

A Cross-Platform Study of Human Situational Awareness for Heterogeneous Low Altitude Autonomy

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Abstract—Human-autonomy teaming in the Low Altitude Economy (LAE) requires operators to manage both ground and aerial autonomous agents under time pressure, spatial uncertainty, and cognitive load. This study investigates how visual and haptic feedback affect operator situational awareness (SA) in simulated collision avoidance tasks involving cars and drones. A high-fidelity virtual environment was built using Unreal Engine 4 and AirSim, with haptic cues delivered through a wearable bHaptics vest. Twenty-two participants performed within-subject trials across visual-only and visual-haptic conditions. Results showed that haptic feedback significantly enhanced SA, particularly in dimensions related to information acquisition and spare mental capacity. Improvements were more consistent in car-based tasks, while drone scenarios exhibited greater inter-individual variability. These findings demonstrate the potential of multimodal interfaces to support cognitive performance and reduce platform-related disparities in operator SA. This work provides empirical evidence for designing adaptive, perception-aware interfaces in safety-critical human-autonomy teaming systems.

I. INTRODUCTION

Situational awareness (SA) plays a critical role in human-autonomy teaming, directly affecting risk perception and task performance in time-sensitive environments [1], [2]. As heterogeneous systems integrate both ground and aerial autonomous agents, SA demands diverge across platforms due to differences in spatial layout, mobility constraints, and perceptual complexity [3], [4]. Ground-based operations often involve dense, obstacle-rich environments that require continuous visual monitoring and rapid reaction. Aerial tasks, by contrast, demand vertical tracking, broader field-of-view integration, and anticipation of high-speed threats. These differences impose platform-specific cognitive loads that challenge operator performance, especially in the context of the Low Altitude Economy (LAE) [5], [6].

While visual displays remain dominant in interface design, haptic feedback has emerged as a complementary channel that may help reduce visual workload and enhance perception under stress [7], [8]. However, its cross-platform effectiveness in safety-critical, dynamic tasks remains under-explored. This study investigates how haptic feedback influences SA in simulated car and drone collision detection tasks. A high-fidelity environment was developed using Unreal

Engine 4 (UE4) and AirSim, enabling controlled comparison of visual-only and visual-haptic interfaces. Twenty-two participants completed within-subject trials, and SA was measured using the Situation Awareness Rating Techniques (SART) scale.

The key contributions of this work are:

- Developed a UE4–AirSim platform simulating car and drone threats under multimodal feedback.
- Conducted a within-subject study comparing SA under visual-only and visual-haptic interfaces.
- Identified interface- and platform-specific effects on SA with statistical evidence.

II. RELATED WORK

Understanding operator performance under different feedback modalities in autonomous control tasks requires grounding in prior research on SA and human-machine interface design [7], [8]. SA is central to risk perception in dynamic, time-critical environments and is essential for effective supervision of autonomous systems [9], [10]. Although wearable and multimodal interfaces have shown promise for enhancing SA, few studies offer systematic comparisons of interface modalities in safety-critical settings [11], [12].

A. SA in Autonomous Systems

SA is most commonly defined by Endsley’s three-level model: perception, comprehension, and projection [13], [14]. In autonomous contexts, high SA supports timely responses to emerging threats and uncertainties [15]. However, real-time assessment techniques often disrupt task flow, limiting their applicability in fast-paced control environments [8], [16]. To overcome this, our study adopts the SART scale—a validated, post-task self-assessment that captures SA across nine cognitive dimensions without interfering with performance.

While SA has been widely explored in aviation, driving, and defense applications, research on SA in heterogeneous autonomous platforms—especially comparing ground and aerial agents—remains limited. Moreover, the effects of interface design, particularly feedback modality, on SA metrics are rarely addressed in cross-platform contexts [5], [16].

