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The State of the Pupil: Moving Toward Enabling Real-World Use of Pupillometry- Based Estimation of Human States

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14. ABSTRACT In the future Army battlespace, human and intelligent agents are expected to be able to team together to accomplish mission-critical goals. To enable adaptable technology-supported teaming in real-world missions, sensors must be able to reliably and robustly estimate human states while embedded in complex, dynamic environments. We propose that eye tracking-based pupil-size monitoring can be used as a cost-effective, reliable, robust data source to estimate Soldier states for a variety of Army relevant use cases. This report details potential use cases and the gaps in the science and knowledge that remain as obstacles to enabling intelligent agents to exploit pupil size data for human-agent teaming.					
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1. Introduction

In the future Army battlespace, human and intelligent agents are expected to be able to team together to accomplish mission-critical goals. Introducing intelligent agents into human teams allows for the possibility of mixed teams to not only cover gaps in teammates' capabilities but to generate new capabilities leading to adversarial overmatch. In these teams, humans will rely on sensors of the external environment and internal human physiology as well as interpretation of those sensors by intelligent agents. For example, Soldiers in the Next-Generation Combat Vehicle will be required to operate a number of technological devices while navigating environments and detecting threats. Given human attentional limits in a stressful context, a human may show trade-offs between navigation and threat detection. Shifting focus to navigation at the expense of threat detection may lead to a reduction of situational awareness and overall degradation in mission performance. However, intelligent agents may help to maintain situational awareness by optimizing when attentional focus should be directed toward navigation or threat detection, or by "picking up the slack". Yet, human individuals and teams vary widely in their capabilities both temporarily due to situational demands and at baseline due to trait differences. As such, intelligent agents must have adaptable behaviors to conform to mission goals and current human capabilities. This report will detail a research line that will enable intelligent agent's adaptive capabilities.

2. Why the Army Should Be Interested in Pupil-Based Eye Tracking Technology and Research

To enable adaptable technology-supported teaming in real-world missions, sensors must be able to reliably and robustly estimate human states while embedded in complex, dynamic environments. Ideally, sensors could measure brain activity as done using functional magnetic resonance imaging or electroencephalography; however, the hardware used in these methods is not currently suitable for field deployment. An alternative method is to measure peripheral physiology using technology such as body-worn sensors or eye trackers. While the organs monitored by these technologies (e.g., eye, heart) are primarily modulated by reflexive, noncognitive processes and autonomic functions (e.g., heart rate), recent research has shown that they are also indirectly influenced by higher-level cognitive processes. A major challenge for scientists has been parsing out specific aspects of peripheral physiological signals and linking them to human states while also accounting for noncognitive influences on the same signals. Once decoded, however, human state information can be used by intelligent agents in a teaming context to enable adaptive behaviors that optimize individual and team performance.

In this technical report we focus on the current state of research aiming to estimate human states in real-world contexts using patterns of pupillary dilation and constriction collected via eye-tracking technologies. We focus on eye tracking because this technology will likely be field deployable within the next 5 years and in some instances is already being incorporated into Soldier wearables, such as the Integrated Visual Augmented System. We believe that using the pupil as an indirect measure of the brain via eye-tracking technology will enable robust, reliable, and cost-effective measurements of human states. In turn, human-state estimation can be used to inform adaptable intelligent agents and improve teaming processes with humans.

3. Potential Real-World Applications of Basic Research Findings

Pupil size has been used for decades as a window into the brain,¹ given its status as the only internal organ that has visible changes from outside the body and is directly influenced by the brain. Pupil features have been found to reflect a variety of cognitive processes that may be of interest to Soldier operations with respect to interpretation by an intelligent agent, including mental workload,^{1,2} vigilance/fatigue,^{3,4} novelty,⁵ target detection,⁶⁻⁸ and decision making.^{9,10} It is important to note that physiological signal- and pupil-based human-state estimates are objective measurements that do not require subjectively querying the Soldier. This is highly advantageous compared to the potential obtrusiveness of surveys or probes and in some cases may be the only means to estimate the status of a Soldier when direct subjective reporting is unavailable due to 1) inability to report due to injury, 2) limited understanding of complex states (e.g., language is not sufficient to describe the state), 3) unwillingness to directly report, and/or 4) when reporting interferes with mission-critical behaviors.

