Developing Eye Movement-based Situation Awareness Measurement in Multi-Module Operation

Tae Ryoun Kim[a], Jonghyun Kim[a*]

[a] Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and
Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea, {bkteddy00,
jonghyun.kim}@kaist.ac.kr
Corresponding author

Abstract: Situation awareness (SA) is a core human factor directly linked to the safety of nuclear power plant (NPP) operation, and its importance is heightened in small modular reactors (SMRs) where a single operator concurrently supervises multiple modules. However, conventional survey-based SA measurement techniques have inherent limitations of intermittency, subjectivity, and disruption of task execution, motivating the establishment of an objective and continuous SA measurement method that is scalable with the number of supervised modules. This paper proposes a gaze-based measurement method to quantitatively evaluate operators' SA in such minimized-crew multi-module SMR operating environments. In this study, the operator's gaze data is decomposed into a within-module organization index, Micro entropy (H_{micro}), and a between-module organization index, Macro entropy (H_{macro}). Both indices are defined as functions of the supervised module count N so that the same algebraic form of the relationship applies at arbitrary N. To validate this framework, 46 operating experiments on the Compact Nuclear Simulator were conducted with participants wearing a commercial head-mounted eye-tracker. The SA score was taken as the sensitivity index A′ from the SACRI (Situation Awareness Control Room Inventory) questionnaire, and the relationship between A′ and the entropy values was quantified through Pearson correlation and linear regression analysis. Both H_{micro} and H_{macro} showed statistically significant negative correlations with A′ and were confirmed as independent predictors without multicollinearity. The regression analysis demonstrated that a one-bit increase in H_{micro} lowers the operator's A′ by approximately 0.43, and a unit increase in the normalized H_{macro} additionally lowers A′ by approximately 0.37 (linear $R^2 = 0.280$). All regression coefficients were consistently negative. Meanwhile, since H_{macro} takes a value of zero by construction in single-module operation, the derived relationship continuously reduces to a single-module form, enabling the proposed framework to cover one-operator/one-module operation through one-operator/multi-module operation within a consistent algebraic form. Accordingly, this paper demonstrates that deterioration in the organization of gaze transitions within and between modules quantitatively lowers the operator's SA level. Furthermore, the derived relationship can serve as a non-intrusive, N-extensible evaluation criterion for continuous SA monitoring in multi-module advanced reactors.

---

1. INTRODUCTION

Situation awareness (SA) reflects an operator's ability to perceive, comprehend, and project the state of a complex system, and is a recognised predictor of human performance in nuclear power plant (NPP) control rooms [1]. A large share of human errors in safety-critical operation has been traced to failures in maintaining SA rather than to defects in subsequent action [1]. Ensuring and verifying operator SA therefore remains a core design and safety-assurance objective for NPP main control rooms, and this concern is heightened by the advent of small modular reactors (SMRs). To contain operating cost while preserving safety, SMR concepts increasingly adopt minimized crew complements in which one operator monitors and controls two or more reactor modules concurrently [2,3]. Under such conditions the operator must distribute attention across several parallel processes presented through consolidated interfaces, and human-factors analyses identify the maintenance of SA as a central challenge of these new operating concepts [4].

Historically, SA in NPP control rooms has been assessed through subjective and query-based instruments such as the Situation Awareness Rating Technique (SART), the Situation Awareness Global Assessment Technique (SAGAT), and — specifically for control rooms — the Situation Awareness Control Room Inventory (SACRI) [5]. SACRI queries operators on the past, present, and future trend of safety-relevant plant parameters and scores their answers within a Signal Detection Theory framework to yield the non-parametric sensitivity index A′ [5]. SACRI provides a performance-grounded scalar but, like all survey instruments, it is intermittent, interrupts the task, and may diverge from the operator's actual situational understanding. These properties motivate the search for objective, continuous, unobtrusive SA indicators that can be obtained during task execution.

