

Stress-Integrated Learning and Decision Framework (SILDF): A Comprehensive Theoretical Model for High-Stress Learning Environments

Gregory Henderson*, Christan Horton

Department of Rehabilitation Counseling, Winston-Salem State University, Winston-Salem, NC, USA

Email: *hendersong@wssu.edu, hortonc@wssu.edu

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Abstract

This paper introduces the Stress-Integrated Learning and Decision Framework (SILDF), describing how discriminative stress cues (S^* cues) modulate attention, learning, memory, and decision-making in high-stress environments. SILDF proposes that S^* cues from time pressure, social-evaluative threat, physiological arousal, task complexity, and resource uncertainty act as critical signals reshaping human information processing during high-stakes performance. The framework provides a mechanistically specified account of how S^* cues interact with appraisal, emotion regulation, working memory, and schema structures to produce outcomes from catastrophic failure to remarkable resilience. These interactions are governed by trainable mechanisms spanning milliseconds to months. SILDF specifies how structured training builds cue-to-schema associations accessible under acute and chronic stress. The framework organizes its contributions around five processing stages, eight falsifiable propositions, and a measurement/training architecture applicable across domains (e.g., military, aviation, surgery, athletics, law enforcement). SILDF relates to established predecessors—Attentional Control Theory, Processing Efficiency Theory, the Biopsychosocial Model of Challenge and Threat, and Catastrophe Theory—identifying theoretical inheritance and extensions. Neurobiological substrates include HPA axis cortisol dynamics, LC-NE phasic/tonic signaling, prefrontal-amygdala regulation, hippocampal-striatal competition, and dopaminergic reward systems. The model addresses chronic stress and allostatic load reshaping these substrates over time. Proposed methods include laboratory paradigms, VR simulations, wearable monitoring, ecological momentary assessment, and longitudinal field studies. Outcome measures span behavioral, cognitive, physiolog-

ical, neural (EEG/fMRI), and well-being indicators. The paper concludes with implications for curriculum design, simulation standards, individual differences, equity, learner well-being, ethical governance, and translational pathways optimizing performance and long-term learner health.

Keywords

Discriminative Stress Cues (S* Cues), Schema Retrieval, Challenge-Threat Appraisal, Allostatic Load, High-Stress Learning Environments, Emotion Regulation, Simulation-Based Training

1. Introduction

In high-stakes professional, educational, and performance domains, the ability to learn effectively under stress and to reliably retrieve and execute acquired knowledge under pressure is not merely an advantage—it is often a precondition for safety, success, and survival. Yet, despite decades of research across cognitive psychology, neuroscience, and human performance science, the field has lacked a unified theoretical framework that systematically explains how stress cues reshape the architecture of learning and decision-making, and perhaps more critically, how structured training can build performance capabilities that remain intact under both acute and chronic stress. The Stress-Integrated Learning and Decision Framework (SILDF) is proposed to fill this gap.

1.1. The Problem of Stress-Dependent Performance

Learning and performing under conditions of acute and chronic stress represent foundational challenges in any environment where the consequences of error carry significant human, material, organizational, or societal cost. Across an extraordinarily diverse range of domains—military special operations, commercial and military aviation, surgical and procedural medicine, emergency medical services, law enforcement and hostage negotiation, competitive and elite athletics, orchestral and theatrical performance, air traffic control, nuclear plant operation, and high-stakes professional and academic examination—learners and practitioners must acquire complex, hierarchically organized knowledge and skill sets that remain reliably accessible and flawlessly executable under conditions of severe physiological arousal, compressed temporal horizons, ambiguous or incomplete information, social-evaluative scrutiny, and cognitive demand that systematically exceeds routine processing capacities (LeBlanc, 2009; Salas et al., 2018; Vine et al., 2015).

The fundamental tension that animates research and practice in these domains is one of profound practical consequence: the conditions under which human beings must perform at their highest levels are, paradoxically, among the conditions least hospitable to the cognitive and neural systems that support skilled perfor-

mance. Stress narrows attention in ways that can blind performers to critical peripheral information. It biases memory retrieval toward emotionally salient but task-irrelevant associations. It shifts decision-making architecture from flexible, goal-directed deliberation toward rigid, habitual responding. It disrupts the metacognitive monitoring systems that allow skilled practitioners to detect and correct their own errors in real time. And it does all of this through neurobiological mechanisms that are, in evolutionary terms, entirely functional—designed to maximize survival probability in environments very different from modern high-stakes professional contexts (Arnsten, 2015; Schwabe et al., 2022).

A recurrent and practically costly finding across high-stress domains is that performance capabilities painstakingly developed during training under relatively benign conditions frequently, sometimes catastrophically, degrade when redeployed under authentic operational stress. This phenomenon—described variously as choking under pressure (Beilock & Carr, 2001; Mosley & Laborde, 2024), skill failure (Masters & Maxwell, 2008), stress-induced performance decrement (Heissel et al., 2021), or task-irrelevant processing interference (Eysenck & Derakshan, 2011)—represents not merely an academic curiosity but a genuine safety and performance crisis with documented consequences in aviation accidents, surgical errors, military operational failures, and emergency response breakdowns.

1.2. Stress as a Conditional Moderator, Not a Simple Disruptor

Importantly, however, the empirical literature does not support a simple, universally negative account of stress-performance relationships. Meta-analytic evidence compiled across thousands of individual studies and millions of participants confirms that the direction, magnitude, and duration of stress effects on performance are profoundly conditional—shaped by the nature of the stressor, the characteristics of the performance task, the preparation history of the performer, the individual's appraisal of the stress encounter, their available regulatory resources, the social and environmental context, and the neurobiological profile of their stress response (Behnke & Kaczmarek, 2018; Crum et al., 2020; Jamieson et al., 2016).

Under appropriate conditions—conditions that stress researchers are increasingly able to specify with precision—stress arousal can enhance attentional engagement with task-relevant stimuli, accelerate retrieval of well-consolidated action schemas, prime rapid pattern recognition in expert practitioners, and increase motivational intensity in ways that produce performance gains rather than decrements (Crum et al., 2020; Jamieson et al., 2016; Shields et al., 2017). Elite military operators, experienced surgeons, veteran competitive athletes, and master performing artists often describe performing their best work under exactly the conditions of high pressure and elevated arousal that devastate less prepared performers. Understanding the mechanisms that differentiate these outcomes is not merely scientifically interesting—it is practically essential for designing training systems capable of reliably producing stress-resilient performance across domains.

To provide conceptual clarity, the following distinctions are adopted. *Stress* refers broadly to the organism's response to perceived environmental demands that exceed perceived adaptive capacity, encompassing both cognitive and physiological components (LeBlanc, 2009). *Anxiety* is the affective-cognitive component of stress, characterized by worry, apprehension, and task-irrelevant thinking that can disrupt attentional control (Eysenck & Derakshan, 2011). *Arousal* refers to the physiological activation dimension—sympathetic, neuroendocrine, and cardiovascular—which can range from low to high and is not inherently positive or negative (Vine et al., 2015). *Pressure* denotes the objective or perceived increase in performance stakes, consequences of error, or evaluative scrutiny, which typically elevates both anxiety and arousal (Beilock & Carr, 2001). Finally, *challenge versus threat appraisal* captures the individual's subjective evaluation of whether they have sufficient resources to meet situational demands; a challenge appraisal produces adaptive cardiovascular and performance patterns, whereas a threat appraisal leads to maladaptive patterns (Behnke & Kaczmarek, 2018). These constructs overlap and interact; however, distinguishing them allows SILDF to specify where and how training should intervene: for example, reducing maladaptive anxiety, optimizing arousal levels, reframing pressure, and shifting appraisal from threat to challenge.

1.3. The Gap That SILDF Addresses

Despite substantial theoretical and empirical progress in the psychology and neuroscience of stress and performance, a significant and practically consequential gap has persisted: the absence of an integrative framework that simultaneously 1) specifies the mechanisms by which structured training can build durable stress-resilient performance capabilities, 2) links these mechanisms to identifiable neurobiological substrates, 3) accounts for both acute and chronic stress effects across different timescales, 4) addresses group-level and team dynamics alongside individual processes, 5) translates mechanistic understanding into actionable and evidence-based training design principles, and 6) organizes these elements into a formally stated, testable, and falsifiable theoretical structure.

Existing frameworks, while enormously valuable, each address portions of this problem space without offering comprehensive integration. Attentional Control Theory (Eysenck & Derakshan, 2011) provides an exceptionally well-specified account of how anxiety impairs attentional control mechanisms but does not specify how training can build cue-driven retrieval pathways that partially compensate for these impairments. Processing Efficiency Theory (Eysenck & Calvo, 1992) distinguishes performance effectiveness from processing efficiency under anxiety but does not specify the learning mechanisms through which efficiency can be maintained under pressure. Models of challenge and threat appraisal (Behnke & Kaczmarek, 2018) illuminate the cardiovascular and affective correlates of adaptive versus maladaptive stress responses but do not provide a detailed account of how training shapes appraisal processes or builds schema structures accessible under

stress. Simulation-based learning research (Harvey et al., 2012; LeBlanc & Posner, 2022; Vage et al., 2024) documents the efficacy of stress exposure training without embedding outcomes in a mechanistically specified theoretical framework.

The Stress-Integrated Learning and Decision Framework (SILDF) addresses this gap by proposing a conceptual architecture in which discriminative stress cues (S^* cues) —environmental, physiological, social-evaluative, and task-complexity signals that reliably predict imminent high-stakes demands—function as the organizing construct linking perception, appraisal, memory retrieval, cognitive control, regulation, action selection, and outcome-based learning. SILDF proposes that systematic training can build durable cue-to-schema associations that, once established, enable rapid, accurate, and regulation-supported performance under conditions of severe stress—and that the mechanisms through which this occurs are specifiable, measurable, and subject to empirical disconfirmation.

1.4. Scope, Aims, and Organization

The scope of SILDF is deliberately broad. High-stress learning environments share deep structural similarities—time pressure, elevated stakes, physiological arousal, social-evaluative demands, informational uncertainty—that justify a domain-general theoretical account, while also differing in ways that require domain-specific calibration of the model's core constructs. SILDF is designed to accommodate both the commonalities and the important differences across military, aviation, medical, athletic, emergency response, performing arts, and high-stakes academic and professional domains.

The specific aims of this paper:

- 1) To articulate SILDF as a theoretically coherent, mechanistically specified, and domain-general theoretical model of stress-integrated learning and decision-making.
- 2) To situate SILDF comprehensively relative to existing theoretical frameworks, identifying points of inheritance, extension, and departure.
- 3) To specify the neurobiological substrates that ground SILDF mechanisms in contemporary cognitive and affective neuroscience.
- 4) To generate a set of formally stated, falsifiable propositions that render the framework empirically tractable and subject to systematic evaluation.
- 5) To propose a multi-method empirical research program adequate to testing SILDF across laboratory, simulation, and field contexts.
- 6) To develop detailed and practically actionable implications for training design, simulation architecture, technology integration, assessment, and feedback systems.
- 7) To address equity, accessibility, well-being, and ethical considerations essential for responsible implementation of SILDF-based training across diverse learner populations.
- 8) To identify current limitations and establish a roadmap for future theoretical refinement and empirical extension.

The paper is organized as follows: Section 2 positions SILDF relative to existing theoretical frameworks. Section 3 provides the theoretical grounding and integrative rationale. Section 4 specifies the neurobiological substrates. Section 5 presents the full SILDF model, including core constructs, mechanisms, processing stages, and boundary conditions. Section 6 states the formal propositions with falsifiability criteria. Section 7 proposes the empirical research program. Section 8 develops training design implications. Section 9 addresses well-being, equity, and ethical considerations. Section 10 acknowledges limitations. Section 11 provides an integrative discussion. Section 12 offers a conclusion.

2. Positioning SILDF Relative to Existing Theoretical Frameworks

SILDF builds on and extends a lineage of established frameworks. This section positions SILDF relative to five key predecessors: Attentional Control Theory (ACT), Processing Efficiency Theory (PET), the Integrative Model of Stress, Arousal, and Performance, the Biopsychosocial Model of Challenge and Threat, and Catastrophe Models. For each, points of theoretical inheritance and substantive extensions are identified. The section concludes with SILDF's distinctive contribution.

2.1. Attentional Control Theory

ACT (Berggren & Derakshan, 2013; Eysenck & Derakshan, 2011) proposes that anxiety impairs two components of attentional control: inhibition (suppressing task-irrelevant information) and shifting (flexibly redirecting attention). The third component, updating (refreshing working memory), is less directly impaired, though indirect effects can compromise it. ACT's core proposition—anxiety creates a dual-processing burden where attentional resources are captured by threat-relevant monitoring at the expense of goal-directed control—has been validated behaviorally, electrophysiologically, and neuroimaging (Berggren & Derakshan, 2013; Eysenck & Derakshan, 2011).