Measuring mental workload via pupil size was first popularized by Kahneman et al. after showing results from a task in which participants needed to keep in memory an increasing amount of information.¹ In line with this paradigm, subsequent research has found that pupil size both transiently increases in relation to an acute increase in memory load² and experiences a sustained increase in pupil size in response to prolonged difficulty.¹¹ These results suggest that pupil responses can track arousal levels of the brain. Tracking arousal levels has potential to enable several applications to human-autonomy teaming. For example, in the Next-Generation Combat Vehicle, Soldiers need to simultaneously operate machinery, detect targets, communicate with other team members, and so forth. These scenarios may lead to cognitive overload, which may be detectable by intelligent agents via cognitive load-linked pupil features. Accordingly, the intelligent agent

can attempt to reduce cognitive load and improve situational awareness by restricting information, reprioritizing tasks, alerting teammates, or delivering neurofeedback¹² to assist the Soldier. An objective measure of cognitive load could further be useful as an outcome measure to be minimized in research studies that evaluate human factors-based system design, or in closed-loop, on-the-job learner systems to identify when a learner has reached a desired level of task expertise. Relatedly, vigilance and fatigue states, as estimated by pupil features, may be used to augment situational awareness.

In addition to cognitive load, transient pupil changes are elicited in response to the presentation of novel,⁵ surprising,⁵ and target⁶ stimuli, indicating that pupil size reflects rapid changes in the recruitment of attentional resources. Current efforts such as the Tactical Awareness via Collective Knowledge (TACK) are attempting to enhance situational awareness by using eye moments to enable automatic detection of individual human-level points of interest as well as estimating team-level states from group-level eye movement dynamics. This capability may be used to automatically annotate a shared virtual operational environment to create increased situational awareness for the team or signal when an intelligent agent should assist the team. Conversely, such a map also indicates locations that are not considered a point of interest so that resources are not wasted exploring that area. Alternatively, the unattended location may contain a missed threat and represent a human “blind spot”, whereby an intelligent agent could adaptively fill this gap for the human teammate.

Recent pupil-focused research has found that pupil size shows a robust relationship with decision-making processes.^{9,10,13-15} Specifically, the pupil has been found to dilate until a decision has been made and subsequently begins to constrict, tracking the temporal dimension of decision formation with high fidelity even on the single trial level.¹³ Einhauser et al. reported that the decision process could be tracked by pupil dilations, even without the participant making a behavioral response.¹⁴ Being able to objectively monitor when a decision process is engaged, and when it has completed, may be useful for an intelligent agent to appropriately deliver “just-in-time” information.¹⁶ For example, information delivered while a previous decision is being made can lead to increased errors, while delayed information can lead to inefficient task completion.

4. Other Potential Uses of Eye Tracking

While this report focuses on use cases for eye tracking technology with respect to the cognitive pupil response, eye-tracking technology also generates other data types useful for a number of applications. Researchers in the clinical domain have found that the pupillary light reflex (PLR) indicates deviations for populations with psychological disorders including Alzheimer's, Parkinson's, autism, and traumatic brain injury. Some research has indicated that the pupil response also exhibits alterations after exposure to alcohol, MDMA (3,4-methylenedioxy methamphetamine), cannabis, nerve agents, pesticides (e.g., organophosphates and botulinum toxins), and infections (for review see Hall and Chilcott¹⁷). In particular, the Army may be interested in using the PLR for diagnosing nerve-agent exposure and traumatic brain injury.

There exists a large body of literature that uses eye movements as a window into cognitive processes, including features such as fixation durations,¹⁸ blink rate,¹⁹ saccades,²⁰ and eye movement patterns.²¹ These features have been used to investigate a number of cognitive processes, including expertise,²² memory,²¹ target detection,²³ fatigue,²⁴ and cognitive workload¹⁹ among others.

While pupil size is a promising avenue to achieve remote human state estimation that enables efficient human-autonomy teaming, the aforementioned body of literature has, in general, been collected in carefully controlled lab environments that do not represent real-world contexts. In contrast to lab environments, real-world contexts introduce substantial noncognitive influences on the pupil.