Eye tracking has emerged as one of the most promising such approaches because visual scanning and attention allocation are the perceptual-cognitive processes that directly support SA [6]. In an NPP emergency-accident study, Lee et al. reported that operators' SA correlated significantly and negatively with gaze entropy [7], and Miao et al. found analogous associations in a multi-module high-temperature gas-cooled reactor setting [8]. These studies establish that gaze entropy is an informative SA indicator, but they treat the operator's whole-display gaze stream as a single stationary process — an approach that conflates two qualitatively different organisation properties in multi-module operation: how systematic the operator's scanning is *within* each supervised module, and how systematic the *switching between* modules is. A whole-display entropy cannot distinguish them, yet either can deteriorate independently.

The present study addresses this gap by formulating a gaze-based, N-extrapolatable quantification of multi-module SA. The operator's scan is decomposed into two non-overlapping organisation indices: a Micro (within-module) entropy $Hmicro(N)$ that captures the systematicity of scanning inside each supervised module, and a Macro (between-module) entropy $Hmacro(N)$ that captures the systematicity of switching across modules. Both are written as explicit functions of the supervised module count N so that the same algebraic A′ equation form applies at $N = 1$, $N = 2$, and $N \geq 3$. The decomposition is applied to 46 Compact Nuclear Simulator recordings and A′ is modelled by linear, fractional-logistic and beta specifications. The result is intended to provide an objective, N-scalable basis for continuous SA estimation directly from the gaze stream in minimized-crew, multi-module operating concepts. The remainder of the paper develops the quantification method (Section 2), describes the experiment (Section 3), reports the correlation and regression results (Section 4), and concludes with the discussion (Section 5).

2. GAZE-BASED SITUATION AWARENESS QUANTIFICATION METHOD

This section defines the two gaze entropies used in the study and the N-parameterised A′ equation form they enter. The module-decomposed quantities are written as explicit functions of the supervised module count N so that the resulting A′ equation has the same algebraic form at $N = 1$, $N = 2$, and $N \geq 3$.

2.1. Notation

Let an operator's gaze record cover modules indexed by $k = 1, \ldots, N$, each module endowed with a set of scenario-specific areas of interest (AOIs). For module k, let fk denote the number of fixations on its AOIs, and let the within-module AOI graph carry a count $cij(k)$ of first-order transitions from AOI i to AOI j. Module-level occupancy is defined as $\pi k = fk / \Sigma\ell\ f\ell$, so that $\Sigma k\ \pi k = 1$. Between-module transitions are indexed by a count $ck{\to}\ell(macro)$ of fixation-to-fixation transitions that cross from module k to module ℓ, with the corresponding macro Markov transition matrix $Pk{\to}\ell(macro)$ and stationary distribution $\pi k(macro)$. Logarithms are taken to base 2, so all entropies are expressed in bits.

2.2. Micro (within-module) entropy

Let HT(k) denote the Markov (transition) entropy computed within module k's AOI graph, defined as the conditional entropy of the next AOI given the current one and averaged over the originating distribution. The Micro entropy of an operator supervising N modules is the occupancy-weighted average of these within-module entropies,

$$H_{\text{micro}}(N) \;=\; \textstyle\sum_k \pi_k \;\cdot\; H_{\text{T}}(k) \tag{1}$$

Hmicro(N) measures how organised the operator's scanning is inside the supervised modules, weighted by how much each module is attended. By construction Hmicro(1) = HT(1), so the Micro entropy reduces exactly to the ordinary within-module Markov entropy used in single-module gaze-entropy studies at N = 1 [7]. The index is low when the operator scans the parameters of each module in a predictable, procedure-consistent sequence and high when within-module transitions are disordered.

2.3. Macro (between-module) entropy

Define the macro Markov entropy from the between-module transition matrix Pk→ℓ(macro) and its stationary distribution πk(macro), normalised by its theoretical maximum log2 N,

$$H_{\text{macro}}(N) \;=\; -\frac{\sum_k \pi_k{}^{\text{macro}} \sum_\ell P_{k\ell}{}^{\text{macro}} \log_2 P_{k\ell}{}^{\text{macro}}}{\log_2 N} \tag{2}$$

For N = 1 there is no between-module transition and the denominator log2 1 = 0 is undefined; by convention Hmacro(1) ≡ 0. For N ≥ 2, Hmacro(N) is bounded to 0 and1 — equal to 0 when the operator never crosses between modules, and 1 when between-module transitions are maximally disordered. Normalisation by log2 N makes Hmacro(N) comparable across module counts, so the regression coefficient on Hmacro retains the same interpretation as N grows. By construction, Hmicro contains only within-module transitions and Hmacro only between-module ones — the two indices are non-overlapping and together they decompose the organisation of the operator's whole scan into within-module and between-module components.