B. Integrating Haptic Feedback into Human-Autonomy Interfaces

Recent survey work on explainable interfaces for human-autonomy teaming highlights the importance of designing feedback systems aligned with human cognitive

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processes, including perception, comprehension, and trust development [17]. While most of these efforts focus on high-level system transparency and symbolic explanation strategies, there remains a need for empirical studies that investigate low-level perceptual interfaces and their role in enhancing SA under operational task constraints. Haptic feedback offers a complementary channel, reducing visual burden and promoting more resilient awareness under stress [18], [19]. Wearable devices such as the bHaptics TactSuit have been applied in both aerial and ground domains to convey spatial or directional cues.

Prior studies suggest that haptic cues can improve reaction time, user engagement, and workload distribution in virtual reality, teleoperation, and simulation training [20], [21]. However, most existing work emphasizes usability outcomes over structured evaluations of SA dimensions, with limited attention to how specific feedback types influence core cognitive dimensions of awareness [16]. Our work contributes to this direction by systematically evaluating the effects of spatially encoded haptic feedback on operator awareness and task performance across heterogeneous autonomous platforms.

C. Research Gap and Contribution

Despite advances in multimodal interface design, few studies directly compare visual-only and visual-haptic feedback across heterogeneous autonomous systems. Quantitative assessments linking feedback modality to SA structure are particularly scarce [15]. To address this, we present a controlled, cross-platform study examining subjective SA and task performance in simulated collision detection tasks involving drones and ground vehicles. By isolating the effects of interface modality and platform type, our work extends existing literature and informs the design of more effective human-autonomy teaming strategies.

III. EXPERIMENT DESIGN

A. Setup and Procedure

This study evaluated the effects of haptic feedback on operator SA during high-risk autonomous control tasks. As illustrated in Fig. 1, participants completed two interface conditions: visual-only and visual-haptic. Each condition included four simulation trials—two ground-based (car) and two aerial (drone) scenarios—with one to three adversarial agents introduced randomly to simulate collision threats. The behavior and direction of these agents followed predefined randomized patterns.

The simulation environment was built using UE4 and AirSim and displayed across a three-screen immersive setup. In the visual-haptic condition, participants wore a bHaptics TactSuit X40 vest that conveyed directional vibration signals. For ground tasks, only back-side actuators were activated to indicate horizontal threats; for aerial tasks, front-side actuators encoded vertical directions. Fig. 2 illustrates the haptic feedback mapping, where colored dots represent threat directions—each triggering localized vibration on the corresponding area of the vest.

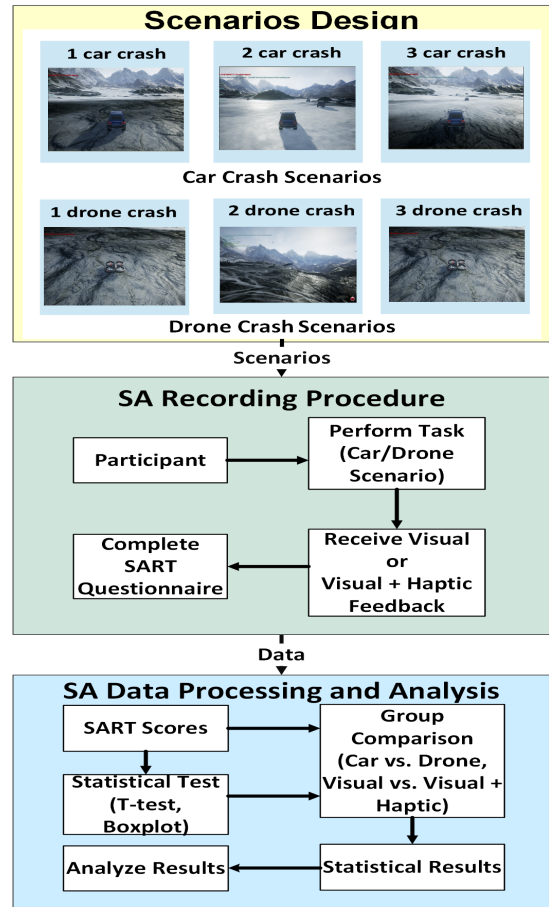


Fig. 1. Overview of Experimental Design, Task Procedure, and Data Analysis Workflow .