5. Obstacles to Using the Pupil in Real-World Contexts

To illustrate the substantial influence of noncognitive influences on the pupil, take the example of a luminance change. Look into a mirror and notice how your pupils change after closing them for a brief period of time and opening them again. Upon opening your eyes, you should notice that your pupils will rapidly constrict. Researchers have characterized this effect as the pupillary light reflex¹⁷ (PLR), which occurs when the eye is presented with a substantially brighter light stimulus than what was previously being fixated (Fig. 1).

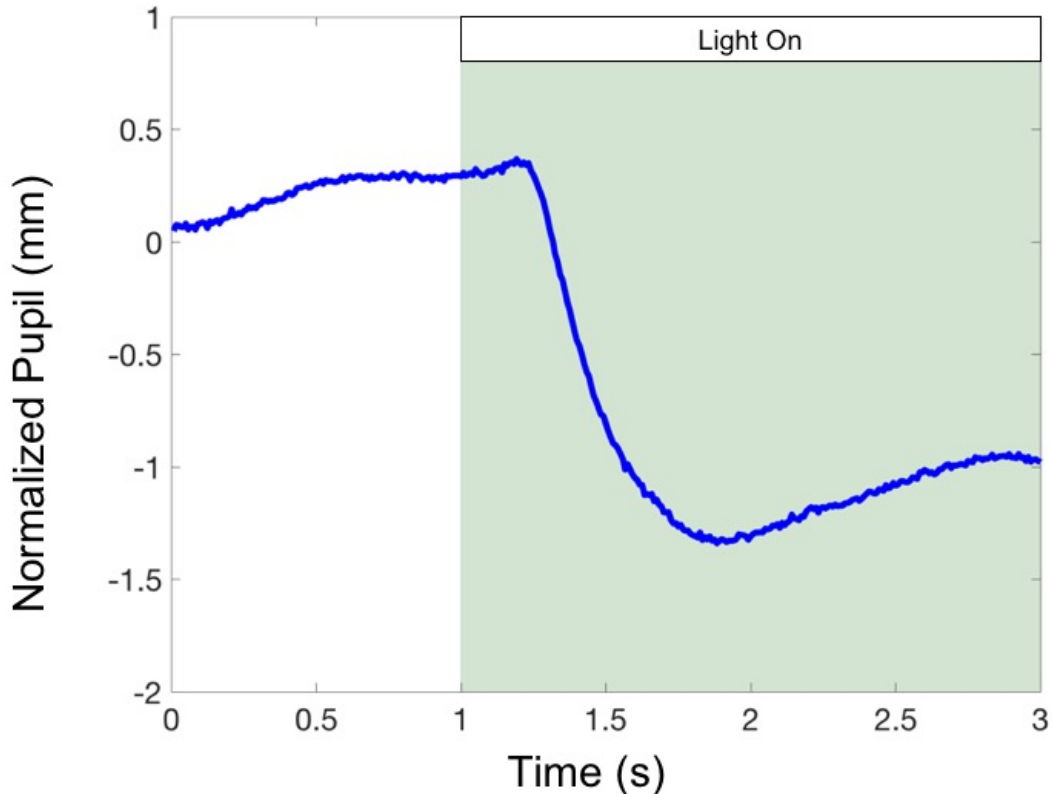


Fig. 1 After being in dark for a prolonged period of time (e.g., 20 min), the pupil dilates (time <0), and when presented with a light stimulus (time 1), rapidly constricts. Based on figures from Hall and Chilcott.¹⁷

To understand the nature of the cognitive influence on the pupil, researchers typically account for noncognitive influences by controlling them.^{25,26} As an example, in the laboratory equiluminant stimuli can be used to avoid any changes in the pupil due to the PLR, thus allowing for attribution of cognitive influences on the pupil. However, equiluminant stimuli have limitations that make this strategy implausible when collecting data in real-world contexts or when using naturalistic stimuli. Furthermore, in real-world contexts, luminance can be highly variable from moment-to-moment, changing from eye movement to eye movement. For example, depending on task goals, participants can change their eye fixation location on average 2–4 times a second.^{27,28} The pupil does not instantaneously change in response to light, however, but exhibits a delayed response ranging from 0.1 to 0.3 s in response to noncognitive events.²⁵ This time-lagged mapping from stimulus to pupil response remains a great obstacle for attributing cognitive influences to pupil size changes. Current research lacks an understanding of the temporal dynamics of the pupil in response to visual stimulation that is complex and continually changing. To further illustrate the scope of the problem, known noncognitive influences on the pupil response are detailed in the next section.