SILDF incorporates ACT's account of anxiety-induced attentional impairment within its second and third processing stages (Appraisal and Arousal Modulation; Schema Retrieval and Cognitive Control) and extends ACT in three directions:

- First, while ACT characterizes stress-related disruption as a liability, SILDF proposes that systematically trained S^* cues can capitalize on the stimulus-driven system's attentional prioritization by linking cue detection to validated schema retrieval rather than to threat processing.
- Second, ACT is primarily synchronic (describing attentional control at a moment of anxiety); SILDF adds a diachronic account of how training reshapes cue-attention-retrieval relationships over repeated stress exposures.
- Third, SILDF extends ACT's scope by incorporating neurobiological substrates, group-level dynamics, chronic stress effects, and training design implications.

2.2. Processing Efficiency Theory

PET (Eysenck & Calvo, 1992) distinguishes performance effectiveness (quality/accuracy) from processing efficiency (performance quality relative to cognitive resources consumed). Anxiety impairs efficiency more than effectiveness because anxious individuals compensate for degraded control by investing additional effort, maintaining acceptable performance while incurring elevated processing costs. A performer under stress may appear adequate by outcome metrics while operating at cognitive capacity limits, leaving no reserve for unexpected demands or error correction.

SILDF incorporates PET's effectiveness-efficiency distinction, proposing that S^* cue-driven schema retrieval functions as an efficiency-preservation mechanism—providing rapid, reliable access to validated schemas, reducing cognitive search demands, and freeing capacity for monitoring, error detection, and adaptive modification. SILDF extends PET by specifying learning mechanisms to systematically build and maintain processing efficiency—a dimension PET does not address in detail—and by incorporating neurobiological substrates of efficiency (prefrontal-mediated control, noradrenergic gain modulation) and chronic stress erosion of compensatory effort capacity.

2.3. The Integrative Model of Stress, Arousal, and Performance

Vine et al.'s (2016) Integrative Model synthesizes catastrophe theory, attentional control, psychomotor efficiency, and expertise-based accounts, emphasizing that arousal-performance relationships are complex, nonlinear, and expertise-dependent—not the simple inverted U of Yerkes-Dodson.

SILDF incorporates this core insight and adds three dimensions the integrative model does not systematically address: 1) a learning and consolidation account specifying how stress-resilient expertise is built through repeated structured practice with S^* cues; 2) a neurobiological substrate specification; and 3) a group-level extension addressing team performance under collective stress.

2.4. The Biopsychosocial Model of Challenge and Threat

The Biopsychosocial Model (Behnke & Kaczmarek, 2018; Blascovich & Tomaka, 1996) proposes that individuals appraise high-stakes demands by weighing situational demands against personal resources. When resources match or exceed demands, a challenge state is generated (adaptive cardiovascular reactivity, positive affect, approach motivation). When demands exceed resources, a threat state is generated (maladaptive cardiovascular reactivity, negative affect, avoidance motivation). Challenge states predict superior performance across many domains (Behnke & Kaczmarek, 2018).

SILDF explicitly integrates challenge-threat appraisal as a central moderator within its second processing stage (Appraisal and Arousal Modulation). SILDF proposes that S^* cue training influences appraisal by systematically increasing the perceived resource side of the equation—each successful training trial where S^*

cues trigger effective performance strengthens the learner's appraisal that they possess adequate resources for high-stakes demands. Over training, accumulated cue-triggered competence shifts the appraisal balance toward challenge, with corresponding improvements in cardiovascular reactivity, emotional state, and performance. SILDF thus specifies a learning mechanism for cultivating challenge appraisal—a dimension the biopsychosocial model itself does not specify.

2.5. Catastrophe Models of Performance

Catastrophe models (Hardy et al., 2007; Fazey & Hardy, 1988) propose that under high cognitive anxiety combined with elevated somatic arousal, small incremental changes in arousal can produce sudden, dramatic, and difficult-to-reverse performance collapses. Recovery requires substantial arousal reduction.

SILDF accommodates catastrophe dynamics while proposing that cue-driven retrieval pathways can stabilize performance, extending the performance plateau against arousal and anxiety increases, and reducing the probability of catastrophic collapse. By providing rapid, reliable access to validated action schemas that do not require sustained deliberate processing under high arousal, S* cue training may raise the threshold for catastrophic failure—a testable extension of catastrophe theory.

2.6. Positioning SILDF Relative to Stress Inoculation Training and Naturalistic Decision-Making

Beyond the theoretical frameworks already discussed, SILDF also differs from and extends two influential applied approaches: stress inoculation training (SIT) and recognition-primed decision (RPD)/naturalistic decision-making (NDM) models.

Stress inoculation training (Ketelaars et al., 2024; Meichenbaum, 1985; Saunders et al., 1996) is a three-phase cognitive-behavioral intervention (conceptualization, skill acquisition and rehearsal, application) designed to help individuals cope with anxiety and performance stress. While SIT has demonstrated effectiveness across clinical and performance domains, it does not specify the discriminative cue mechanisms through which stress exposure produces transferable resilience, nor does it articulate the neurobiological learning pathways (e.g., striatal habit formation, dopaminergic reward prediction) that SILDF leverages. SILDF complements SIT by providing a mechanistic account of why graduated exposure works—through S* cue-to-schema association building—and by specifying how to optimize cue reliability, salience, and compound structure during training. SILDF also extends SIT by explicitly addressing chronic stress and allostatic load, which SIT's acute-focused protocols largely omit.

Recognition-primed decision (RPD) models (Klein, 1993, 1997) from naturalistic decision-making research describe how experienced practitioners in time-pressured, high-stakes environments generate satisfactory decisions by recognizing situation patterns and mentally simulating action options. RPD captures expert performance under uncertainty but does not explain how such recognitional

expertise is built through training under stress, nor does it specify how discriminative stress cues become integrated into pattern recognition. SILDF provides the learning and consolidation mechanisms underlying RPD-style recognition: repeated paired presentation of S^* cues with validated schemas strengthens cue-to-schema associations to the point where recognition becomes automatic and stress-resilient. Moreover, SILDF addresses a gap in RPD by specifying how training can avoid overgeneralization and fixation (see Section 5.5 on failure modes) and how team-level shared cue recognition supports collective RPD processes.

Thus, SILDF is not a replacement for SIT or RPD but a neurobiologically grounded, learning-theoretic foundation that explains how these approaches achieve their effects and provides actionable design principles for enhancing them.

2.7. SILDF's Distinctive Contribution

Across these frameworks, SILDF's distinctive contribution is the explicit linkage of discriminative cue mechanisms—drawn from learning and memory science—to stress-and-performance theory. While prior frameworks describe how stress affects performance, SILDF specifies how structured training systematically builds the cue-to-schema associations that render performance stress-resilient. This linkage—between S^* cue properties, training design, schema development, retrieval mechanisms, and performance under stress—has not been formally articulated and represents SILDF's central conceptual innovation.

3. Theoretical Grounding and Integrative Rationale

This section establishes the empirical and conceptual foundations for SILDF. Eight lines of research are reviewed: stress effects on dual cognitive control systems; stress-induced attentional narrowing and selective memory consolidation; cognitive appraisal and the challenge-threat distinction; emotion regulation under stress; deliberate practice, expertise, and transfer; stress mindset and arousal reappraisal; simulation-based learning under stress; and chronic stress with allostatic load. For each domain, key findings are identified, followed by how SILDF integrates, extends, or challenges existing accounts. The purpose is to show that SILDF's central proposal—discriminative stress cues (S^* cues) can be systematically trained to trigger adaptive, stress-resilient performance—is grounded in established mechanisms from cognitive psychology, neuroscience, and skill acquisition science.

3.1. Stress and Dual Cognitive Control Systems

A robust finding is that acute stress shifts the balance between two cognitive control architectures: goal-directed (model-based) control (deliberate, flexible decision-making guided by action-outcome contingencies) and habitual (model-free) control (stimulus-bound responding governed by learned stimulus-response associations) (Goldfarb et al., 2017; Schwabe et al., 2022; Schwabe & Wolf, 2013).

Under low stress, goal-directed control predominates in novel or complex situations; habitual control governs routine behaviors. Under acute stress, the balance shifts toward habitual control even in situations that would ordinarily engage goal-directed deliberation (Schwabe et al., 2022). This shift is mediated by cortisol and norepinephrine effects on prefrontal cortex and striatal dopamine, favoring striatum-mediated stimulus-response learning over prefrontal-mediated goal-directed reasoning.

SILDF's integration is central to its core logic. If acute stress shifts control toward habitual responding, the critical training question becomes: what stimulus-bound responses should be built, and how can training ensure that the most appropriate responses become habitual for the most important stress cues? SILDF proposes that systematic S* cue training answers this question—by pairing specific stress cues with validated response schemas across sufficient repetitions, building habitual control pathways that produce adaptive responding when stress induces this shift.

This insight reframes the stress-induced shift toward habitual control: rather than treating it solely as a liability, SILDF proposes that well-designed training can transform it into an asset by ensuring that habitual responses triggered under stress are precisely those effective performance requires.

3.2. Stress, Attention, and Selective Memory

Acute stress reliably produces attentional narrowing—concentrating resources on the most immediately salient stimuli (threat-relevant or goal-relevant) at the expense of broader monitoring (Starcke & Brand, 2016). This narrowing can be adaptive (focusing resources where needed) or maladaptive (e.g., emergency responders fixating on one symptom while missing the broader picture).

Regarding memory, elevated cortisol and norepinephrine, particularly with emotional arousal, enhance consolidation of emotionally salient, stress-congruent, and self-relevant information while impairing consolidation of neutral or peripheral material (Quaedflieg & Schwabe, 2018; Shields et al., 2017). Thus, skills rehearsed under high arousal are disproportionately consolidated, but valence and relevance shape what is consolidated.

SILDF proposes that training can capitalize on stress-enhanced consolidation by ensuring that the most critical schemas—those that must be retrieved most reliably under operational stress—are rehearsed under appropriate arousal, with S* cues paired with successful schema execution during consolidation-enhancing states. This direct application of stress neuroscience to training design has not been systematically articulated in prior frameworks.

3.3. Cognitive Appraisal and the Challenge-Threat Distinction

Subjective interpretations of stress encounters—specifically the relationship between perceived demands and perceived resources—shape both the physiological signature of stress and performance consequences (Behnke & Kaczmarek, 2018;

Jamieson et al., 2016). Challenge appraisals (resources match or exceed demands) produce adaptive cardiovascular reactivity associated with enhanced performance. Threat appraisals (demands exceed resources) produce maladaptive profiles and performance decrements.

Appraisal processes are malleable. Arousal reappraisal interventions—interpreting physiological stress responses as energizing—have demonstrated reliable performance benefits across academic testing, athletic competition, and medical simulation (Crum et al., 2020; Jamieson et al., 2016), operating through shifts toward more adaptive cardiovascular reactivity profiles.

SILDF incorporates appraisal malleability as a critical training target. Repeated experience with S^* cues in training—particularly where S^* cues trigger successful performance despite high arousal—progressively calibrates appraisal toward challenge. Each successful training trial becomes an experiential demonstration that the learner possesses adequate resources, gradually reshaping automatic appraisal in operational contexts.

3.4. Emotion Regulation and Cognitive Control

The capacity to regulate emotional responses under stress is a critical individual difference variable and training target (Ford & Troy, 2019; McRae & Gross, 2020). Among emotion regulation strategies, cognitive reappraisal (reinterpreting stressful situations) and attentional deployment (strategically directing attention) have demonstrated robust evidence for preserving cognitive control under stress (McRae & Gross, 2020).

Emotion regulation interacts bidirectionally with cognitive control. Regulatory strategies that preserve executive function enable more effective schema retrieval, action selection, and error monitoring. However, emotion regulation is itself cognitively demanding, competing for the same working memory and executive resources that high-stress performance requires (Ford & Troy, 2019).

SILDF proposes that emotion regulation training is most effective when regulatory skills are developed to relative automaticity—initiated by S^* cues themselves as part of the cue-triggered retrieval pipeline rather than requiring effortful deliberate application under depleted regulatory resources. This distinguishes reactive regulation (after performance has degraded) from proactive regulation trained as integral components of S^* cue-triggered sequences.

3.5. Deliberate Practice, Expertise, and Transfer

Skill acquisition science grounds SILDF's account of how training builds stress-resilient performance. Deliberate practice research (Ericsson et al., 1993; Macnamara & Maitra, 2019) establishes that expert performance is primarily a function of structured, effortful, feedback-rich practice designed to push beyond current limits.

Contextual interference research (Soderstrom & Bjork, 2015) finds that interleaved, varied practice conditions—which produce more errors and feel more dif-

ficult during acquisition—produce substantially better long-term retention and transfer than blocked, predictable practice. This is particularly relevant for SILDF: if stress-resilient performance requires skills to remain accessible across varied high-stress contexts, then training designs incorporating controlled contextual variability should produce superior transfer to novel operational stress contexts.

SILDF synthesizes these insights to propose training design principles (Section 8) that leverage variability, contextual interference, and spaced practice to build maximally transferable and stress-robust cue-to-schema associations.