2.4. N-extrapolatable A′ equation form

The N-parameterised gaze quantities enter the A′ regression equation as

$$A'(N) \;=\; \beta_0 \;+\; \beta_{\text{micro}} H_{\text{micro}}(N) \;+\; \beta_{\text{macro}} H_{\text{macro}}(N) \tag{3}$$

where A′ is the overall SACRI sensitivity index. Specialisations follow directly. At N = 1, Hmacro(1) = 0 by construction, so the equation collapses to A′(1) = β0 + βmicro · Hmicro — a single-feature equation in within-module transition entropy that coincides with the form used in single-module gaze-entropy studies [7]. At N = 2, both predictors are active; Hmacro(N=2) is normalised by log2(2) = 1 and lies in 0 and 1. At N ≥ 3, both terms remain well defined, with Hmacro continuing to be normalised by log2 N so that βmacro retains the same interpretation. The form of the equation does not change, only the value of N used to compute Hmicro(N) and Hmacro(N). This is the N-extrapolatable property of the framework: the coefficients (β0, βmicro, βmacro) estimated from the available N = 1 and N = 2 records continue to apply as operators supervise larger numbers of modules.

3. EXPERIMENTAL SETUP

3.1. Multi-Module Operating Environment and Simulator Platform

The experiment was designed to emulate the operating concept of the Korean innovative SMR (i-SMR), a four-module light-water design intended to support one-operator/multi-module supervision through extensive autonomous operation [9]. The study compared a single-module condition (N = 1) with a dual-module condition (N = 2), the latter being the minimum non-trivial multi-module case in which one operator must distribute attention across two simultaneously evolving modules. Each module was represented by the Compact Nuclear Simulator (CNS), a research-grade simulator maintained at the Korea Atomic Energy Research Institute that models a three-loop Westinghouse pressurized-water reactor (Kori Unit 3/4 reference plant, 993 MWe) and presents the plant through a compact human–system interface [10].

3.2. Eye-Tracking Apparatus

Operators' eye movements were recorded with a commercial, wearable head-mounted binocular eye tracker that estimates the point of gaze on a forward-facing scene camera. A head-mounted device was preferred over a screen-based remote tracker because the multi-module layout distributes the relevant information across spatially separated displays and the operator continuously turns the head and body to scan between them — a configuration in which a remote tracker would lose gaze whenever the operator turned to a different display. Gaze data were exported and AOI-mapped in the manufacturer's analysis software.

3.3. Ground-Truth SA Measurement: SACRI

Operator SA was measured using SACRI [5] and used as the ground-truth reference. SACRI provides a per-module evaluation through nine questions covering the past, present, and future trends of nine safety-function-related plant parameters; it was administered once per module immediately after the operator had diagnosed that module's accident. Responses were scored under Signal Detection Theory as hit, miss, false alarm, or correct acceptance, and the non-parametric sensitivity index A′ was computed from all nine items following NUREG/IA-0137 [3] and Hogg et al. [5]. In this study the overall A′ — derived from all nine SACRI items — serves as the single ground-truth SA score against which the gaze entropies are evaluated.

3.4. Areas of Interest

An area of interest (AOI) is a region within the visual stimulus that the researcher defines in order to extract the eye-tracking data falling within it [12]. Following the attentional-resource approach of Ha and Seong [13], in which AOIs are placed on the parameters most significant for monitoring and detection of a given plant state, the AOIs for each accident were taken from the diagnostic parameters listed in the emergency operating procedure together with the significant parametric indications reported in [13]; reactor power was excluded because the scenarios were diagnosed after reactor trip and its variation is negligible. In the dual-module condition the same scenario-specific AOI set was defined separately on each module's board (left and right). All gaze features were computed only over the AOIs belonging to each module's accident scenario.