6. A Multitude of Factors Drive the Pupil Response

Much of the understanding gained about underlying processes and factors that drive the pupil response has been conducted in the field of ophthalmology. Research has focused on clinical applications to diagnose abnormalities in the brain as indicated by deviations from a normal PLR.¹⁷ Specifically, researchers have developed a methodology called pupil campimetry²⁹ whereby stimuli are presented in multiple locations in the participant's field of view to probe the visual field. This methodology relies on the assumption that given processing of a light stimulus input by the visual system, the output should be a change in pupil size in response to the stimulus. Using this methodology, researchers have been able to characterize the various factors, and underlying neural circuitry, that give rise to modulations of the pupil. A typical visual presentation within this experimental protocol is shown in Fig. 2.

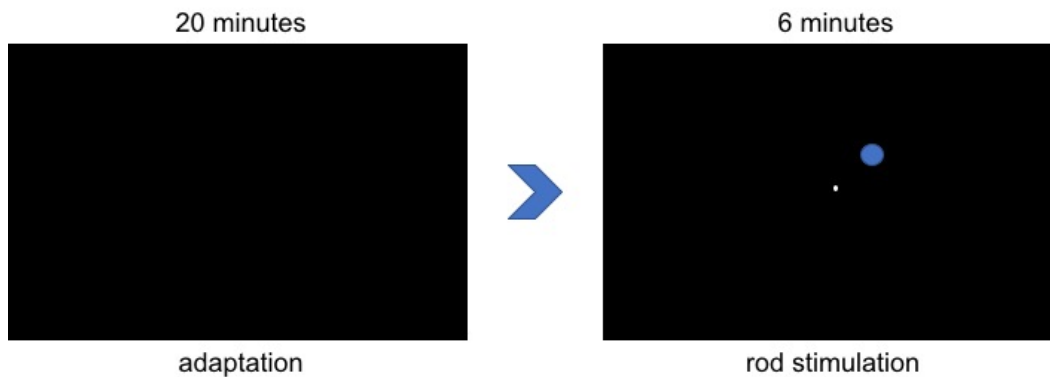


Fig. 2 Typical pupil campimetry paradigm to understand the mapping of stimulus influences on pupil size

Here participants go through an adaptation period before being presented with colored stimuli at a given size and eccentricity to fixation. This type of protocol is designed to target the various cell populations (i.e., rods, cones, and intrinsically photosensitive retinal ganglion cells [ipRGC]) known to be involved in the circuit that gives rise to the PLR.³⁰ For example, research has found that prolonged exposure without lighting for approximately 20 min (i.e., dark adaptation) deactivates cones and ipRGC cells such that the PLR is mainly mediated by rods.³⁰ Conversely, daylight adaptation has been found to deactivate rods, while near-dark lighting (i.e., mesopic) conditions indicate a mixture of cell influences.¹⁷ Additionally, this paradigm has provided evidence for distinct cell populations and circuitry pathways recruited in response to stimulus properties such as adapting luminance,¹⁷ monocular presentation,³¹ color spectrum,³² eccentricity,³³ size,³² depth³⁴ and eye movements³⁵ (e.g., blinks and saccades); traits such as age³¹; and mental health disorders. All of these factors can influence the PLR.

While this paradigm has been useful in helping researchers understand the mechanisms underlying the PLR, further understanding of the temporal dynamics of the transformation from circuitry to pupil response has been limited. This knowledge is necessary when trying to understand the influence of complex and changing stimuli (i.e., those found in naturalistic contexts) where multiple pupillary-influencing stimulus properties are simultaneously and rapidly changing. To illustrate this point, compare a pupillary constriction (Fig. 3a) in response to a bright stimulus change with a pupillary dilation in response to a dark stimulus change (Fig. 3b). These figures illustrate a much slower dilation rate when compared with the faster constriction rate. This is likely due to the difference in characteristics of the sympathetic and parasympathetic systems that, respectively, control the dilation and constriction muscles.¹⁷ The temporal complexity of these two interacting systems is revealed when stimuli are rapidly presented (e.g., every 0.03 s). In Fig. 3c the pupil exhibits a robust constriction in response to the briefly presented bright stimulus. By comparison, the pupil exhibits no observable dilation in response to the briefly presented dark stimulus (Fig. 3d). However, upon offset of the dark stimulus (thereby leading to a bright stimulus change back to the baseline background color), a constriction can be observed. This constriction is of a lesser magnitude than the constriction to the single pulse of light (Fig. 3c). One explanation for the reduced constriction is that the interaction between the delayed activation of the dilation muscle and faster activation of the constriction muscle leads to an overall reduced constriction.³⁶