3.6. Stress Mindset and Arousal Reappraisal

Stress mindset research (Crum et al., 2013, 2020) establishes that individuals hold implicit theories about whether stress is enhancing or debilitating. Individuals with stress-is-enhancing mindsets demonstrate more adaptive cortisol responses, higher growth and learning following stressful experiences, and superior performance outcomes compared to those with stress-is-debilitating mindsets, even when objective stress levels are equivalent.

Stress mindsets are trainable through brief interventions, with substantial performance effects comparable to more extensive behavioral interventions (Crum et al., 2020). Mechanisms involve direct physiological pathways (HPA axis dynamics, cardiovascular reactivity) and indirect cognitive pathways (appraisal, attention allocation, effort mobilization).

SILDF incorporates stress mindset as a moderating variable (amplifying or attenuating S^* cue training effectiveness) and as a training target directly addressed in comprehensive SILDF-based training programs.

3.7. Simulation-Based Learning under Stress

High-fidelity simulation across military, aviation, medical, and emergency response domains has created opportunities to study and develop stress-resilient performance without operational risks (Harvey et al., 2012; LeBlanc & Posner, 2022). Simulation-based stress training documents benefits for stress inoculation—graduated exposure to increasingly intense stressors building habituation, coping capacity, and performance maintenance—as well as near and far transfer.

Particularly relevant for SILDF, advances in virtual reality simulation have expanded fidelity and accessibility of stress-inducing environments, enabling systematic manipulation of S^* cue properties, high-precision measurement of physiological and behavioral responses, and adaptive calibration of scenario difficulty based on real-time trainee state (Harris et al., 2020). These capabilities make SILDF-based research designs more feasible than even five years ago.

3.8. Chronic Stress and Allostatic Load

Perhaps the most frequently neglected dimension—and one SILDF explicitly prioritizes—is the cumulative effect of repeated or sustained stress on neurobiological systems supporting learning and performance. Allostatic load (Guidi et al.,

2020; McEwen, 2017) refers to cumulative physiological wear and tear from repeated stress response activation, generating systemic damage to the neural, endocrine, immune, and cardiovascular systems that acute stress was designed to protect.

Chronic stress and elevated allostatic load directly target the prefrontal, hippocampal, and amygdalar systems central to SILDF (McEwen, 2017). Chronic glucocorticoid exposure produces dendritic retraction and synaptic pruning in prefrontal neurons—reducing executive control, working memory, and regulation (Arnsten, 2015). Simultaneously, chronic stress produces dendritic hypertrophy in basolateral amygdala neurons—increasing threat detection and stress reactivity while reducing regulatory capacity (Hermans et al., 2014).

In the hippocampus—central to contextual learning, schema development, and flexible retrieval—chronic stress suppresses adult neurogenesis, reduces spine density, and impairs long-term potentiation underlying memory consolidation (Quaedflieg & Schwabe, 2018). These changes compromise flexible, contextually appropriate schema retrieval essential for adaptive performance.

SILDF's implications are both theoretical and practical. Theoretically, S^* cue training effectiveness will be systematically attenuated in individuals with high allostatic load—not because cue-to-schema learning mechanisms are absent, but because prefrontal regulatory capacity is structurally compromised. Thus, SILDF benefits are greatest in those without significant allostatic overload, diminishing as allostatic load increases.

Practically, high-stress training programs (military, emergency response, medical residency) must be designed with explicit attention to cumulative stress monitoring, recovery provision, burnout prevention, and learner well-being. Training that optimizes acute stress exposure while ignoring chronic accumulation may generate neurobiological conditions that undermine long-term retention and transfer. This dynamic is addressed in Sections 8 and 9.

4. Neurobiological Substrates of SILDF

A framework proposing mechanistic accounts of stress effects on learning and memory must be grounded in neurobiological systems. SILDF is anchored in five systems mediating acute and chronic stress effects on cognition: the hypothalamic-pituitary-adrenal (HPA) axis; the locus coeruleus-norepinephrine (LC-NE) system; prefrontal cortex-amygdala regulation; hippocampal-striatal competition; and dopaminergic reward-prediction circuits. For each system, this section specifies how stress-induced changes produce performance outcomes SILDF aims to explain and how structured training with S^* cues can work with—rather than against—these mechanisms to build stress-resilient performance.

4.1. The Hypothalamic-Pituitary-Adrenal Axis

The HPA axis translates psychological stress into physiological responses affecting learning and memory. In response to perceived threat, the hypothalamus releases

CRH, stimulating pituitary ACTH release, which drives cortisol release. Cortisol acts through brain mineralocorticoid and glucocorticoid receptors, affecting neuronal function and synaptic plasticity (Schwabe et al., 2022).

Cortisol effects are dose-, time-, and region-dependent. At moderate doses during acute stress, cortisol enhances consolidation of emotionally relevant memories via noradrenergic and amygdala interactions (Quaedflieg & Schwabe, 2018)—a mechanism stress-inclusive training can exploit. However, high doses or prolonged exposure impair hippocampal function, disrupt prefrontal processing, and compromise retrieval, contributing to allostatic load.

SILDF proposes that the optimal cortisol window for training-induced schema consolidation lies within moderate arousal associated with challenge (not threat) appraisal—high enough to activate consolidation-enhancing mechanisms without prefrontal impairment. This generates testable predictions (Section 7).

4.2. The Locus Coeruleus-Norepinephrine System

The LC-NE system is a second critical mechanism. The locus coeruleus is the primary norepinephrine (NE) source throughout the brain, projecting to prefrontal cortex, hippocampus, amygdala, and cortical regions. LC-NE activity is exquisitely sensitive to behaviorally significant and unexpected stimuli—the class of events S^* cues represent—producing effects central to SILDF (Mather et al., 2016).

The LC-NE system operates in two relevant modes. Phasic mode (brief, high-amplitude NE bursts triggered by discrete salient stimuli) produces sharp increases in cortical signal-to-noise ratio, prioritizing attended stimuli—corresponding to rapid attentional capture and schema priming by S^* cues. Tonic mode (sustained NE release) enhances arousal but reduces discriminative signal-to-noise gains.

The GANE model (Mather et al., 2016) proposes that phasic NE release interacts with local glutamatergic activity to create “hot spots” of enhanced excitation at active goal representations—a cellular mechanism for selectively amplifying attended stimuli while suppressing competitors. In SILDF terms, this explains how well-trained S^* cue associations direct NE-mediated attentional amplification toward task-relevant schemas during acute stress.

4.3. Prefrontal Cortex-Amygdala Dynamics

The regulatory relationship between prefrontal cortex (PFC)—particularly dlPFC, vlPFC, and mPFC—and the amygdala is a central circuit in stress and cognitive control research, constituting a key SILDF substrate (Arnsten, 2015; Hermans et al., 2014).

Under low stress, PFC regions exert top-down control over amygdala reactivity, modulating emotional responses, biasing attention toward task-relevant stimuli, and maintaining goal representations. This supports flexible, goal-directed performance characteristic of low-stress expertise.

Under acute stress, this regulation is disrupted. Catecholamine surges—partic-

ularly high NE acting through alpha-1 adrenoceptors—reduce prefrontal pyramidal neuron firing, weakening top-down signals that constrain amygdala reactivity (Arnsten, 2015). Simultaneously, the amygdala becomes hyperactivated, producing enhanced bottom-up threat-related signals competing with prefrontal goal representations. The net effect is a shift from prefrontal-dominated, goal-directed control toward amygdala-influenced, stimulus-reactive control—the dynamic stress-induced performance decrements reflect.

SILDF proposes that effective S^* cue training offsets this through two mechanisms. First, building highly consolidated cue-to-schema associations in striatal and hippocampal systems reduces schema retrieval dependence on intact prefrontal processing—skilled schema activation can proceed through partially prefrontal-independent pathways. Second, training regulatory skills as integral components of S^* cue-triggered sequences builds habits of emotion regulation initiation requiring less prefrontal effort, preserving capacity for ongoing performance monitoring and error correction.

4.4. Hippocampal-Striatal Memory System Competition

A critical distinction concerns competition between hippocampal (explicit, relational, contextual) and striatal (implicit, procedural, stimulus-response) memory systems under stress (Schwabe et al., 2022). Under low stress, hippocampal systems support flexible retrieval. Under stress, the balance shifts toward striatal, stimulus-response-based systems.

This shift has asymmetric implications. For well-learned procedural skills (surgical techniques, aircraft handling, athletic motor sequences), striatal dominance under stress may support reliable execution because these skills are represented in striatal circuits accessible under stress. For knowledge-intensive, contextually flexible performance (diagnostic reasoning, strategic planning), striatal dominance is limiting because these functions depend on hippocampal contextual systems that are selectively impaired.

SILDF proposes that training can optimize this tradeoff. Critical performance elements requiring reliable execution under extreme stress should be practiced to sufficient depth that their neural representations include strong striatal components. For elements requiring contextually flexible adaptation, training should incorporate sufficient stress exposure to develop partial stress tolerance in hippocampal pathways, while regulatory training preserves prefrontal function to support hippocampal-dependent performance under moderate stress.

4.5. Dopaminergic Reward-Prediction Systems

The mesolimbic and mesocortical dopaminergic systems (ventral tegmental area projecting to nucleus accumbens, prefrontal cortex, and hippocampus) play essential roles in reinforcement learning establishing and updating cue-to-outcome associations (Schultz, 2016). Dopaminergic reward-prediction error signals—encoding discrepancies between expected and actual outcomes—drive synaptic

strengthening for associations producing better-than-expected outcomes and weakening for worse-than-expected outcomes.

In SILDF training, these systems constitute a critical mechanism for cue recalibration (Stage 5). Each training trial where S* cue-triggered schema retrieval produces successful performance generates a positive reward-prediction error strengthening the cue-to-schema association. Each trial with inadequate performance generates a negative prediction error, weakening the association and driving exploratory search for alternative schemas. Over training, this reinforcement process progressively selects and strengthens the most effective associations.

Importantly, dopaminergic signaling is stress-sensitive: acute stress produces rapid prefrontal dopamine release transiently enhancing cognitive flexibility, while chronic stress produces blunted dopaminergic responsivity impairing reward-prediction error signaling and slowing reinforcement learning (Arnsten, 2015). This provides an additional mechanism through which allostatic load impairs SILDF training effectiveness—by degrading the very reward-prediction error signals through which cue-to-schema associations are learned and refined.

5. SILDF: Core Constructs, Mechanisms, and Full Model Specification

This section specifies SILDF's core constructs, processing mechanisms, and overall architecture. It defines discriminative stress cues (S* cues) and describes schema structures and retrieval pathways. The five processing stages are then presented: cue detection and attentional capture, appraisal and arousal modulation, schema retrieval under cognitive control, action execution with real-time regulation, and feedback integration, consolidation, and cue recalibration. The section closes with cross-cutting moderators—regulatory capacity, training history, stress reactivity, challenge-threat tendencies, allostatic load, team dynamics, and cultural context—that shape how these mechanisms play out in real-world learners and performance settings.

5.1. Defining Discriminative Stress Cues (S* Cues)

S* cues are the conceptual cornerstone of SILDF. They are defined as environmental, physiological, social-evaluative, or task-structural signals that reliably predict the imminent onset or current presence of high-stakes performance demands—characterized by elevated consequences for error, compressed temporal resources, elevated arousal, or significant social-evaluative scrutiny. Functioning as discriminative stimuli, they signal conditions under which specific responses will be effective, triggering associated response patterns through learning history.

S* cues vary along several theoretically important dimensions:

- **Modality:** Visual (e.g., cockpit warning), auditory (e.g., trauma alert), proprioceptive/interoceptive (physiological arousal), social-evaluative (presence of evaluators), or cognitive-structural (perceived time pressure).
- **Reliability:** High-reliability cues build stronger, more rapidly accessible cue-

to-schema associations than low-reliability cues.

- **Salience:** Highly salient cues—with strong perceptual distinctiveness, high temporal immediacy, or emotional significance—generate more powerful attentional capture and rapid schema priming.
- **Generality:** Domain-specific (e.g., a particular trauma presentation) vs. domain-general (e.g., physiological arousal). Domain-general cues, especially interoceptive signals, are important training targets because they appear across all high-stress contexts.
- **Compound structure:** In operational contexts, S^* cues rarely appear in isolation; most high-stakes demands are signaled by compounds of multiple cues. Training should develop compound recognition.
- **For empirical operationalization:** Cue reliability can be quantified as the conditional probability of a high-stakes demand given cue presentation (e.g., proportion of trials where an auditory alert precedes an emergency); cue salience can be indexed by reaction time to cue onset or first-fixation duration in eye-tracking; compound structure recognition can be measured as accuracy in identifying the full set of co-occurring cues from a display or scenario.

5.2. Schema Structures and Retrieval Pathways

Schemas—organized knowledge and action networks representing integrated patterns of perception, cognition, and response—constitute the second core construct of SILDF. In high-stress environments, domain-relevant schemas encode perceptual patterns, action sequences, communication protocols, regulatory procedures, and outcome expectations that characterize effective performance.

Schema retrieval under stress is the central process SILDF training aims to optimize. Well-consolidated schemas retrieved through S^* cue-driven pathways reduce working memory demands, reduce deliberation time, support performance monitoring, and embed regulatory actions as integral components.