After each trial, participants completed the SART questionnaire to assess SA across nine cognitive dimensions:

- Demand: instability, complexity, variability of the situation.
- Supply: arousal, concentration, spare mental capacity.
- Understanding: information quantity, familiarity, and division of attention.

Responses were recorded on a 1–10 Likert scale. Post-task evaluation was used to prevent interference with task performance. The overall workflow—including scenario logic, interface conditions, and evaluation steps—is outlined in Fig. 1.

SART scores were analyzed using paired t-tests across four comparisons: (1) haptic vs. non-haptic in car tasks, (2) haptic vs. visual-only in drone tasks, (3) car vs. drone without haptics, and (4) car vs. drone with haptics. Given the exploratory nature of the study, no correction for multiple comparisons was applied.

B. Participants

A total of 22 participants, aged 21–32, were recruited. Ten were over 26 years old; the remaining twelve were aged 21–26. Nineteen participants were male and three were female, reflecting the demographics of the volunteer pool.

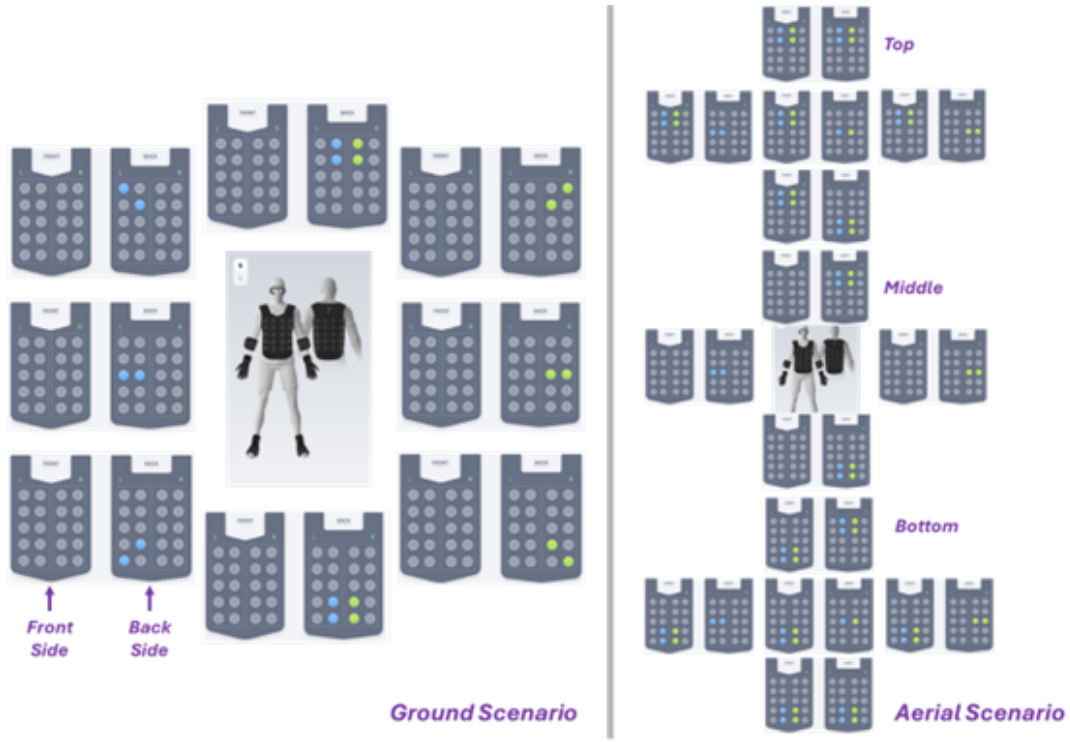


Fig. 2. Layout of tactile cues via haptic vest under visual-haptic condition.