In sum, the difficulty in understanding the temporal dynamics of the pupillary system is due to the 1) slower pupil dilations when compared with constrictions, 2) a unitary output signal that encodes multiple and overlapping inputs, and 3) the unknown mapping from a complex image space (with varied patterns of brightness over 2D space) to the PLR.

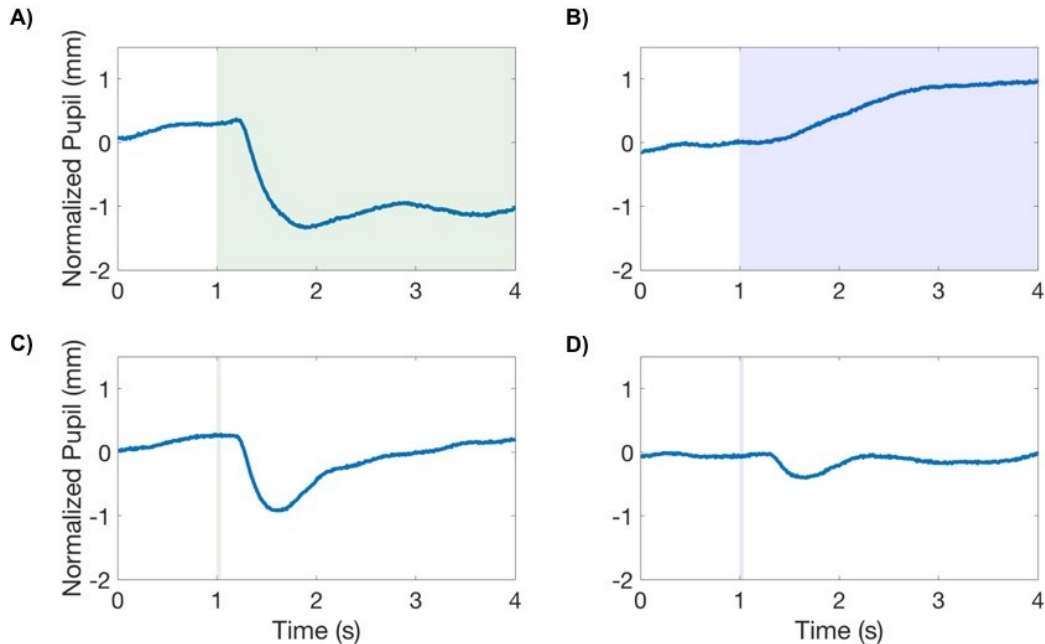


Fig. 3 Pupil responses to gray scale stimuli for 3 s (A and B) and 0.3 s (C and D). (A, C) A lighter stimulus (compared with previous stimulus) leads to a rapid constriction of the pupil. (B) A darker stimulus leads to a slower dilation of the pupil. (D) A briefly presented dark stimulus, and subsequent brighter stimulus at the dark stimulus offset, leads to a reduced constriction.

7. What We Have Learned and Need to Learn About Pupil Size Changes

Researchers have forged a number of ways to predict and account for the influence of noncognitive influences on pupil size. These modeling efforts have given rise to a number of insights about influences on the pupil that do not reflect cognitive processes per se.

Most recently, the modeling conducted by Watson and Yellot is exemplary of synthesizing previous research and data.³¹ In this seminal study, previous model predictions of pupil size in response to stimuli were unified to create a predictive formula of pupil size. Findings from this research indicate that pupil size changes are influenced by traits such as participant age and experimental-design properties such as stimulus luminance and size, and whether the study used monocular or binocular presentation of stimuli (for more information see Watson and Yellot³¹). Other studies have also found trait-like influences on the pupil, such as psychopathologies.^{17,37}

While the aforementioned formula is useful in predicting normalized stable-state pupil changes to light, these modeling efforts were conducted in response to

prolonged stimulus presentations after light adaptation (i.e., > 10 s) which does not necessarily translate to rapid and transient stimulus changes.