Cue-to-schema association strength—determined by training history, consolidation depth, retrieval practice frequency, and arousal states during training—determines retrieval reliability. SILDF proposes that training systematically builds this strength through the mechanisms below.

5.3. The Five-Stage SILDF Processing Architecture

SILDF proposes five processing stages from initial detection through outcome-based recalibration. These stages are sequential in logical organization but implemented in rapid, partially parallel, recursive processes.

Stage 1: S^* Cue Detection and Attentional Capture

Detection of S^* cues in the environment or physiological state, and capture of attentional resources. In trained performers, detection is automatic—via well-established perceptual templates—critical under stress when deliberate processing is reduced.

Neurobiological implementation: Distributed network including sensory cor-

tex, superior colliculus/pulvinar (attentional orienting), amygdala (threat relevance), and LC-NE system (arousal-mediated amplification). Patterned activity generates rapid, high-confidence cue identification.

Training implications: Built through extensive exposure to high-fidelity S* cues across varied contexts. Eye-tracking and EEG provide indices of Stage 1 efficiency.

Moderators: Chronic stress, allostatic load, fatigue, anxiety, and trauma history can impair Stage 1.

Stage 2: Appraisal and Arousal Modulation

Upon S* cue detection, a rapid appraisal process evaluates cue significance and modulates autonomic/neuroendocrine arousal accordingly. This is the primary locus of challenge-versus-threat differentiation and where regulatory interventions (arousal reappraisal, stress mindset activation) exert strongest effects.

The appraisal involves primary appraisal (relevance/significance) and secondary appraisal (coping resources). Their interaction determines challenge-versus-threat outcome and autonomic profile.

Arousal modulation: HPA axis (cortisol) and sympathetic activation. Challenge appraisals produce adaptive cardiovascular profiles (increased cardiac output, stable vascular resistance), associated with preserved prefrontal function. Threat appraisals produce maladaptive profiles (increased vascular resistance), associated with prefrontal impairment.

Training implications: Built through arousal reappraisal, stress mindset development, secondary appraisal recalibration (via successful training), and biofeedback-supported regulation.

Stage 3: Schema Retrieval and Cognitive Control

The central mechanism of SILDF: activation and retrieval of domain-relevant schemas from long-term memory, guided by Stage 1 priming and shaped by Stage 2 arousal/appraisal context. Schema retrieval translates S* cue detection into adaptive action selection.

Schema retrieval under stress involves competition among schema candidates, weighted by cue match strength, training-determined association weights, working memory capacity, and contextual signals. Well-trained performers rapidly resolve competition in favor of the most appropriate schema. Undertrained performers or extreme stress produce hesitation or inappropriate retrieval.

Cognitive control at Stage 3: Working memory maintenance, inhibitory control, flexible shifting, and metacognitive monitoring. These are impaired by acute stress. SILDF proposes that training enhances stress-resilient performance by reducing schema retrieval dependence on intact prefrontal cognitive control.

Training implications: Built through extensive retrieval practice under stress—actively retrieving schemas in response to S* cues—with systematic variation in cue presentation, stress intensity, and context. Testing and desirable difficulties paradigms (Soderstrom & Bjork, 2015) are particularly relevant.

Stage 4: Action Selection, Execution, and Real-Time Regulation

Translates retrieved schemas into behavioral output—action selection, execution, and real-time monitoring/regulation. Encompasses cognitive actions (diagnostic reasoning, communication) and motor actions (procedural execution, physical performance).

Action selection: Chooses responses from the retrieved schema. Under moderate stress, it is schema-directed with minimal deliberation. Under extreme stress, it may default to strongly reinforced stimulus-response associations—which SILDF training aims to make adaptive.

Real-time regulation: Involves ongoing monitoring of performance quality and arousal, with regulatory adjustments as needed. Regulatory actions (controlled breathing, attentional refocusing, self-instruction, team-based social regulation) can be trained as explicit schema components, reducing deliberate effort under stress.

Error detection and correction: Depend on performance monitoring quality. Under moderate stress, experienced performers maintain effective error monitoring; under extreme stress, error monitoring can fail catastrophically (inattentional blindness to one's own errors).

Stage 5: Feedback Integration, Consolidation, and Cue Recalibration

Bridges performance episodes: Integration of outcome feedback into evaluative representations; stress-modulated consolidation of performance memories; and recalibration of cue salience, schema accessibility, and appraisal expectations.

Feedback integration: Depends on feedback quality and timing. Immediate, specific, accurate, interpretively framed feedback—addressing why performance succeeded or failed and which cue-schema-action associations contributed—produces more effective Stage 5 learning than delayed or outcome-focused feedback.

Stress-modulated consolidation: Involves post-performance cortisol and norepinephrine effects on memory strength. Moderate post-performance arousal enhances consolidation of emotionally relevant memories—a mechanism training designers should exploit by ensuring significant training experiences occur under appropriate arousal, followed by structured debrief during the consolidation window.

Cue recalibration: Updates cue-to-schema association strength based on performance outcomes—strengthening effective associations, weakening ineffective ones. Implemented through dopaminergic reward-prediction error mechanisms (Section 4.5), this constitutes the primary long-term learning mechanism through which repeated training progressively optimizes cue-driven retrieval.

5.4. Cross-Cutting Moderators

Operating laterally across Stages 2 through 5, the following moderators amplify or attenuate SILDF effectiveness:

- **Regulatory capacity:** Available reserves of executive control and emotion regulation, determined by trait differences, current state (fatigue, sleep quality, prior depletion), and training history. Higher capacity predicts more effective

appraisal, retrieval, and real-time regulation.

- **Training history and schema consolidation depth:** Accumulated S* cue-paired training determines cue-to-schema association strength, specificity, breadth, and retrieval robustness.
- **Stress reactivity:** Individual differences in HPA axis, sympathetic, and cardiovascular stress responses. Higher reactivity increases demands on regulatory capacity and the degree of prefrontal impairment to be compensated.
- **Challenge versus threat appraisal tendencies:** Dispositional bias toward challenge or threat evaluation, shaped by stress mindset, self-efficacy, prior success, and regulatory history.
- **Chronic stress and allostatic load:** Cumulative allostatic burden (Section 3.8) systematically attenuates SILDF effectiveness by degrading prefrontal regulation, hippocampal flexibility, and dopaminergic reinforcement learning.
- **Group context and team dynamics:** In collective performance contexts, team-level variables—shared mental models, communication protocols, trust, role clarity, collective regulation—amplify or undermine individual SILDF effectiveness (Salas et al., 2018).
- **Cultural and contextual factors:** Cultural meanings of stress cues shape appraisal and social-evaluative significance. SILDF training must be calibrated to target populations' cultural contexts.

A detailed diagram description of the SILDF processing architecture is presented in **Appendix A**.

5.5. Failure Modes of S* Cue Training

While S* cue training aims to build adaptive, stress-resilient retrieval, the same mechanisms can produce maladaptive outcomes when training design is suboptimal or when operational contexts deviate from training conditions. Three failure modes warrant explicit attention. First, cue overgeneralization occurs when learners acquire associations between S* cues and response schemas that are too broad, causing them to apply a trained schema in situations where it is inappropriate or where a different schema would be more effective. For example, a surgical trainee who learns to activate hemorrhage control schemas in response to a specific combination of blood pressure drop and surgical field appearance may subsequently overgeneralize to any blood pressure drop, triggering unnecessary interventions. Overgeneralization can be mitigated by training with a variety of near-miss cues and by including explicit discrimination practice where similar cues signal different required responses. Second, false positives arise when neutral or irrelevant stimuli become inadvertently paired with high-stakes responses due to coincidental co-occurrence during training. A pilot who experiences a stall warning simultaneously with a particular radio transmission may later respond to the neutral radio transmission alone with unnecessary emergency actions. False positives can be reduced by ensuring that S* cue training includes clear discriminative contingencies and by incorporating extinction trials where cues appear without the pre-

dicted high-stakes demand. Third, schema fixation refers to the rigid application of a well-learned schema even when situational feedback indicates it is no longer appropriate—a phenomenon analogous to cognitive set-shifting deficits under stress (Schwabe et al., 2022). Schema fixation is particularly likely when S* cues are trained with very high reliability in invariant contexts, leading to automatic retrieval that overrides deliberate monitoring. Mitigation strategies include variable-context training, periodic schema-switching exercises, and metacognitive training that supports active evaluation of schema adequacy during performance. Recognizing and designing against these failure modes is essential for responsible SILDF implementation.

6. Formal Propositions, Hypotheses, and Falsifiability Criteria

A theoretical model that aspires to advance beyond post-hoc explanation must generate testable predictions and specify the conditions under which it could be disconfirmed. This section formally states eight propositions derived from the SILDF framework, each accompanied by its mechanistic rationale, a concrete testable prediction, and explicit falsifiability criteria. The propositions span the full scope of SILDF—from the foundational role of S* cue reliability and cue-paired success, through moderators such as regulatory capacity, stress mindset, and allostatic load, to transfer effects from multicontext exposure, the nonlinear functional arousal window, metacognitive and debrief enhancements, chronic stress attenuation, and team-level shared cue recognition. Together, these propositions provide a roadmap for empirical evaluation of SILDF across laboratory, simulation, and field settings.

6.1. Proposition 1: S* Cue Reliability and Retrieval Efficiency

- **Formal Statement:** S* cues that reliably, specifically, and consistently predict high-stakes performance demands across training contexts will produce faster schema retrieval latencies, higher schema retrieval accuracy, and smaller performance decrements under matched stress conditions than semantically equivalent performance demands presented without S* cue marking, at equivalent levels of domain knowledge and training volume.
- **Mechanistic rationale:** Reliable S* cues build high-strength, high-specificity cue-to-schema associations through repeated reinforced retrieval, reducing the cognitive search required for schema activation and reducing dependence on prefrontal deliberative processing that is impaired under stress.
- **Testable prediction:** In a 2 (reliable S* cue training vs. control training without systematic cue marking) $\times$ 3 (low, moderate, high stress induction) design, the reliable S* cue condition will show smaller performance decrement scores across the stress gradient and shorter decision latencies at each stress level.
- **Falsifiability:** This proposition is disconfirmed if reliable S* cue training produces no significant reduction in decision latency or improvement in accuracy

under matched stress conditions across at least two independent domains with adequate statistical power. It is also disconfirmed if performance benefits of S* cue training disappear when controlling for total practice time, suggesting that any benefit reflects practice volume rather than cue-specific mechanisms.

6.2. Proposition 2: Cue-Paired Success and Association Strength

- **Formal Statement:** Pairing S* cues with successful schema execution during training—through designs that ensure reliable cue-outcome contingencies with appropriately spaced reinforcement schedules—will produce stronger, more stress-robust cue-to-schema associations than equivalent training volume without explicit cue-outcome pairing, as evidenced by superior performance under acute stress, faster cue-triggered schema activation, and greater retention at delayed assessment.
- **Mechanistic rationale:** Successful cue-paired execution generates dopaminergic reward-prediction error signals that strengthen cue-to-schema associations through synaptic reinforcement; these associations, once consolidated, are partially independent of prefrontal deliberative control and thus remain accessible under stress-induced prefrontal impairment.
- **Testable prediction:** Learners trained with explicit cue-success pairing will demonstrate faster cue-to-schema activation (indexed by N2/P3 EEG components in response to S* cues) and superior schema recall accuracy under stress conditions imposed two weeks post-training relative to learners trained without explicit pairing.
- **Falsifiability:** Disconfirmed if explicit cue-success pairing produces no advantage over equivalent practice without pairing in at least two pre-registered replication studies using matched practice volume controls.

6.3. Proposition 3: Regulatory Capacity and Stress Mindset as Moderators

- **Formal Statement:** Individual differences in emotion regulation capacity (specifically cognitive reappraisal ability and working memory capacity), stress mindset, and trait challenge-versus-threat appraisal tendencies will significantly moderate SILDF training effectiveness and stress-resilient performance outcomes, such that higher regulatory capacity and more challenge-oriented stress mindset predict greater training-induced performance stability under stress and superior transfer to novel stress contexts.
- **Mechanistic rationale:** Regulatory capacity determines the quality of Stage 2 appraisal and arousal modulation and the effectiveness of Stage 4 real-time regulation; stress mindset shapes the automatic secondary appraisal that determines challenge-versus-threat state; together, these moderators determine how much of the prefrontal regulatory impairment produced by acute stress is compensated for within the SILDF pipeline.
- **Testable prediction:** In a multi-site study ($N \geq 400$) with pre-training assess-

ments of regulatory capacity (working memory span tasks, cognitive reappraisal questionnaire, ERQ), stress mindset (SMS-Brief), and challenge-threat appraisal style, these pre-training measures will significantly predict residualized gain scores in stress-resilient performance from pre- to post-training assessment, independent of domain knowledge and training volume.

