single test or a [range] to summarize multiple tests.

VS task. We found significant main effects of WM load, $F(3, 38309) = 25.06$, $p < 0.05$ (supporting H1) and noise level, $F(3, 38309) = 2.82$, $p < 0.05$ (supporting H2), and their interaction, $F(9, 38309) = 2.71$, $p < 0.05$, on VS accuracy. Post hoc assessments revealed that the isolated VS task in 60 dB, $M = 98.84\%$, $SD = 10.72\%$ and 70 dB, $M = 98.52\%$, $SD = 12.08\%$, were more accurate than the VS task paired with the 3-back in 60 dB, $M = 96.78\%$, $SD = 17.65\%$, $z = 5.22$, $p < 0.05$ and 70 dB, $M = 97.30\%$, $SD = 16.22\%$, $z = 3.29$, $p < 0.05$, respectively. Lastly, the isolated VS task in 80 dB, $M = 99.11\%$, $SD = 9.38\%$, was more accurate than the VS task paired with the 2-back in 80 dB, $M = 96.53\%$, $SD = 18.30\%$, $z = 6.69$, $p < 0.05$. Alternative to our hypothesis, the isolated VS task in quiet, $M = 98.14\%$, $SD = 13.52\%$, is less accurate than the isolated VS task in 80 dB, $z = -3.64$, $p < 0.05$.

WM task. We found significant main effects of context (single- v. dual-tasking), $F(1, 19012) = 111.37$, $p < 0.05$, WM load (n-back), $F(2, 19012) = 1089.44$, $p < 0.05$, supporting H1, and noise level $F(3, 19012) = 11.16$, $p < 0.05$, supporting H2, on WM task hit rate. Additionally, there was an interaction between noise level and WM load on the WM task (n-back) hit rate, $F(6, 19012) = 10.51$, $p < 0.05$. Post hoc assessments revealed that in all noise levels, the 1-back, $M = [92.88\%, 93.85\%]$, $SD = [24.02\%, 25.72\%]$, was more accurate than the 2-back, $M = [83.21\%, 87.93\%]$, $SD = [32.59\%, 37.39\%]$, $z = [4.35, 7.56]$, $p < 0.05$, and the 3-back, $M = [57.47\%, 68.55\%]$, $SD = [46.45\%, 49.46\%]$, $z = [19.38, 28.14]$, $p < 0.05$. In all noise conditions, participants had higher accuracy in the 2-back condition than the 3-back, $z = [13.83, 22.27]$, $p < 0.05$, collapsed across single- and dual-tasking. Participants' 2-back accuracy was higher in 70 dB noise, $M = 87.93\%$, $SD = 32.59\%$, compared to 80 dB, $M = 83.21\%$, $SD = 37.39\%$, $z = 3.62$, $p < 0.05$, partially supporting H2. Alternative to H2, the 3-back in quiet had lower accuracy than when completed in any noise level, $z = [-8.47, -6.22]$, $p < 0.05$.

3.3.2 Multitasking Cost

As a reminder, cost controls for how well individuals perform the task in an "unlimited capacity" environment (i.e., no second task, desired noise level). For each individual, a baseline (single-task) performance was collected in each noise level. These baselines were then compared to their dual-task performance in each level of noise, respectively. If the resulting cost score is equal to 0 and thus unlimited, processing efficiency remains consistent, while a score < 0 denotes a limited capacity and slower processing efficiency, and a score of > 0 demonstrates an increase in processing efficiency and super capacity (for reference see [2, 13]).