Recent research has attempted to account for changes in pupil size in response to more rapid events. In this approach, researchers have attempted to model the output signals of the neural circuitry onto the pupil response.^{35,36,38} In these methods, an event (e.g., blink, saccade, surprising stimulus) is assumed to induce an underlying canonical response that can then be mapped onto the pupil response. To estimate the canonical response waveform, either the data are fit by using a model around a specified event to estimate the waveform⁴ or by assuming a particular response shape and convolving the waveform with a specified event to then predict the data.^{35,39,40} This research line has adopted methods and theories from modeling hemodynamic blood flow as used in functional magnetic resonance imaging research. Current applications of these techniques assume that 1) there exists a canonical response waveform and 2) the waveforms sum linearly. These assumptions have allowed for increasingly better model fits to the data, enabling a deeper understanding of the mechanisms and factors that influence pupil size.

While these modeling efforts are promising as a transition to modeling pupil size in real-world contexts, the data used to evaluate these models have come from single-session experiments. Single-session pupil data sets have limited data for understanding individual variation. For example, other research, including our own, indicates a substantial variation in pupil responses across subjects and within the same subject during repeated sampling. It is unclear whether these differences arise from variation in circuit-to-pupil response waveforms, nonlinear summation of underlying systems, and/or influences of states and traits. The following section covers ongoing efforts and routes to address these knowledge gaps.

8. Research Efforts in Addressing Knowledge Gaps to Make Progress on Enabling Real-World Use of Pupillometry

Unlocking real-world applications of pupil dynamics requires a multipronged research approach consisting of applied and basic knowledge-generating thrusts. Applied thrusts can focus on identifying a feature-behavior-cognition space that is agnostic and robust to noncognitive influences. Some progress in this vein has been made by identifying features such as baseline (Cohen Hoffing R, Thurman S, unpublished data), peak response time,¹³ and time-frequency features,¹¹ which may be robustly correlated with cognition across a variety of tasks and contexts.

Basic knowledge thrusts can focus on understanding and parsing the noncognitive temporal dynamics of the pupil in response to varied and rapidly changing stimuli. For example, current efforts in the TACK project are aimed at investigating whether

pupil size can be used to estimate human states within a realistic virtual environment. Specifically, we are currently extending recent modeling approaches^{35,36,38} to model and map the complex space that relates luminance changes at various spatial and temporal frequencies to pupil size. Future efforts will focus on other pupil-influencing properties such as depth, color spectrum, and eye movements. Additionally, other basic research efforts can focus on careful measurement of pupil size in response to multiple pupil-influencing stimulus properties and their temporal interactions. Complementary to this research effort would be not only developing methods and understanding of the mapping from stimulus properties to pupil responses, but also determining what factors differ according to an individual.

Similarly, researchers can make further progress on understanding the dynamics of the underlying neural circuits and neurochemical systems that give rise to cognitive and noncognitive pupil responses.⁴¹ Together, these efforts will offer a multifaceted view of pupillary dynamics, including functional models and underlying mechanisms, to serve as a foundation for further basic and applied research.

9. Conclusion

Eye tracking technologies—specifically, pupil size gathered from this technology—show great promise in being able to estimate human states that can be utilized by intelligent agents to enable efficient teaming with Soldiers. However, there remain obstacles to using pupil size changes to enable state estimation in real-world contexts. Much remains to be learned about the temporal dynamics of pupil size changes in response to pupil-influencing stimulus properties unrelated to cognitive processes. If achieved, pupil size may prove to be an accessible, robust, and cost-effective data source to estimate human states, improve situational awareness for the Soldier, and enable effective human-agent teaming.

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List of Symbols, Abbreviations, and Acronyms

ipRGC	intrinsically photosensitive retinal ganglion cells
PLR	pupillary light reflex
TACK	Tactical Awareness via Collective Knowledge

1 DEFENSE TECHNICAL
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