- **Falsifiability:** Disconfirmed if regulatory capacity, stress mindset, and challenge-threat appraisal show no significant moderating effects on training outcomes across three or more well-powered independent studies with pre-registered hypotheses and adequate measurement fidelity for all proposed moderators. Disconfirmation would suggest that SILDF effectiveness is driven primarily by domain-specific training volume rather than by regulatory and appraisal mechanisms, requiring fundamental revision of the framework's Stage 2 architecture.

6.4. Proposition 4: Multicontext Exposure and Transfer Advantage

- **Formal Statement:** Training that systematically exposes learners to S^* cues across multiple varied contextual configurations—varying the specific environmental features, task parameters, social-evaluative conditions, and physiological arousal intensities under which S^* cues are encountered—will produce superior transfer of stress-resilient performance to novel, untrained high-stress contexts relative to equivalent training volume conducted within a single, invariant contextual configuration, even when the single-context training produces higher within-context acquisition performance.
- **Mechanistic rationale:** Multicontext S^* cue exposure builds contextually general cue-detection templates and schema retrieval pathways that are not tightly bound to specific surface features of training environments, enabling effective cue recognition and schema activation when novel contextual configurations are encountered in operational settings. This mechanism directly reflects the contextual interference literature's account of variable practice advantages for transfer (Soderstrom & Bjork, 2015).
- **Testable prediction:** In a pre-registered experimental study, learners randomly assigned to multicontext S^* cue training (with systematic variation in at least three contextual parameters across training sessions) will demonstrate significantly higher performance scores on a standardized novel-context transfer assessment administered under stress conditions than learners assigned to single-context training at equivalent total practice time, despite the single-context group demonstrating higher performance scores on within-context retention assessments.
- **Falsifiability:** Disconfirmed if multicontext training produces no significant transfer advantage over single-context training in novel high-stress contexts across two or more pre-registered replications with adequate transfer-versus-retention assessment distinction. Disconfirmation would challenge SILDF's

contextual generalization account and suggest that stress-resilient performance is more context-bound than the framework proposes.

6.5. Proposition 5: Functional Arousal Window and Appraisal-Regulation Interaction

- **Formal Statement:** Effectiveness of S^* cue-driven schema retrieval is a non-linear (inverted-U) function of arousal; moderate arousal (challenge appraisal) produces optimal performance, while very low or very high arousal suboptimal. Appraisal interventions and regulatory skills widen the effective arousal range, extending performance maintenance to higher absolute arousal levels.
- **Mechanistic rationale:** Moderate arousal corresponds to optimal LC-NE phasic signaling that maximizes signal-to-noise in cue-relevant networks while preserving prefrontal function; appraisal and regulation interventions prevent transition to maladaptive extreme arousal by maintaining challenge states.
- **Testable prediction:** Using continuous physiological monitoring (HRV, EDA, pupil dilation) as arousal indices and cognitive performance tasks as retrieval efficiency measures, a significant inverted-U relationship between arousal and S^* cue-driven retrieval efficiency will be observed, with the inflection point at higher absolute arousal levels in the arousal-reappraisal condition than in the control condition, and superior performance maintenance at high arousal levels in participants with higher regulatory skill scores.
- **Falsifiability:** Disconfirmed if the arousal-retrieval relationship is linear rather than curvilinear across the measured range, or if appraisal/regulatory interventions produce no significant shift in the effective arousal window across two or more well-powered studies with continuous physiological monitoring.

6.6. Proposition 6: Metacognitive Awareness and Structured Feedback Enhancement

- **Formal Statement:** Learners receiving structured metacognitive training (monitoring cue detection, appraisal, schema retrieval, regulation) combined with systematic post-performance debriefs addressing cue interpretation and regulation will demonstrate faster SILDF skill development, more accurate self-assessment, and superior long-term retention compared to those without these components.
- **Mechanistic rationale:** Metacognitive awareness enables identification of stage-specific failures and targeted intervention; structured debriefs during the post-performance consolidation window enhance memory encoding for cue-schema-outcome relationships through elaborative processing.
- **Testable prediction:** In a three-arm randomized trial comparing standard stress training, stress training plus post-performance debrief, and stress training plus metacognitive instruction plus structured debrief, the combined metacognitive-plus-debrief condition will demonstrate significantly superior per-

formance on both immediate retention and six-week delayed transfer assessments, with superior self-assessment calibration (correlation between self-rated and objectively assessed performance) as a secondary outcome.

- **Falsifiability:** Disconfirmed if metacognitive training and structured debrief produce no significant advantage over training-only conditions in at least two well-powered pre-registered studies, or if improved self-assessment calibration does not predict superior transfer performance.

6.7. Proposition 7: Chronic Stress and Allostatic Load Attenuation

- **Formal Statement:** Accumulated chronic stress burden (validated allostatic load indices: cortisol awakening response, resting HRV, inflammatory markers, sleep quality, burnout) significantly and negatively predicts SILDF training effectiveness—slower learning, less stable retrieval under acute stress, greater performance decrement—even after controlling for domain knowledge, practice volume, and regulatory capacity. Interventions that reduce allostatic load prior to training enhance effectiveness in high-load populations.
- **Mechanistic rationale:** Allostatic load degrades prefrontal regulation, hippocampal consolidation, and dopaminergic reinforcement learning essential for cue-to-schema association building, creating a neurobiologically determined ceiling on training effectiveness.
- **Testable prediction:** In a longitudinal study of healthcare trainees, military personnel, or emergency response professionals—populations with documented high allostatic load prevalence—baseline allostatic load indices will significantly negatively predict slope of improvement on stress-resilient performance measures across a standardized SILDF training program, independent of baseline domain knowledge and prior training volume. A pre-registered intervention study will test whether six weeks of allostatic load reduction protocol (sleep hygiene, graduated recovery, mindfulness-based stress reduction) prior to SILDF training improves training effectiveness indices relative to immediate SILDF training.
- **Falsifiability:** Disconfirmed if allostatic load indices show no significant predictive relationship with SILDF training effectiveness in two or more adequately powered longitudinal studies, or if allostatic load reduction interventions produce no enhancement of subsequent training outcomes.

6.8. Proposition 8: Team-Level Shared Cue Recognition and Collective Performance Amplification

Before stating the proposition, it is necessary to clarify which SILDF constructs operate at the individual level, which are shared team constructs, and which remain preliminary. Individual-level constructs (Stages 1-5) include S* cue detection, appraisal, schema retrieval, action execution, and feedback integration. These are defined and measured within each team member. Shared team constructs refer to emergent properties of the team that are not reducible to any

single member's attributes. For SILDF, these shared constructs include: (a) shared mental models of S^* cues (the degree to which team members hold consistent, accurate, and accessible representations of cue identities, meanings, and predicted demands) (Behlau & Dreiskämper, 2025); (b) coordinated response schemas (shared action sequences and communication protocols triggered by collective cue recognition); (c) collective regulatory dynamics (mutual monitoring, backup behavior, and shared emotion regulation); and (d) team-level cue recalibration (joint debrief processes that update team schemas). The claims regarding team-level processes are preliminary, as less empirical work has directly tested SILDF in collective contexts relative to individual mechanisms. Proposition 8 is therefore offered as a directional extension requiring substantial future research.

- **Formal Statement:** In collective performance contexts, shared team constructs—particularly shared mental models of S^* cues and coordinated response schemas—predict collective performance under stress over and above the aggregation of individual-level SILDF constructs (individual cue detection, schema retrieval, and regulation). Team-level SILDF training that explicitly develops shared mental models and coordinated response schemas produces superior collective stress-resilient performance compared to aggregated individual training without team integration (Lines et al., 2022).
- **Mechanistic rationale (team-level extension):** Effective collective response to S^* cues requires not only that each individual retrieves appropriate schemas but also that the team rapidly communicates cue status, coordinates action selection, provides mutual regulatory support, and engages in collective meta-cognitive monitoring. These emergent processes amplify individual SILDF effectiveness when well trained; when absent or dysfunctional, they can undermine even well-trained individual capabilities (Halgas et al., 2023). The shared team constructs are hypothesized to mediate the relationship between team-level training and collective performance, but this mediation claim is preliminary pending empirical testing.
- **Testable prediction:** Surgical teams, military fire teams, or emergency response crews randomly assigned to team-level SILDF training (explicit shared cue recognition, coordinated schema development, collective debrief) will demonstrate significantly superior performance on standardized high-fidelity team simulation assessments under stress compared to teams composed of individually SILDF-trained members without team-level integration. Shared mental model quality is proposed as a mediator, but this mediation hypothesis is preliminary.
- **Falsifiability:** Disconfirmed if team-level SILDF training produces no significant collective performance advantage over aggregated individual training in two or more well-powered team studies, or if shared mental model quality shows no mediating relationship after controlling for individual-level SILDF effectiveness.

The eight formal propositions and their falsifiability criteria are summarized in **Appendix B**.

7. Empirical Research Program

Testing the SILDF's eight propositions requires an empirical strategy spanning multiple complementary approaches. This section outlines a three-phase research program. Phase 1 uses controlled laboratory mechanistic studies isolating causal relationships between S^* cue training, stress induction, and performance outcomes using behavioral, physiological, and neural measures. Phase 2 moves to high-fidelity and virtual reality simulations, where greater ecological validity allows testing under operationally relevant conditions while retaining experimental control. Phase 3 comprises longitudinal field studies in authentic operational settings, assessing transfer, long-term retention, and real-world outcomes. Across all phases, emphasis is placed on pre-registration, adequate statistical power, effect size reporting, and open science practices to ensure rigorous and reproducible evidence.

7.1. Overview and Multi-Method Rationale

Comprehensive testing of SILDF requires a multi-method strategy spanning controlled laboratory paradigms (isolating causal mechanisms), high-fidelity and VR simulations (ecological validity with experimental control), and longitudinal field studies (transfer, retention, real-world outcomes). No single method tests all propositions; each offers complementary validity strengths. The three-phase research program increases ecological validity across phases, each building on preceding insights from the preceding phase. Effect sizes, power calculations, and pre-registration are emphasized throughout, reflecting the framework's commitment to rigorous, reproducible science.

7.2. Phase 1: Laboratory Mechanistic Studies

7.2.1. Design and Participants

Phase 1 studies employ controlled laboratory paradigms with undergraduate, graduate, and professional populations to test SILDF mechanisms under conditions of precise experimental control. Core designs use $2 (S^* \text{ cue training vs. matched control training}) \times 3 (\text{low, moderate, high stress induction})$ fully crossed factorial structures with random assignment, allowing estimation of main effects, interaction effects, and moderation by individual difference variables assessed at baseline.

Target sample sizes for each study are determined by power analyses based on effect sizes from the most directly relevant prior literature, with minimum $N = 150$ per study to provide 80% power for medium-effect-size interactions ($f^2 = 0.15$) at $\alpha = 0.05$, with pre-registration on OSF prior to data collection. Participants span multiple domains (undergraduates, medical students/residents, military officer candidates, competitive athletes) to test domain-generalizability.

7.2.2. Stress Induction Protocols

Phase 1 studies will employ multiple validated stress induction protocols calibrated to produce the different stress levels specified in the experimental design:

- **Low stress:** Quiet, non-evaluated task performance under standard laboratory conditions with no time pressure, no performance feedback implications, and no social evaluation.
- **Moderate stress:** The Trier Social Stress Test (TSST) (Kirschbaum et al., 2008) adapted for laboratory performance contexts, involving performance of target tasks before evaluators with explicit evaluation framing and video recording; or the socially evaluated cold pressor test for physiological stress induction with social-evaluative overlay.
- **High stress:** Combined stressor protocols incorporating time pressure, social evaluation, performance contingency (monetary outcomes or professional record implications where ethically appropriate), and physiological demand through exercise-induced arousal combined with cognitive task performance under evaluation.

Stress induction effectiveness will be verified in each participant through real-time physiological monitoring and post-task subjective stress ratings, ensuring that stress level manipulation checks confirm adequate separation between conditions.

7.2.3. Behavioral and Cognitive Measures

Primary behavioral measures will include:

- **Schema retrieval latency:** Reaction time from S* cue presentation to initiation of schema-consistent response, indexed through response timing hardware with millisecond precision.
- **Schema retrieval accuracy:** Percentage of correct schema-consistent responses across performance trials, with domain-specific accuracy criteria established through expert consensus.
- **Decision quality scores:** Composite indices of decision accuracy, appropriateness, and efficiency derived from domain-specific performance rubrics validated through expert review.
- **Working memory performance:** Dual-task paradigms assessing residual working memory capacity during concurrent S* cue-based performance tasks, providing indirect indices of cognitive load at Stage 3.
- **Error detection and correction rates:** Proportion of self-generated performance errors detected and corrected within trials, as indices of Stage 4 metacognitive monitoring quality.
- **Transfer performance:** Performance on novel S* cue configurations and stress contexts not encountered during training, as primary indices of learning generalization.

Secondary cognitive measures will include standardized assessments of working memory capacity (operation span, reading span), cognitive reappraisal ability (Emotion Regulation Questionnaire), stress mindset (Stress Mindset Measure), and trait anxiety (State-Trait Anxiety Inventory) as moderator variables, admin-

istered at baseline prior to experimental manipulation.