VS task. There was a main effect of WM load on VS cost, $F(2, 154) = 11.81$, $p < .05$ (see Figure 4). Specifically, VS paired with the auditory 1-back, $M_{cost} = -0.13$, $SD_{cost} = 3.49$, was more efficient than with 2-back, $M_{cost} = -1.91$, $SD_{cost} = 3.68$; $t(154) = 3.49$, $p < 0.05$, and 3-back, $M_{cost} = -2.51$, $SD_{cost} = 3.87$; $t(154) = 4.67$, $p < 0.05$, supporting H1. Additionally, there was a main effect of noise level on VS cost, $F(3, 154) = 11.66, p < .05$ (see Figure 4). Specifically, VS cost in quiet, $M_{cost} = 0.60$, $SD_{cost} = 4.30$, was higher (i.e., more efficient) than in 60 dB, $M_{cost} = -2.02$, $SD_{cost} = 4.17$; $t(154) = 4.46$, $p < 0.05$, 70 dB, $M_{cost} = -2.24$, $SD_{cost} = 3.16$; $t(154) = 4.83$, $p < 0.05$, and 80 dB, $M_{cost} = -2.41$, $SD_{cost} = 2.57$; $t(154) = 5.12$, $p < 0.05$, partially supporting H2.

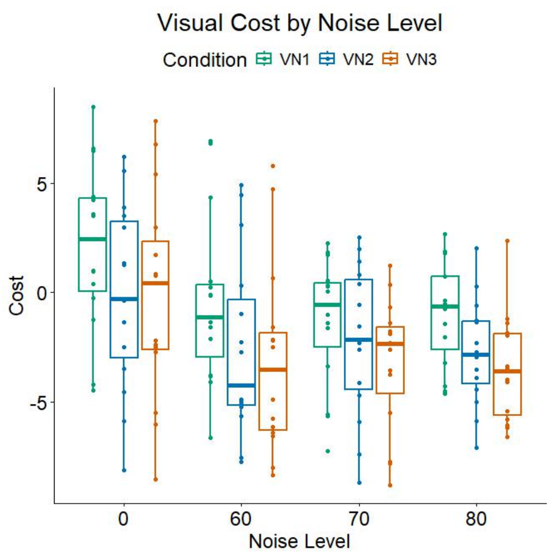

Figure 4. Visual search (VS) cost by noise level and condition. VN1 is an auditory 1-back, VN2 is 2-back, and VN3 is 3-back. All were paired with the VS task.

WM task. There were no main effects of difficulty (n-back) or noise level (quiet, 60, 70, 80 dB), or their interaction, on WM task cost.

3.4 Survey Analyses

NSS scores were computed from individuals' survey answers at the start of the experiment. HAAS surveys were filled out prior to and after completion of tasks in each session; the difference in the scores was used to detect changes in affect due to the noise level, see Table 2.

NSS and HAAS. Using a simple linear regression model, we found a significant main effect of NSS score on degree of change in negative affect, $F(1, 13) = 6.08,\ p < 0.05$, see Figure 5. Post hoc simple slopes analyses revealed that the greater one's NSS score, the more their negative affect increased due to quiet, $t(32.57) = 2.47,\ p < 0.05$, and 70 dB noise, $t(32.57) = 2.34,\ p < 0.05$, partially supporting H3.

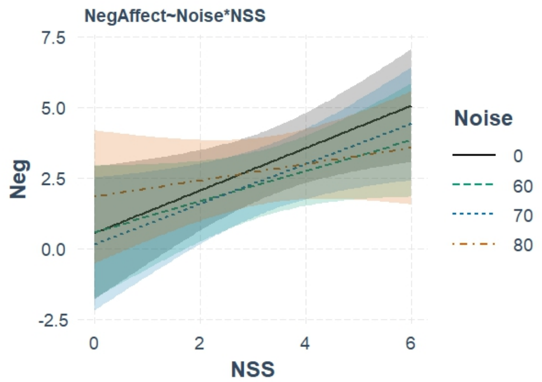

Figure 5. Change in negative affect (NegAffect) by noise level and Noise Sensitivity Scale (NSS) score.

Table 2. Means (standard deviations) for changes (Δ) in positive (Pos) and negative (Neg) affect across noise levels.