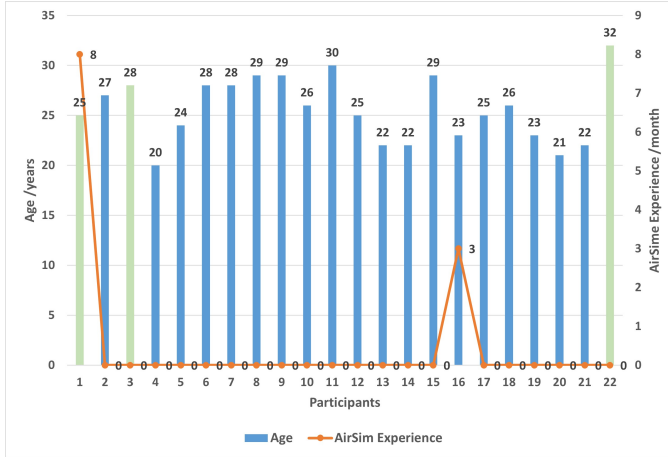


Fig. 3. The detailed information about participants.

and the technical nature of the task. As shown in Fig. 3, participants 1, 3, and 22 are highlighted in distinct colors to indicate female participants.

Only two participants reported prior experience with the AirSim platform, each with less than one year of exposure, minimizing familiarity bias. All participants provided written informed consent. The study was approved by the Cranfield University ethics committee (Ref No. CURES/24590/2025).

IV. RESULTS AND DISCUSSION

A. SA Distribution Across Conditions

Fig. 4 and Fig. 5 show the distribution of SART scores across four task conditions: car and drone scenarios under

visual-only (P1) and visual-haptic (P2) interfaces. Median scores in P2 were generally higher across most dimensions, while minimum values remained comparable between conditions. However, Complexity and Division of Attention showed slightly higher medians in the visual-only condition. These patterns reflect localized task segments with low haptic cue relevance or a possible floor effect in less demanding moments.

As shown in Fig. 4, median SART scores under the visual-haptic condition (P2) exceeded those under visual-only (P1) across most dimensions, except for Complexity and Division, where P1 yielded slightly higher values. Maximum scores of 10 were observed across all dimensions in P2, while only Complexity, Concentration, Information Quantity, and Familiarity reached this level in P1. Minimum values showed negligible differences between conditions. This reflects a floor effect or the presence of low-demand segments within the task, where haptic feedback had limited additional impact. These results suggest that P1 imposes greater SA demands, particularly in the demand, supply, and understanding dimensions. Moreover, a higher number of outliers in P1 indicates greater variability in individual responses. Haptic cues in car scenarios further contributed to enhanced SA levels.

Across participants, visual-haptic conditions yielded a greater number of maximum (score=10) ratings in several dimensions. Nevertheless, the higher number of outliers in P1 indicates greater variability in individual responses. These effects appeared more prominent in car tasks than drone tasks, though the overall pattern was consistent across platforms.