7.2.4. Physiological Measures

A comprehensive physiological measurement battery will be employed across Phase 1 studies:

- **Autonomic:** Continuous ECG for HRV (RMSSD for parasympathetic regulation, LF/HF for sympathovagal balance), EDA (sympathetic arousal), impedance cardiography (cardiac output, total peripheral resistance for challenge/threat profiles).
- **Neuroendocrine:** Salivary cortisol (baseline, +10, +20, +30, +45 min post-induction) for reactivity and recovery; salivary alpha-amylase (sympathetic/noradrenergic activation).
- **Ocular:** High-resolution pupillometry (LC-NE activity, cognitive load; pupil dilation as biomarker of Stage 1 detection and Stage 3 retrieval demand).
- **Eye-tracking:** Gaze patterns (attentional capture at Stage 1, visual search at Stage 3).

7.2.5. Neural Measures

EEG will be recorded during performance tasks using 64-channel active electrode systems with online artifact monitoring, enabling analysis of event-related potentials (ERPs) and time-frequency decompositions:

- **N2 and P3** to S* cues (cue discrimination accuracy, attentional allocation). Predicted: larger N2/P3 for trained versus untrained cues.
- **Frontal theta power (4 - 8 Hz)** (prefrontal cognitive control engagement at Stage 3).
- **Alpha power suppression** (cortical activation, attentional engagement).
- **Error-related negativity (ERN)** (error detection efficiency at Stage 4). Prediction: ERN maintained under moderate stress in well-trained performers, attenuated under high stress in undertrained.

The complete recommended measurement battery is compiled in **Appendix C**.

7.2.6. Analytic Approach

- **Primary:** Linear mixed-effects models (participant random factor; stress and training conditions fixed; individual differences as moderators) in R (lme4), with effect sizes (Cohen's d , η^2p , f^2) and 95% CI.
- **Mediation:** PROCESS macro (10,000 bootstrap iterations) testing whether physiological arousal (cortisol, HRV) mediates stress-performance relationships and whether S* cue training moderates these pathways.
- **Bayesian estimation:** Supplementing frequentist moderation analyses (Bayes factors, posterior distributions).

7.3. Phase 2: High-Fidelity and Virtual Reality Simulation Studies

7.3.1. Design Rationale and Setting

Phase 2 bridges laboratory and field contexts using high-fidelity simulations approximating perceptual, cognitive, and social complexity of authentic high-stakes

performance while maintaining experimental control. Studies will be conducted across medical simulation centers (high-fidelity patient simulators), military training facilities (tactical decision-making simulators), aviation simulation centers (part-task and full-flight simulators), and custom VR environments. The multi-facility approach tests domain-generalizability and builds cross-domain evidence.

7.3.2. Technology Integration

Virtual reality (VR) simulation platforms offer three specific advantages: 1) fully controlled, precisely reproducible S* cue presentation (same cue configurations, intensities, timings, compounds across participants); 2) systematic parametric variation of cue properties (salience, reliability, modality, compound structure); 3) continuous, unobtrusive measurement of gaze, movement kinematics, and response timing. Wearable physiological monitoring (research-grade wrist-worn HRV/EDA, lightweight EEG, camera-based photoplethysmography) enables continuous measurement without laboratory constraints, with real-time data integration for adaptive scenario calibration. AI-adaptive systems adjust difficulty, S* cue intensity, and time pressure based on trainee performance and physiological state, maintaining optimal challenge zone (Harris et al., 2020). Learning analytics dashboards aggregate data across sessions for longitudinal tracking and personalized recommendations.

7.3.3. Outcome Measures

Primary outcome measures in Phase 2 will include domain-specific performance quality ratings—developed through expert consensus and inter-rater reliability validation for each simulation domain—along with the behavioral and physiological measures carried forward from Phase 1. Additional Phase 2-specific outcomes will include:

- **Gaze behavior analysis:** Time-to-first-fixation on S* cues, total fixation time on task-relevant versus task-irrelevant regions, saccadic pattern analysis, and Area of Interest (AOI) transition sequences as direct behavioral indices of attentional prioritization during simulation performance.
- **Communication analysis:** In team simulation contexts, automated and expert-coded analysis of communication frequency, content, clarity, and coordination quality as indices of team-level SILDF processes, including shared cue recognition and coordinated response schema deployment.
- **Autonomic recovery profiles:** Time-course analysis of HRV and EDA recovery following high-stress scenario episodes as indices of regulatory effectiveness and resilience, with faster and more complete recovery predicting better sustained performance across extended simulation sessions.
- **Self-efficacy and metacognitive accuracy:** Post-scenario assessments of perceived performance quality and self-efficacy, correlated with objective performance ratings to assess metacognitive calibration quality and its development across training.

7.3.4. Analytic Approach

Phase 2 analyses will employ multilevel models accounting for nested data structures (trials within sessions within participants; in team studies, participants within teams). Bayesian multilevel models Stan (via the brms package in R) provide probabilistic estimates with uncertainty quantification. Functional data analysis applied to continuous physiological time-series (dynamic trajectories of arousal, regulation, recovery). Growth curve modeling will characterize individual trajectories of SILDF skill development across training sessions, identifying subgroups with different developmental trajectories and testing predictors of more versus less adaptive developmental patterns.

7.4. Phase 3: Longitudinal Field Studies and Operational Transfer Assessment

7.4.1. Design and Setting

Phase 3 assesses whether laboratory and simulation effects translate to authentic performance improvements in real-world high-stakes contexts. Longitudinal field studies will partner with military training institutions, hospital systems, emergency medical services, aviation training organizations, and athletics programs. Ethical governance frameworks (participant privacy, data security, informed consent, protection against coercive data use) must be established prior to data collection. A dedicated research ethics committee (including organizational stakeholders, participant representatives, and independent specialists) will review all Phase 3 protocols.

7.4.2. Longitudinal Design

Field studies will employ prospective longitudinal cohort designs tracking participants from entry into training programs through training completion and into operational deployment or professional practice. Assessment points will be structured to capture:

- **Baseline:** Domain knowledge, regulatory capacity, stress reactivity, allostatic load markers, stress mindset, demographics.
- **Mid-training:** Skill acquisition trajectories, cue-schema association strength, regulation skill development, cumulative stress burden.
- **Post-training:** All primary/secondary outcomes under standardized stress (compared to pre-training).
- **Transfer assessments:** 1, 3, and 12 months post-training—retention and transfer to operational contexts (standardized simulation and, where feasible/ethical, operational performance records).
- **Well-being monitoring:** At each point—burnout (Maslach Burnout Inventory), sleep quality (Pittsburgh Sleep Quality Index), perceived recovery (Recovery-Stress Questionnaire), psychological safety.

7.4.3. Transfer and Retention Outcome Measures

- **Near transfer:** Simulation scenarios with high fidelity to training but novel S* cue configurations and content (generalization within domain).

- **Far transfer:** Simulation scenarios sharing general stress structure but differing substantially in domain, task demands, or cue modality (domain-general mechanisms).
- **Operational performance indicators:** Where ethically governed—error incident rates, efficiency metrics, peer/supervisor ratings, competency assessments.
- **Error and incident analysis:** In domains with systematic recording (aviation, medicine, military)—analysis of error type, frequency, severity before/after SILDF implementation.

7.4.4. Analytic Approach

Latent growth curve modeling characterizes developmental trajectories (shape, rate of improvement, stability of transfer). Moderated mediation models test whether allostatic load moderates the mediated pathway from SILDF training through cue-schema association strength to operational outcomes. Multi-group structural equation modeling tests equivalence of SILDF pathways across domains, demographic groups, and organizational contexts (domain-general claim).

8. Training Design Implications

The theoretical mechanisms of SILDF carry direct implications for designing, delivering, and evaluating training in high-stress environments. This section translates the five-stage processing architecture into concrete design principles. Foundational principles are presented first, followed by stage-specific recommendations: building cue detection expertise (Stage 1), developing adaptive appraisal and arousal regulation (Stage 2), building stress-robust schema retrieval (Stage 3), developing real-time regulation and error recovery (Stage 4), and optimizing feedback, debrief, and consolidation (Stage 5). Cross-cutting architectural principles—graduated stress inoculation, deliberate practice, recovery integration, assessment-integrated training, and instructor calibration—are then discussed. The section concludes with brief domain-specific application sketches across military, aviation, surgical, emergency response, athletic, and high-stakes examination contexts.

8.1. Foundational Principles of SILDF-Informed Training Design

SILDF's mechanistic account of how discriminative stress cues, schema retrieval, appraisal, and regulation interact under pressure generates training design principles that go beyond generic "stress exposure training" to specify features that build cue-to-schema associations and regulatory capabilities required for stress-resilient performance. These principles are organized around the five SILDF processing stages, followed by cross-cutting architectural principles.

8.2. Stage 1 Training: Building Cue Detection Expertise

Stage 1 training develops perceptual expertise in S^* cue detection—rapid, accurate, automatic identification of cues that signal high-stakes demands across var-

ied and degraded conditions.

- **Explicit cue identification instruction:** Training programs should begin with explicit instruction in the specific S^* cues that are most diagnostically relevant in the target performance domain, including their characteristic perceptual features, their typical temporal sequence in high-stakes situations, and the performance demands they predict. This establishes initial cue representations that perceptual practice then automatizes through repetition.
- **Perceptual discrimination training:** Structured exercises requiring learners to rapidly discriminate S^* cues from perceptually similar but diagnostically different stimuli build the high-resolution cue templates that enable fast, accurate detection under stress. Research in perceptual expertise demonstrates that discrimination training—particularly training that requires responses to subtle cue variations—produces more transferable perceptual expertise than simple recognition training (Kellman & Garrigan, 2009).
- **Degraded condition exposure:** Because authentic operational stress frequently degrades perceptual conditions—through environmental noise, attentional narrowing, fatigue, or information overload— S^* cue detection training should include systematic exposure to degraded, partial, or compound cue presentations that mirror the perceptual challenges of operational contexts.
- **Immediate cue-identification feedback:** Rapid, accurate feedback on cue identification responses during perceptual training accelerates the development of high-fidelity cue templates and prevents consolidation of inaccurate detection patterns that would undermine Stage 1 effectiveness in operational contexts.

8.3. Stage 2 Training: Developing Adaptive Appraisal and Arousal Regulation

Stage 2 training builds appraisal skills and regulatory capacities that translate S^* cue detection into challenge (rather than threat) arousal states and maintain functional arousal within the range supporting optimal Stage 3 and Stage 4 performance.

Stress mindset development: Brief but empirically validated stress mindset interventions (Crum et al., 2020) should be integrated into SILDF training programs as early-stage components, establishing the cognitive framework within which subsequent stress exposure training is interpreted. These include psychoeducation about the adaptive functions of stress responses, reflection exercises examining personal evidence for stress-enhanced performance, and commitment exercises establishing intentions to approach rather than avoid stress arousal.

- **Arousal reappraisal skill training:** Explicit instruction in cognitive reappraisal of physiological stress arousal—interpreting racing heart, elevated respiration, and activation as functional preparation rather than inability to cope—paired with induced stress arousal during training so learners practice reappraisal in the relevant physiological state.
- **Physiological regulation skills:** Train evidence-based techniques: cyclic sigh-

ing and paced resonance breathing (HRV enhancement), progressive muscle relaxation, tactical breathing (4-4-4-4 box breathing), and mindfulness-based attentional regulation, with explicit instruction on when and how to deploy each relative to S^* cues.

- **Biofeedback-supported regulation training:** Real-time biofeedback of HRV, EDA, or respiration rate provides immediate, objective evidence of regulatory effectiveness, accelerating voluntary autonomic regulation and increasing confidence in regulatory capacity.
- **Challenge framing of training demands:** Training language, instructor communication, and assessment framing should consistently present demands as challenges to be met through skilled preparation rather than threats to be survived. Mastery-oriented, challenge-framed environments produce superior skill development and more adaptive stress response.

8.4. Stage 3 Training: Building Stress-Robust Schema Retrieval

The core of SILDF training involves the systematic development of strong, reliable, and contextually flexible cue-to-schema associations through carefully structured retrieval practice under varied stress conditions.

- **Retrieval practice over restudy:** Training designs should consistently prioritize active schema retrieval from memory—in response to presented S^* cues—over passive review or restudy of schema content. The testing effect (Roediger & Butler, 2011) demonstrates that retrieval practice produces substantially stronger, more durable, and more transfer-resistant memory traces than equivalent time spent reviewing material, with effects that are particularly pronounced under conditions that partially interfere with retrieval—precisely the conditions of acute stress.
- **Spaced retrieval schedules:** Distribute retrieval practice across time using expanding schedules (shorter initial intervals lengthening progressively) rather than massed sessions. Spaced practice produces superior long-term retention, critical for cue-schema associations that must survive weeks or months between training and deployment.
- **Contextual interference and variable practice:** As specified in Proposition 4, systematically vary contextual features of S^* cue presentations (environmental configurations, cue compounds, timing, scenario content) across sessions rather than blocking identical presentations. Variable practice produces superior transfer to novel operational contexts despite more errors during acquisition.
- **Interleaved schema practice:** Interleave practice across multiple schemas from early training, requiring learners to discriminate among S^* cues for different schemas and select appropriate responses. Interleaved practice is more cognitively demanding but produces superior discrimination and more transfer-resistant retrieval.
- **Progressive stress exposure:** Schema retrieval practice should occur across a systematically escalating range of stress intensities—beginning with moderate stress

for consolidation benefits without exceeding regulatory capacity, progressing toward high stress as cue-schema associations strengthen. Abrupt extreme stress before adequate consolidation risks building stress-avoidance associations.