Noise Level	Δ Pos	Δ Neg
0	-3.6 (3.70)	3.07 (2.81)
60	-3.00 (2.59)	2.40 (2.47)
70	-2.33 (2.29)	2.53 (2.74)
80	-3.13 (2.77)	2.80 (1.78)

We found no significant main effect of Noise and NSS, or their interaction, to predict changes in positive affect.

VS task. Our results indicated a significant interaction between NSS score and noise level on VS task cost, $F(3, 159) = 3.48,\ p < 0.05$, see Figure 6, partially supporting H3. Post hoc paired-samples analyses revealed that for both low and moderate NSS scores, peoples' VS task efficiency decreased in all noise levels compared to quiet, $t(159) = [-5.42,\ -3.21],\ p < 0.05$. Alternatively, those with high NSS scores are only less efficient in 60 dB noise, $t(159) = -2.91,\ p < 0.05$, compared to quiet.

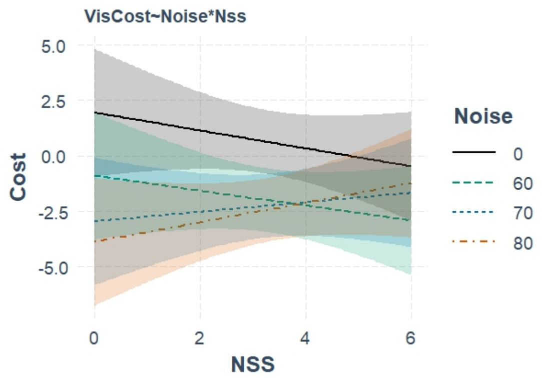

Figure 6. Visual search task cost (VisCost) by noise level and Noise Sensitivity Scale (NSS) score.

WM task. Our results indicated a significant interaction between NSS score and noise level on WM task cost, $F(3, 339) = 7.42,\ p < 0.05$, see Figure 7, partially supporting H3. Specifically, post hoc paired-samples analyses revealed that when participants had a lower NSS score, they were more efficient in the WM task in 60 dB noise, $t(339) = 3.13,\ p < 0.05$, compared to quiet. Alternatively, participants with a higher NSS score had lower efficiency in the WM task in 60 dB, $t(339) = -2.35,\ p < 0.05$, compared to quiet.

4. DISCUSSION

We investigated the relationship of three levels of steady-state F-35 noise and performance in concurrent VS and auditory WM tasks of varying difficulty levels. Importantly, we found no notable shifts in auditory thresholds due to noise exposure and CEP fit improved across session.

First, we found multitasking and WM load influenced performance in both tasks, supporting H1. In particular, VS task accuracy decreased due to multitasking and

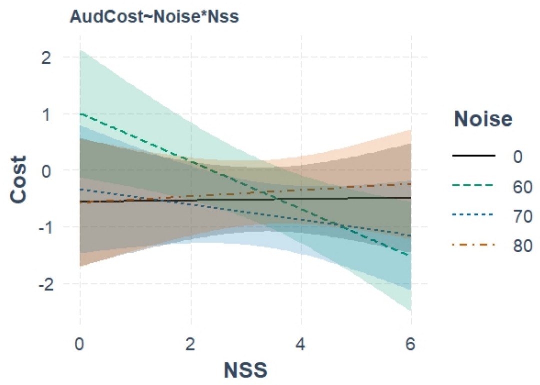

Figure 7. Working memory (WM) task cost (AudCost) by noise level and Noise Sensitivity Scale (NSS) score.

cross-modal WM load. In addition, participants' accuracy in both tasks significantly differed as a function of noise condition, partially supporting H2. Contrary to H2, 80 dB noise increased single VS accuracy; all noise levels led to higher WM accuracy when multitasking under a high load. Lastly, we found multitask efficiency (VS but not WM) decreased in noise, providing partial support for H2.