3.5. Participants and Analysed Scenarios

Each participant performed two N = 1 and two N = 2 scenarios. The analysed set comprised 46 operator recordings with valid A′ (25 N = 1, 21 N = 2). Participants had coursework or program experience relevant to NPP systems, reactor safety, or thermal-hydraulics. Three off-normal conditions were used — Loss-of-Coolant Accident, Steam-Generator Tube Rupture, and Excess Steam Demand Event — chosen as representative design-basis accidents that all trigger a reactor trip and Safety Injection yet present distinct safety-function signatures. Each scenario was executed under the diagnostic emergency procedure up to the step at which the specific accident is diagnosed; SACRI was administered at that point, and only eye-tracking data up to the diagnosis step were used.

3.6. Statistical Analysis

The relationship between gaze features and overall A′ was developed in three steps. First, Pearson product–moment correlation quantified the linear association of each gaze entropy (Hmicro, Hmacro) with A′ and screened candidate predictors at $p < 0.05$. Second, the most explanatory non-redundant subset was selected using the adjusted coefficient of determination (adjusted R^2) and the Akaike Information Criterion (AIC), under the constraint that every predictor's Variance Inflation Factor (VIF) remained below 5. Third, A′ was modelled on the selected predictors using three regression families: ordinary-least-squares (OLS) linear regression, fractional logistic regression (a binomial/logit generalised linear model) [14], and beta regression (a Beta-distributed response with logit link on the mean) [15]. Agreement of the three families in the sign and significance of the coefficients was taken as evidence that the derived relationship is not an artefact of any single modelling assumption.

4. RESULTS

4.1. Pearson Correlation

Table 1 reports Pearson correlations between the two module-decomposed gaze entropies and the overall SACRI A′, pooled over the N = 1 and N = 2 conditions (n = 46). Both predictors are significantly negatively correlated with A′ — $r = -0.396$ for within-module Micro entropy ($p = .006$) and $r = -0.335$ for between-module Macro entropy ($p = .023$) — so that more disordered scanning, whether within modules or between modules, accompanies lower SA.

Table 1. Pearson correlations between the two module-decomposed gaze entropies and overall A′, pooled over N = 1 and N = 2 (n = 46). * *p* < .05, ** *p* < .01.

Metric	**r (overall A′)**
Hmicro (within-module)	−0.396 (.006)**
Hmacro (between-module)	−0.335 (.023)*

Per-condition correlations show the expected behaviour of the decomposition (Table 2). Within the single-module subset (N = 1) Hmacro is identically zero by construction, while Hmicro reproduces the ordinary within-module Markov entropy result exactly because Hmicro(1) = HT(1). Within the dual-module subset (N = 2) Hmicro remains significantly negatively associated with A′; most of Hmacro's pooled-table signal therefore reflects the contrast between N = 1 (where Hmacro = 0) and N = 2 (where it varies), consistent with Hmacro being the predictor that turns on as soon as the operator begins to supervise more than one module.

Table 2. Pearson correlations between H_{micro}, H_{macro} and overall A′ computed separately for the N = 1 and N = 2 conditions; H_{macro} is identically zero at N = 1.

Metric	**r (N = 1, n = 25)**	**r (N = 2, n = 21)**
Hmicro	−0.422 (.036)*	−0.485 (.026)*
Hmacro	—	−0.089 (.701)

4.2. Adopted Equation

Table 3 reports the regression of overall A′ on Hmicro and Hmacro, fit pooled over N = 1 and N = 2 (n = 46). Both predictors enter the linear specification with negative, individually significant coefficients (Hmicro $b = -0.427$, $p = .003$; Hmacro $b = -0.374$, $p = .011$), and the beta specification confirms the same direction and significance ($p = .004$ and $p = .006$). The VIFs are both 1.36, well below the 5 threshold, so the two predictors are effectively non-collinear and the N-extrapolatable form is identifiable in the data. The adopted N-extrapolatable equation is