8.5. Stage 4 Training: Developing Real-Time Regulation and Error Recovery

Training for Stage 4 focuses on developing the real-time monitoring, regulatory, and error correction capabilities that maintain execution quality across extended high-stress performance episodes.

- **Performance monitoring skill development:** Explicit training in metacognitive skills of real-time performance monitoring—attending to performance quality indices while executing tasks—essential for Stage 4 error detection under stress. Includes attention division techniques, time-pressured checklists, and error pattern recognition specific to the domain.
- **Regulatory action integration as schema components:** A critical SILDF training design principle: regulatory actions (breathing, attentional refocusing, reappraisal statements, communication protocols) should be trained as integral, sequenced components of performance schemas, not separate skills applied reactively. When embedded as standard procedural elements triggered by S^* cues, they require less deliberate effort and are more reliably deployed under depleted regulatory resource.

For example, in surgical training contexts, a schema for managing unexpected intraoperative hemorrhage might explicitly include as its second step—immediately following cue detection and initial control—a brief paced breathing cycle and a standardized team communication announcement that initiates help-seeking and provides a regulatory pause before cognitively demanding decisions.

- **Error recovery schema training:** High-stress environments inevitably produce errors; the capacity to detect, interpret, and recover rapidly without catastrophic disruption is a trainable skill. Include explicit error recovery schema training: structured practice in recognizing common error signatures, executing validated recovery sequences, and re-engaging effective performance without rumination or anxiety escalation.
- **Deliberate exposure to failure states:** Deliberately expose learners to performance failure under controlled conditions (scenarios calibrated to exceed current capability). Failure experiences, followed by effective debrief and schema correction, produce disproportionately powerful learning due to affective salience driving consolidation (Section 3.2), provided the failure occurs in a psychologically safe environment where failure is framed as learning information rather than negative evaluation.

8.6. Stage 5 Training: Optimizing Feedback, Debrief, and Consolidation

The effectiveness of Stage 5 learning processes—feedback integration, stress-mod-

ulated consolidation, and cue recalibration—is critically dependent on the quality, timing, structure, and framing of the feedback and debrief processes that follow each performance episode.

- **Immediate performance feedback:** Where technologically feasible, immediate feedback on critical parameters (within seconds) provides temporally precise reward-prediction error signals that most effectively drive dopaminergic cue-schema recalibration. In simulation environments, use visual/auditory displays; in live training, instructor observation with standardized protocols.
- **Structured post-performance debrief:** The 30 - 60 minutes immediately following a significant stress episode—cortisol elevated but declining—is a neurobiologically privileged consolidation window. Exploit this with structured debrief protocols including:
 - 1) *Physiological settling phase:* 5 - 10 minutes of structured recovery (regulated breathing, hydration, transitional activity) before cognitively demanding debrief.
 - 2) *Performance narrative reconstruction:* Guided recall of the complete episode in temporal sequence, attending to S* cue identification, appraisal, schema retrieval, regulation, and outcomes—building an elaborated episodic memory linking all SILDF stages.
 - 3) *Cue interpretation analysis:* Systematic examination of whether S* cues were detected accurately and promptly, compound structures recognized correctly, and any cues missed—providing Stage 1 recalibration.
 - 4) *Schema evaluation:* Expert-facilitated assessment of schema appropriateness, execution completeness/accuracy, and whether alternatives would have been superior—providing Stage 3 recalibration.
 - 5) *Regulatory effectiveness review:* Honest assessment of whether regulatory actions were deployed appropriately and effectively, and whether additional strategies would have helped—providing Stages 2 and 4 recalibration.
 - 6) *Forward planning:* Explicit commitment to specific behavioral changes in subsequent episodes, encoded as prospective intentions to enhance schema modification implementation.
- **Peer debrief and social learning:** Where group training contexts make it feasible, structured peer debrief (learners providing feedback to each other using shared frameworks) produces social learning benefits: perspective-taking, normalized failure discussion, and collaborative problem-solving around challenging S* cue recognition and schema retrieval.

8.7. Cross-Cutting Training Architecture Principles

Beyond Stage-specific design recommendations, SILDF generates several cross-cutting architectural principles that govern the overall structure of effective high-stress training programs:

- **Graduated stress inoculation:** The overall trajectory of stress intensity should follow a systematically graduated arc—beginning well within current regulatory capacity to build cue-schema associations and challenge appraisals, then

progressively escalating toward intensities that approach and occasionally exceed capacity, generating productive failures and adaptive challenges that drive maximal learning. Extreme stress before adequate schema consolidation risks avoidance responses, trauma associations, and debilitating mindsets.

- **Deliberate practice principles:** Embody core deliberate practice (tasks at the edge of capability, immediate informative feedback, full attention, expert guidance) while adding SILDF-specific principle: practice across a systematic range of stress intensities and S* cue configurations, not within a single comfort-zone context.
- **Recovery integration:** Explicitly schedule and protect recovery periods—within sessions, between sessions, across training phases—to allow consolidation, regulatory resource replenishment, and allostatic load management. Maximizing stress exposure at the expense of recovery may paradoxically produce inferior long-term learning, especially for at-risk population.
- **Assessment-integrated training:** Integrate formal performance assessment throughout training, not just as end-of-program summative evaluation, to provide continuous feedback for Stage 5 consolidation and to normalize assessment as learning-supportive rather than high-stakes. This supports challenge rather than threat appraisals to assessment-related S* cues.
- **Instructor training and calibration:** The effectiveness of SILDF-based training depends substantially on instructor quality—ability to calibrate stress intensity, deliver specific constructive feedback, facilitate psychologically safe debrief environments, recognize and respond to learner distress, and model adaptive stress responses. Investment in comprehensive instructor training and ongoing calibration is essential, not secondary.

8.8. Domain-Specific Training Applications

While SILDF is proposed as a domain-general framework, its application requires domain-specific calibration of S* cue identification, schema content, stress induction methods, and outcome assessment approaches. Below, brief domain-specific application sketches illustrate how SILDF principles translate across high-stress learning contexts:

- **Military operational training:** S* cues include tactical situation displays showing enemy contact, physiological arousal signatures of combat proximity, communication patterns indicating rapidly evolving threats, and environmental indicators of ambush conditions. Critical schemas include threat assessment protocols, engagement decision sequences, casualty care initiation, and communication escalation procedures. Stress induction through military-specific scenario simulations with role-players, environmental stressors, and physical demand combinations. Team-level SILDF processes are particularly central given the inherently collective nature of military operational performance.
- **Aviation training:** S* cues include specific instrument configurations indicat-

ing developing emergencies, air traffic control communication patterns signaling airspace conflicts, weather radar presentations indicating severe conditions, and physiological arousal associated with unexpected aircraft system anomalies. Critical schemas include emergency checklists, weather deviation procedures, crew resource management communication protocols, and abnormal aircraft handling techniques. Simulation-based stress induction through part-task and full-flight simulators with scripted emergency scenarios.

- **Surgical and procedural medical training:** S* cues include patient physiological parameter configurations indicating hemodynamic instability, surgical field presentations indicating unexpected anatomical findings or intraoperative complications, anesthesia display patterns indicating patient deterioration, and team communication patterns signaling escalating concern. Critical schemas include hemorrhage control protocols, airway management sequences, emergency team activation procedures, and intraoperative decision algorithms. High-fidelity simulation with standardized patients and task trainers, combined with operating room simulation facilities (White et al., 2025).
- **Emergency response training:** S* cues include dispatch information patterns predicting mass casualty incidents, on-scene visual and environmental cues indicating structural hazard, patient presentation clusters indicating toxicological exposure, and incident command communication patterns signaling resource overwhelm. Critical schemas include incident command establishment procedures, triage decision protocols, resource request sequences, and inter-agency communication standards. Tabletop, functional, and full-scale simulation exercises with standardized scenario scripting and post-exercise debrief.
- **Competitive athletics:** S* cues include opponent behavioral patterns indicating specific tactical approaches, scoreboard and game-clock configurations creating high-pressure decision moments, physiological arousal signatures of competition pressure, and crowd and environmental conditions associated with high-stakes performance demands. Critical schemas include situation-specific tactical decision sequences, technical execution patterns for high-pressure moments, and psychological performance routines for maintaining focus and arousal regulation under competitive stress. Pressure training in practice, simulated competition scenarios, and competition performance analysis.
- **High-stakes academic and professional examinations:** S* cues include examination format features predicting high-difficulty question clusters, time-remaining indicators creating temporal pressure, specific question stem structures signaling required knowledge domains, and physiological arousal signatures of examination anxiety. Critical schemas include domain-specific problem-solving algorithms, time management protocols, metacognitive checking procedures, and anxiety regulation sequences. Practice examination conditions with time pressure, evaluation framing, and systematic debrief of both content performance and regulatory effectiveness.

An implementation checklist for SILDF-based training programs is provided in **Appendix D**.

9. Equity, Accessibility, Well-Being, and Ethical Considerations

Any training framework that deliberately uses stress as a learning tool carries profound ethical responsibilities alongside its performance benefits. This section addresses the equity, accessibility, well-being, and ethical dimensions that must govern responsible SILDF implementation. Equity and accessibility considerations include differential baseline stress reactivity, trauma-informed design, neurodevelopmental diversity, cultural and linguistic diversity, and socioeconomic access to training resources. Learner well-being and burnout prevention are addressed through cumulative stress monitoring, recovery period protection, psychological safety as a training prerequisite, and access to mental health support. Finally, ethical research governance frameworks are specified for the empirical research program outlined in Section 7, covering informed consent, data privacy and security, distress minimization, and avoidance of coercive deployment practices. These considerations are integral features of SILDF: training that ignores equity or harms well-being is not merely ethically problematic but theoretically inconsistent with building sustainable, challenge-oriented stress resilience across diverse learners.

9.1. Equity and Accessibility in SILDF Training Design

SILDF-based training programs without explicit attention to equity and accessibility risk disadvantaging learners whose characteristics (baseline stress reactivity, trauma history, neurodevelopmental profile, cultural background, language, socioeconomic resources) differ from implicit normative assumptions. Addressing equity is not merely ethical but scientific: programs producing systematically differential outcomes across groups fail SILDF's goal of domain-general stress-resilient development.

- **Differential baseline stress reactivity:** Substantial individual variation in HPA axis reactivity, autonomic response magnitude, and regulatory resources exists across populations and does not necessarily reflect learning capacity—it may reflect adaptation to different life environments. SILDF programs should use individual-level physiological monitoring to calibrate stress exposure to each learner's reactivity profile, ensuring every learner experiences challenge-zone arousal levels for optimal learning.
- **Trauma history and trauma-informed design:** Learners with prior trauma (combat, medical, adverse childhood experiences, professional critical incidents) may exhibit trauma-specific S^* cue responses that undermine standard training. Trauma-associated stimuli can become dysregulating pseudo- S^* cues triggering hyperarousal or avoidance incompatible with schema retrieval. SILDF programs should adopt trauma-informed principles: pre-training trauma screening, individualized modifications, instructor training in trauma

response recognition, opt-out protocols for distressing content, and access to psychological support.

- **Neurodevelopmental diversity:** Learners with ADHD, autism spectrum conditions, anxiety disorders, or other neurodevelopmental profiles may interact with S* cue structures and simulation environments differently from neurotypical populations. Universal design principles (accessible to diverse cognitive/sensory profiles without individual accommodations) should guide simulation construction, cue presentation, feedback modality, and debrief facilitation. Specific accommodations for incompatible profiles should be developed collaboratively with affected learners, disability specialists, and domain experts.
- **Cultural and linguistic diversity:** The meanings, salience, and appraisal significance of S* cues are shaped by cultural context—what is a potent social-evaluative threat in one culture may be neutral in another, and appropriate regulation may vary. SILDF programs should be developed with explicit cultural consultation for each target population, ensuring cue libraries, scenario content, appraisal language, and debrief approaches are culturally appropriate and linguistically accessible. Non-native language delivery imposes additional cognitive load and should be addressed through language support or native-language training where feasible.
- **Socioeconomic access:** High-fidelity simulation, wearable physiological monitoring, and VR platforms represent significant resource investments inaccessible to learners and institutions with limited finances. SILDF training design should include low-resource implementation pathways (tabletop exercises, low-fidelity simulation, peer-based stress exposure) that preserve core mechanisms without expensive infrastructure, ensuring evidence-based training is not exclusively available to well-resourced populations.