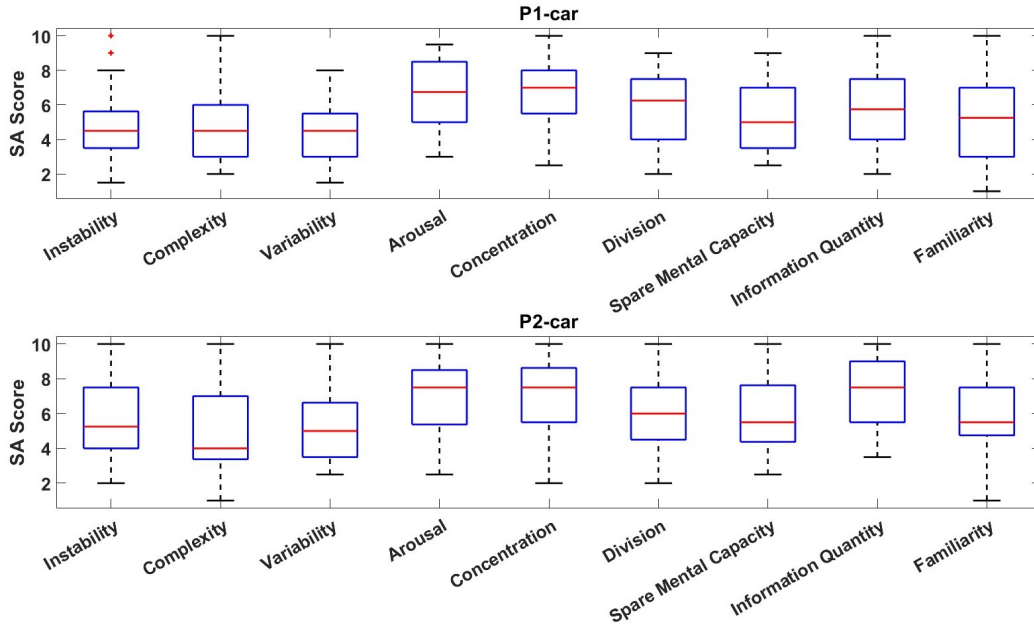


Fig. 4. SA Distribution in Car Scenarios: Boxplot Comparison.

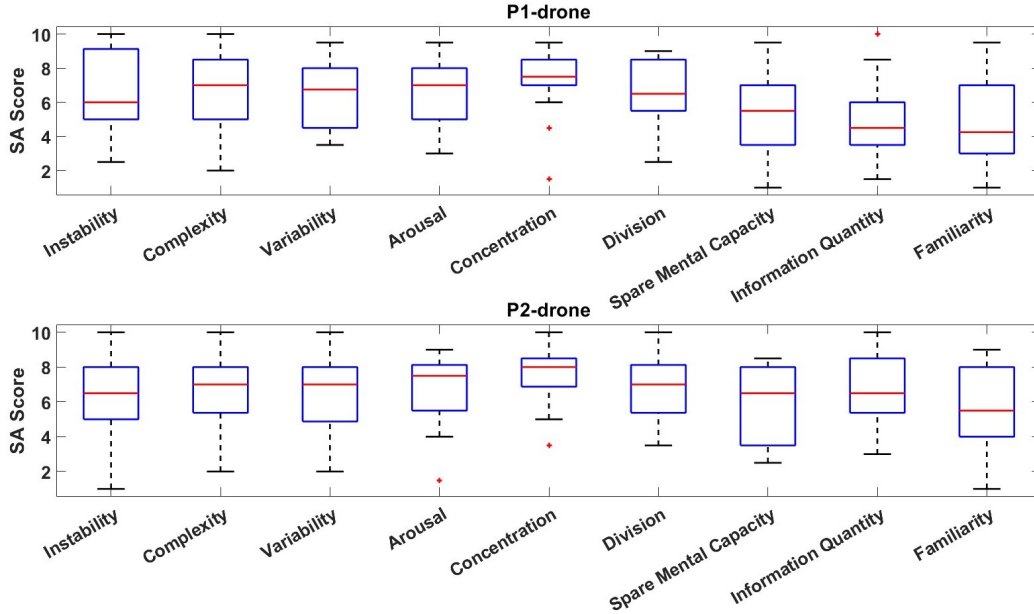


Fig. 5. SA Distribution in Drone Scenarios: Boxplot Comparison.

To facilitate comparison, we computed an Overall SA score based on the standard SART formula [7].

$$\text{Overall SA} = \text{Supply} - \text{Demand} + \text{Understanding} \quad (1)$$

Where,

- represents the complexity, instability, and variability of the situation, which place demands on the operator's attentional resources.
- Supply refers to the attentional resources and mental capacity the individual has available to respond to the

environment.