To investigate how one's sensitivity and emotional response to noise moderates our findings, we first assessed if one's noise sensitivity, as measured by a 6-item scale [8], predicted their degree of change (Δ) in positive and negative affect, as measured by a 12-item scale [7] after noise exposure. We found those with higher sensitivity to noise experienced significantly more negative affect following the quiet and the 70 dB noise conditions. However, no significant differences were found after 60 or 80 dB noise, and no shifts in positive affect were observed for any of the noise levels.

Then, we assessed noise sensitivity as a moderator of our findings and found those with low and moderate sensitivity performed the VS with an unlimited capacity in quiet, but with a limited capacity when exposed to any level of noise. Alternatively, those with high sensitivity to noise performed with an unlimited capacity in quiet, or 70 dB and 80 dB noise, but with a limited capacity in 60 dB noise. Interestingly, those with low sensitivity performed the WM task more efficiently with 60 dB noise than quiet, but those with high sensitivity performed with a more limited capacity in 60 dB noise.

These data suggest that one's degree of noise sensitivity plays a role in the degree of impact and type of interference that steady-state F-35 cockpit noise has on negative affect, and visual (VS task) and auditory (WM task) efficiency, when attempting to multitask. Our study results may indicate that those who are highly sensitive to noise actively work to ignore the noise and focus on maintaining adequate performance in a task of another modality (visual). Alternatively, those with low sensitivity had a within-modality (auditory) boost from the low level of noise, while highly sensitive individuals performed worse in the auditory (WM) task with the same 60 dB noise. Interestingly, those with high sensitivity performed the worst in both tasks when exposed to the low level of noise.

4.1 Limitations and future research

This research has its limitations, but these serve to highlight the importance of future work. First, we chose to control for the level of noise exposure UHP, which necessarily made the level of noise in the room vary across people. The room level may change the degree to which one receives aural information via bone conduction, and the degree to which the sound vibrations may alter effects of physical and cognitive fatigue. Future work should investigate the impact of room level on cognitive performance and use a type of hearing protection that has little variability in the degree of protection between people.

We also chose that Session 1 would always be quiet to mitigate potential harm should participants unknowingly engage in risky behavior (e.g., adjusting their CEPs mid-session). However, future work should fully randomize session order to validate our results.

Our tasks jointly differed in modality and cognitive resource demands so the two cannot be disentangled regarding the impact of noise on cognitive processes. Future work should replicate this study and systematically manipulate perceptual and cognitive resources. While [14] found that distractions that cause higher executive and WM load impacts real-world VS performance, regardless of the source, future research should investigate the moderator of noise sensitivity.

Lastly, we necessarily chose a single source of steady-state aircraft noise, and controlled for the potential effects of fatigue from extended noise exposure. Future work should investigate how variable noise and other types of noise sources may differentially impact cognitive processing and decision-making of single- and multitask demands, and the effects of prolonged exposures that often occur in operational environments [4].

5. CONCLUSIONS

This study provides valuable insights into the effects of aircraft noise on cognitive processes involved in multitasking contexts. We found that noise exposure led to shifts in visual and auditory task performance, especially in multitasking contexts. Additionally, noise sensitivity influenced peoples' cognitive efficiency and emotional impact of noise exposure. Overall, these results underscore the importance of considering individual noise sensitivity when assessing the impact of noise on cognitive and emotional functioning, especially in environments where multitasking is prevalent, such as in aviation or other high-stress operational settings. Future research should build on these findings to further explore how different noise types and individual differences in sensitivity influence cognitive performance across various task demands.

6. DECLARATIONS

6.1 Disclaimer

Distribution A. Approved for public release; distribution unlimited. AFRL-2024-6367; Cleared 15 Nov 2024. This research was supported in part by an appointment to the DOD Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. DOE and the DOD. ORISE is managed by ORAU under DOE contract number DE-SC0014664. The views expressed are those of the author and do not necessarily reflect the official policy or position of the AF, DOD, U.S. government, or ORISE.

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