$$A'(N) = 1.087 - 0.427 \cdot H_{\text{micro}}(N) - 0.374 \cdot H_{\text{macro}}(N) \qquad (4)$$

with linear $R^2 = 0.280$. A one-bit increase in Hmicro lowers A′ by approximately 0.43, while a unit increase in Hmacro (the full normalised range, i.e., from perfectly ordered to maximally disordered between-module switching) lowers A′ by approximately 0.37. At N = 1 the macro term vanishes by construction and the equation collapses continuously to A′(1) = 1.087 − 0.427·Hmicro(1), the natural specialisation to single-module operation; at N ≥ 3 the same algebraic equation applies with Hmacro(N) normalised by log2 N.

Table 3. Regression of overall A′ on H_{micro} + H_{macro} (pooled, n = 46; linear $R^2 = 0.280$). Coefficient *b* with two-sided *p*-value.

Term	Linear (OLS)	Logistic (fractional)	Beta
Constant	+1.087 (.000)***	+2.604 (.046)*	+1.962 (.000)***
Hmicro	−0.427 (.003)**	−1.787 (.121)	−1.461 (.004)**
Hmacro	−0.374 (.011)*	−1.387 (.158)	−1.300 (.006)**

5. DISCUSSION AND CONCLUSION

Scan organisation, decomposed within- and between-module, dominates the gaze–SA relationship in this study. Within-module Micro entropy and between-module Macro entropy are both significantly negatively associated with overall A′, and both enter the adopted equation with individually significant, negative coefficients confirmed across the linear and beta specifications. Macro entropy is the gaze quantity that turns on as soon as the operator must supervise more than one module, and its independent contribution to A′ confirms that the systematicity of between-module switching carries SA-relevant information beyond what is captured by within-module scanning alone. The two indices are non-overlapping by construction and together decompose the operator's whole scan into a within-module sampling structure and a between-module switching structure.

The decomposed equation form scales naturally with the number of supervised modules. By construction Hmacro(1) = 0 and Hmicro(1) = HT(1), so the adopted equation specialises continuously to a single-feature, within-module entropy equation at N = 1 — recovering the form used in single-module gaze-entropy studies [7]. At N = 2 both predictors are active and Hmacro is normalised to [0, 1]; at N ≥ 3 Hmacro continues to be normalised by log2 N so the coefficient βmacro retains the same interpretation as N grows. Crucially, the algebraic form of the equation does not change with N — only the value of N used to compute Hmicro(N) and Hmacro(N). This is the N-extrapolatable property: coefficients estimated jointly from the available N = 1 and N = 2 records continue to apply as operators supervise larger numbers of modules in future i-SMR configurations.

The moderate explained variance ($R^2 = 0.280$) is expected. SA is multiply determined — by expertise, workload, mental model, and memory — so any single behavioural channel captures only part of it; A′ itself is a coarse, bounded index from nine SACRI items whose limited reliability and restricted range attenuate observed correlations; and heterogeneous scenarios and module counts are pooled. By Cohen's conventions [16] the operator-level correlations ($|r| \approx 0.34$–0.40) are medium-to-large effects, and the credibility of the result rests on the convergence of evidence — significant, uniformly negative coefficients across the linear and beta families and a collinearity-free fit — rather than on the magnitude of R^2.

In summary, this study developed an eye-movement-based, N-extrapolatable quantification of operator situation awareness for single- and multi-module NPP operation by decomposing the gaze stream into two non-overlapping organisation indices and relating them to the overall SACRI A′ index. The adopted equation is A′(N) = 1.087 − 0.427·Hmicro(N) − 0.374·Hmacro(N) (linear $R^2 = 0.280$). Three contributions follow. First, the module-decomposed representation separates within-module scan organisation from between-module switching organisation — two qualitatively different properties that whole-display entropy conflates — and both contribute significantly and independently to A′. Second, by writing both entropies as explicit functions of the supervised module count N, the framework yields the same algebraic equation at N = 1, N = 2, and N ≥ 3, providing a single equation form continuous from one-operator/one-unit operation through minimized-crew multi-module operation. Third, because the gaze quantities are window-based summaries over a defined AOI set, the equation can be evaluated on any chosen time window, yielding a continuous, non-intrusive SA estimate without freezing the simulator.