- Understanding reflects the operator's comprehension and clarity regarding the current situation.

Scores were categorized into three levels (low, medium, high) using tertile cutoffs. As shown in Fig. 6, median SA values in all conditions fell within the medium range, with car scenarios yielding slightly higher medians than drone tasks. Minimum SA scores were lower in drone conditions, while maximum scores were comparable across platforms. Drone scenarios also exhibited a wider score range (up to 15.5 points), suggesting greater inter-individual variability

TABLE I
PAIRED T-TEST RESULTS FOR CAR SCENARIO

	H	P-value	SE	T-stat
Instability of Situation	0	0.0824	0.5330	-1.8337
Complexity of Situation	0	0.2428	0.5605	-1.2035
Variability of Situation	0	0.0861	0.5026	-1.8051
Arousal	0	0.4529	0.5470	-0.7655
Concentration of Attention	0	0.4382	0.3529	-0.7911
Division of Attention	0	0.6146	0.3638	-0.5115
Spare Mental Capacity	1	0.0423	0.4718	-2.1693
Information Quantity	1	0.0145	0.4866	-2.6773
Familiarity with Situation	0	0.4306	0.4915	-0.8045

in attentional or cognitive demands.

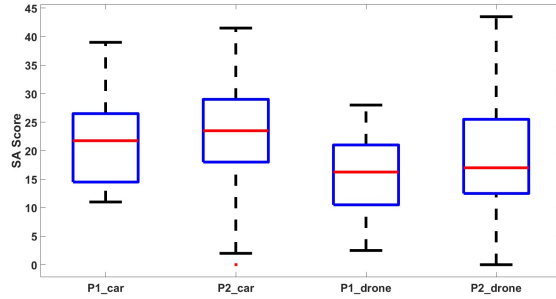


Fig. 6. Boxplot of Overall SA Distribution.

B. Condition Effects: Visual vs. Visual-Haptic

In car-based tasks, visual-haptic feedback was associated with higher SART ratings in several dimensions. Statistically significant improvements were observed in Information Quantity ($T = -2.6773$, $p = 0.0145$) and Spare Mental Capacity ($T = -2.1693$, $p = 0.0423$), while Instability and Variability showed non-significant but suggestive trends ($p = 0.08$), as reported in Table 1. These results indicate that tactile cues supported more efficient allocation of attentional resources during ground-level threat monitoring.

In drone-based tasks, only Information Quantity increased significantly under haptic feedback ($T = -3.7582$, $p = 0.0012$), as reported in Table 2. Other dimensions, including Spare Mental Capacity ($p = 0.1135$), did not show significant differences. This pattern suggest that while haptic input can aid perceptual encoding in aerial scenarios, its contribution to workload management is less pronounced in this context.

C. Platform Effects: Car vs. Drone

When comparing platforms under the visual-only condition, car tasks received higher ratings in Instability ($p = 0.0051$), Complexity ($p = 0.0001$), and Variability ($p = 0.0001$), as reported in Table 3. These findings contrast with initial assumptions that drone tasks would be perceived as more cognitively demanding. One possible explanation is that the ground scenarios featured denser horizontal interactions or more recognizable threat patterns, which have elicited sharper subjective distinctions.

TABLE II
PAIRED T-TEST RESULTS FOR DRONE SCENARIO

	H	P-value	SE	T-stat
Instability of Situation	0	0.7960	0.3637	0.2621
Complexity of Situation	0	0.7596	0.4499	-0.3102
Variability of Situation	0	0.8828	0.4674	-0.1493
Arousal	0	0.3882	0.4747	-0.8821
Concentration of Attention	0	0.6336	0.4324	-0.4841
Division of Attention	0	0.3595	0.3224	-0.9379
Spare Mental Capacity	0	0.1135	0.3513	-1.6553
Information Quantity	1	0.0012	0.4580	-3.7582
Familiarity with Situation	0	0.1323	0.4892	-1.5693