Limitations may have constrained the magnitude of the observed gaze–SA effects rather than implying their absence. The operator-level sample ($n = 46$, with $N = 1$ and $N = 2$ subsets of 25 and 21) is moderate and limits power to resolve weaker associations. Participants were graduate students with coursework-level familiarity, less procedurally consolidated than licensed crews, which probably added between-subject variance. The Compact Nuclear Simulator is research-grade rather than full-scope. Future work should replicate on a higher-fidelity multi-module mockup with $N = 3$ and $N = 4$ operating conditions, as i-SMR control-room designs mature, to verify that the equation coefficients extrapolate beyond the $N = 1$ and $N = 2$ records used here, and augment gaze with complementary bio-signal channels to break the single-channel R^2 ceiling.

Acknowledgements

This work was supported by the Korea Atomic Energy Research Institute, which provided access to the Compact Nuclear Simulator, and by the participants of the experiment. The authors thank colleagues at the Nuclear I&C and Autonomous Operation Laboratory, KAIST, for their support.

References

[1] M. R. Endsley and D. J. Garland, "*Situation Awareness Analysis and Measurement*," Lawrence Erlbaum Associates, 2000, New Jersey.

[2] J. Hartmann, J. Hyvärinen and V. Rintala. "*The operator and the seven small modular reactors — An estimate of the number of reactors that a single reactor operator can safely operate*", Nuclear Engineering and Design, (2023).

[3] U.S. Nuclear Regulatory Commission, "*Control Room Staffing Levels for Advanced Reactors*," NUREG/IA-0137, 2000, Washington, DC.

[4] J. O'Hara and J. Higgins, "*Human Reliability Considerations for Small Modular Reactors," Brookhaven National Laboratory*, BNL-96881-2012, 2012, .

[5] D. N. Hogg, K. Follesø, F. Strand-Volden and B. Torralba. "*Development of a situation awareness measure to evaluate advanced alarm systems in nuclear power plant control rooms*", Ergonomics, 38, pp. 2394–2413, (1995).

[6] P. Bhavsar, B. Srinivasan and R. Srinivasan. "*Quantifying situation awareness of control room operators using eye-gaze behavior*", Computers and Chemical Engineering, 106, pp. 191–201, (2017).

[7] Y. Lee, K.-T. Jung and H.-C. Lee. "*Use of gaze entropy to evaluate situation awareness in emergency accident situations of nuclear power plant", Nuclear Engineering and Technology*, 54, pp. 1261–1270, (2022).

[8] R. Miao, Q. Jia, D. Li and Z. Dong. "*A comprehensive situation awareness measurement method for analyzing the operators' situation awareness of multi-module high temperature gas-cooled reactor plants*", Energies, 16(15), (2024).

[9] J. Kang, S. Lee and H.-G. Lim. "*Light water SMR development status in Korea*", Nuclear Engineering and Design, 419, (2024).

[10] I.-S. Ham et al., "*Development of compact nuclear simulator*," Korea Atomic Energy Research Institute, 1988, Daejeon.

[11] K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka and J. van de Weijer, "*Eye Tracking: A Comprehensive Guide to Methods and Measures*," Oxford University Press, 2011, Oxford.

[12] J. S. Ha and P. H. Seong. "*Attentional-resource effectiveness measures in monitoring and detection tasks in nuclear power plants*", IEEE Transactions on Systems, Man, and Cybernetics — Part A: Systems and Humans, 40(5), (2009).
[13] L. E. Papke and J. M. Wooldridge. "*Econometric methods for fractional response variables with an application to 401(k) plan participation rates*", Journal of Applied Econometrics, 11, pp. 619–632, (1996).
[14] S. L. P. Ferrari and F. Cribari-Neto. "*Beta regression for modelling rates and proportions*", Journal of Applied Statistics, 31, pp. 799–815, (2004).
[15] J. Cohen, "*Statistical Power Analysis for the Behavioral Sciences*," Lawrence Erlbaum Associates, 1988, New Jersey.