TABLE III
PAIRED T-TEST RESULTS FOR CAR AND DRONE SCENARIOS WITHOUT HAPTIC VEST

	H	P-value	SE	T-stat
Instability of Situation	1	0.0051	0.5473	-3.1451
Complexity of Situation	1	0.0001	0.4474	-4.7245
Variability of Situation	1	0.0001	0.4100	-4.7122
Arousal	0	0.7841	0.4915	-0.2775
Concentration of Attention	0	0.0966	0.3397	-1.7394
Division of Attention	0	0.1317	0.4346	-1.5687
Spare Mental Capacity	0	0.8547	0.6128	-0.1855
Information Quantity	0	0.0995	0.5935	1.7232
Familiarity with Situation	0	0.5013	0.4983	0.6842

TABLE IV
PAIRED T-TEST RESULTS FOR CAR AND DRONE SCENARIOS WITH HAPTIC VEST

	H	P-value	SE	T-stat
Instability of Situation	0	0.1192	0.4529	-1.6316
Complexity of Situation	1	0.0003	0.3676	-4.3033
Variability of Situation	1	0.0288	0.4543	-2.3554
Arousal	0	0.8905	0.3335	0.1395
Concentration of Attention	0	0.2705	0.3284	-1.1334
Division of Attention	0	0.0927	0.3821	-1.7655
Spare Mental Capacity	0	0.4385	0.4119	0.7906
Information Quantity	0	0.2306	0.4703	1.2366
Familiarity with Situation	0	0.6878	0.3424	0.4077

Under the visual-haptic condition, platform-related differences were attenuated. Only Complexity ($p = 0.0003$) and Variability ($p = 0.0208$) remained statistically significant, while other dimensions showed no marked differences, as reported in Table 4. This reduction reflect a normalizing effect of haptic feedback, possibly by offering an auxiliary sensory channel to support spatial awareness across mobility types.

D. Interpretation and Reflections

Across all conditions, Information Quantity consistently benefitted from haptic augmentation, suggesting a potential role for tactile feedback in enhancing perceptual SA. In contrast, improvements in Spare Mental Capacity appeared limited to ground scenarios, highlighting a possible interaction between feedback modality and task environment.

Participant interviews offered further context. Several noted that car scenarios felt simpler and more predictable,

with clearer directional cues and fewer active threats. This have made tactile input easier to integrate. Drone scenarios, in contrast, were described as more chaotic or cognitively demanding, possibly reducing the relative impact of added haptic cues. While these impressions are anecdotal, they align with observed inter-individual variability in the drone condition (see Fig. 6).

These findings provide preliminary support for incorporating multimodal interfaces into human-autonomy teaming systems, particularly when tasks involve spatial complexity or high perceptual load. However, caution is warranted in generalizing these results. Scenario familiarity, task pacing, and feedback mapping likely modulate the observed effects. Furthermore, the simplified threat-reporting paradigm limits ecological validity.

Future work should explore more representative operational contexts, including dynamic goal prioritization, multi-agent control, and continuous decision-making under uncertainty. Incorporating more immersive or adaptive haptic systems also shed light on how tactile cues can be best deployed in real-world low-altitude operations.

V. CONCLUSIONS

This study demonstrated that integrating haptic feedback into visual interfaces can effectively enhance operator SA in autonomous control tasks. Statistically significant improvements were observed in both ground and aerial scenarios, particularly in dimensions related to information acquisition and cognitive resource management. These results confirm the utility of multimodal feedback in improving safety and cognitive performance in human-autonomy teaming contexts.

Future research will extend this work by incorporating EEG-based modeling of SA to enable real-time assessment, and by evaluating haptic-only or dynamically adaptive interfaces. Additional studies on spatial mapping and feedback placement may further optimize tactile cue integration for complex, multi-agent operational environments.

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