9.2. Learner Well-Being and Burnout Prevention

The deliberate use of stress as a training tool creates an ethical obligation to protect learner well-being as a non-negotiable design constraint. SILDF training programs that optimize acute stress exposure while ignoring cumulative stress burden risk producing allostatic load accumulation (Section 3.8), a fundamental threat to long-term performance capacity and personal health.

- **Cumulative stress monitoring:** Implement systematic monitoring of well-being indicators: standardized burnout assessment (Maslach Burnout Inventory), sleep quality (Pittsburgh Sleep Quality Index), perceived recovery (Recovery-Stress Questionnaire), psychological safety ratings, and where feasible, objective physiological indices (HRV trends, cortisol awakening response). Monitoring data should trigger individualized intervention when warning thresholds are exceeded, with immediate modification of training intensity and recovery support.
- **Recovery period protection:** Explicitly designate and protect recovery peri-

ods—within training days and across the calendar—free from stress exposure demands, supporting consolidation, regulatory replenishment, and allostatic recovery. These periods should be framed as essential training components with same status as active practice, countering organizational pressures that compress recovery in favor of additional stress exposure.

- **Psychological safety as a training prerequisite:** Effective SILDF training—particularly deliberate failure exposure and honest regulatory self-assessment required for Stages 3 and 5—is only possible within a psychologically safe environment: shared belief that honest reporting of difficulties, acknowledgment of failures, and requests for support will be met with constructive engagement rather than negative evaluation or professional consequence. Creating psychological safety requires explicit instructor modeling, program culture setting, and organizational policy; its absence undermines SILDF training effectiveness.
- **Access to mental health support:** Stress training programs that deliberately expose learners to intense stress have an obligation to ensure timely access to qualified mental health support for learners experiencing distress (whether related to training content or pre-existing vulnerabilities). This requires proactive identification of mental health resources before training begins, normalization of help-seeking, and instructor training in recognizing and responding to learner distress exceeding normal challenge.

9.3. Ethical Research Governance

The empirical research program (Section 7) involves deliberate stress induction, physiological data collection, long-term outcome monitoring, and collaboration with operational organizations—each carrying specific ethical responsibilities requiring appropriate governance frameworks.

- **Informed consent:** All research participants must receive comprehensive, understandable, and genuinely voluntary informed consent before any stress induction or physiological data collection. Consent processes must clearly describe the nature, intensity, and duration of stress exposures, types of physiological data collected, data storage and security arrangements, right to withdraw without consequence, and procedures for distress management. Special attention is required in professional training contexts where power relationships between instructors and trainees may compromise voluntariness.
- **Data privacy and security:** Physiological, performance, and well-being data are sensitive personal data requiring robust security protections, strict access controls, clear retention/destruction policies, and explicit provisions against use for any purpose other than research objectives (no employment decisions, professional credentialing, or insurance determination). Institutional data governance frameworks and applicable regulatory requirements (GDPR, HIPAA) must be fully complied with.
- **Minimizing distress:** Research designs must calibrate stress exposure to the

minimum levels necessary to test SILDF propositions, with continuous distress monitoring and clear stopping rules halting exposure immediately if distress exceeds safe and ethical limits. Validated distress monitoring procedures (standardized real-time subjective ratings, physiological threshold monitoring, behavioral observation protocols) should be implemented in all stress induction studies.

- **Avoidance of coercive deployment:** SILDF-based training must not be implemented coercively, punitively, or as a tool for attrition rather than development. Programs that frame stress exposure as a test of worthiness, use stress to weed out learners rather than develop them, or use performance data as grounds for professional exclusion are ethically problematic and, from a SILDF perspective, likely to build threat rather than challenge appraisal tendencies, undermining the framework's core mechanisms.

10. Limitations and Boundary Conditions

No theoretical framework is without limitations. Transparent acknowledgment of SILDF's constraints is essential for accurate interpretation of its scope and appropriate calibration of confidence in its propositions. This section addresses four categories: theoretical limitations (construct specification complexity, domain tailoring requirements, causal direction ambiguity); neurobiological measurement constraints (field neural measurement limitations, individual variability); the tension between stress fidelity and ethical safety; and cultural and contextual generalizability (primarily WEIRD populations). These limitations do not invalidate SILDF but identify priority areas for future refinement and investigation.

10.1. Current Theoretical Limitations

SILDF, as a new theoretical framework, carries several important limitations that must be acknowledged transparently to support accurate interpretation of the model's scope and appropriate calibration of confidence in its propositions.

- **Construct specification complexity:** SILDF proposes a multi-stage, multi-mechanism, multi-moderator framework that, while theoretically comprehensive, generates substantial complexity in empirical testing. The number of interacting constructs means that clean, unconfounded tests of individual propositions require experimental designs of considerable sophistication, and that the cumulative evidence base needed to confirm or disconfirm the framework as a whole will require sustained multi-site research programs rather than individual studies. Current evidence for many specific SILDF propositions must be regarded as preliminary and directionally consistent rather than definitive.
- **Domain tailoring requirements:** While SILDF is proposed as domain-general, the specific operationalization of S^* cues, schema structures, stress induction approaches, and outcome measures requires substantial domain-specific expertise for each application context. The framework's domain-generalizability is a theoretical claim about shared underlying mechanisms that must be empiri-

cally validated across domains rather than assumed, and current cross-domain evidence is insufficient to establish confident domain-general claims for all SILDF propositions.

- **Causal direction ambiguity in field studies:** Longitudinal field studies are essential for testing SILDF propositions about transfer and long-term retention, but are inherently less causally definitive than controlled laboratory experiments. Observed relationships between SILDF training components and operational performance outcomes in field studies may reflect selection effects, parallel development processes, or shared third variables rather than the causal mechanisms SILDF proposes. Multi-method triangulation across laboratory, simulation, and field contexts is necessary to build confident causal claims.

10.2. Neurobiological Measurement Constraints

- **Field neural measurement limitations:** The neurobiological substrates specified in Section 4—particularly prefrontal cortical dynamics, hippocampal-striatal competition, and amygdalar reactivity—are most precisely measurable through techniques including high-resolution fMRI and intracranial EEG that are fundamentally incompatible with authentic high-stress performance environments. The EEG and physiological measures proposed in the empirical research program provide valuable but imperfect windows into these neurobiological processes, creating a persistent gap between the neurobiological specification of SILDF mechanisms and the measurement approaches available in ecologically valid contexts.
- **Individual variability in neurobiological expression:** The neurobiological mechanisms specified in SILDF represent population-level generalizations drawn from group-average findings in neuroscience research that may not adequately capture the substantial individual variation in how these systems function and respond to stress. Individual differences in HPA axis reactivity, LC-NE system sensitivity, amygdalar threat-detection thresholds, and prefrontal regulatory capacity mean that the same stress intensity and S* cue training protocol may produce substantially different neurobiological outcomes across learners—variability that current SILDF specification addresses through moderator variables but that likely requires more granular individual-level neurobiological assessment than is currently feasible in training contexts.

10.3. Stress Fidelity and Ethical Balance

Ecological validity versus ethical safety: The stress exposures that would most powerfully test SILDF propositions and most effectively build stress-resilient performance—authentic operational stress with genuine high-stakes consequences—are the exposures that raise the most serious ethical concerns about participant safety, distress, and potential harm. Stress fidelity in laboratory and simulation research is necessarily limited by ethical constraints that prevent the use of genu-

inely life-threatening, professionally consequential, or psychologically traumatizing stress exposures, creating an inherent tension between ecological validity and ethical protection that SILDF research cannot fully resolve but must explicitly manage.

10.4. Cultural and Contextual Generalizability

The theoretical constructs, empirical findings, and training design principles that constitute SILDF have been developed primarily from research conducted in WEIRD (Western, Educated, Industrialized, Rich, Democratic) populations and institutional contexts. The generalizability of SILDF mechanisms—and particularly the specific S* cue meanings, appraisal processes, and regulatory strategies the framework proposes—to non-WEIRD populations and contexts requires direct empirical investigation rather than assumption. Cultural variation in stress conceptualization, regulatory norms, social-evaluative contexts, and performance values may substantially moderate SILDF mechanisms in ways that current specification does not adequately capture.

11. Discussion

This final section integrates SILDF's theoretical, empirical, and practical contributions, positioning SILDF as an integrative advance bridging historically separate research traditions—stress and cognition, learning and memory, skill acquisition, emotion regulation, and applied performance psychology—within a unified, mechanistically specified framework. Implications for theory and empirical research include cue-schema association dynamics over extended timescales, individual differences and personalized training, team-level processes, and neural mechanisms of cue-driven schema retrieval. Translational priorities are identified: validated S* cue libraries, technology standards, and implementation science for real-world adoption.

11.1. SILDF as an Integrative Advance

SILDF bridges separate research traditions within a unified, mechanistically specified, empirically tractable framework. Its central conceptual innovation—explicit linkage of discriminative cue mechanisms to stress-and-performance theory through the S* cue construct—provides a new organizing principle for understanding how training builds stress-resilient performance and designing training systems that exploit identified mechanisms.

By proposing that stress effects on performance are conditional phenomena shaped by cue structure, training history, appraisal context, and regulatory capacity, SILDF reframes the training design challenge from “protecting learners from stress” to “building stress-integrated performance capabilities through systematic engagement with appropriate stress.” This reframing has practical implications for training philosophy, curriculum design, simulation architecture, assessment, and organizational culture across high-stress learning environment.

11.2. Implications for Theory and Empirical Research

SILDF generates a substantial empirical research agenda that extends well beyond the specific propositions and study designs specified in Sections 6 and 7. Several particularly important theoretical and empirical questions merit prioritization in future work:

- **Cue-schema association dynamics over extended timescales:** SILDF proposes that cue-to-schema associations are built through training and updated through performance feedback, but the precise dynamics of association strength over extended timescales—including forgetting curves for cue-schema associations under stress conditions, the effects of disuse on retrieval robustness, and the mechanisms through which refresher training restores degraded associations—remain incompletely specified and empirically underexplored. Longitudinal studies tracking cue-schema association strength from training through extended operational deployment will be essential for understanding how SILDF-trained capabilities evolve over realistic professional timescales.
- **Individual differences and personalized training:** The moderator variables specified in SILDF—regulatory capacity, stress reactivity, stress mindset, allostatic load, challenge-threat appraisal tendencies—suggest that optimal SILDF training approaches may differ substantially across learners with different profiles on these dimensions. Future research should develop and validate personalized SILDF training algorithms that dynamically adjust cue exposure intensity, stress level, regulatory training emphasis, and debrief structure based on individual learner profiles, potentially using machine learning approaches applied to continuous physiological and performance monitoring data.
- **Team-level SILDF processes:** Proposition 8 represents SILDF's most preliminary extension, into collective performance contexts that involve team-level emergent processes not fully reducible to individual-level mechanisms. Future theoretical development and empirical research should substantially elaborate the team-level constructs implied by Proposition 8—including shared mental model formation for S^* cues, collective regulatory dynamics, and team-level cue recalibration processes—and develop team-level SILDF training designs and assessment approaches that are grounded in both team science and SILDF theory.
- **Neural mechanisms of cue-driven schema retrieval:** The neurobiological substrate specification in Section 4 represents the current state of relevant neuroscience but is necessarily incomplete. Future research using high-resolution neuroimaging in ecologically valid simulation contexts—leveraging emerging portable neuroimaging technologies including functional near-infrared spectroscopy (fNIRS) and mobile MRI approaches—should test SILDF's specific neural predictions about the roles of LC-NE system phasic signaling, prefrontal-amygdalar regulatory dynamics, and hippocampal-striatal competition in cue-driven schema retrieval under acute stress.

11.3. Translational Priorities

Translating SILDF from theory to practice requires sustained collaboration among academic researchers, training practitioners, organizational stakeholders, simulation technologists, and learner communities. Time-sensitive priorities include:

- **Validated S* cue libraries for priority domains:** Each high-stress domain requires empirically tested libraries of diagnostically important S* cues—perceptual features, compound structures, reliability profiles, associated schema requirements—developed through expert consensus and validated via field and simulation research. This is a prerequisite for systematic SILDF-based training design.
- **Technology standards for SILDF measurement and training:** Wearable physiological monitoring, VR simulation, and AI-adaptive calibration technologies are evolving rapidly with significant variation in quality and validity. Establishing technology standards (minimum specifications, validation requirements, interoperability, data security) will accelerate research and training implementation.
- **Implementation science for SILDF adoption:** Well-designed SILDF training will fail without adequate organizational support. Implementation science frameworks should identify organizational, cultural, resource, and leadership factors predicting successful adoption and develop evidence-based support packages addressing identified barriers.

12. Conclusion

Learning and decision-making under stress are not peripheral concerns in professional education and training—they lie at the core of preparing practitioners for the authentic demands of high-stakes careers in which the consequences of performance failure are measured in human lives, institutional trust, and societal welfare. The Stress-Integrated Learning and Decision Framework provides a theoretically coherent, mechanistically specified, empirically tractable, and formally falsifiable account of how discriminative stress cues shape the full arc of high-stakes performance—from perceptual detection through appraisal and arousal modulation, schema retrieval and cognitive control, real-time action execution, and outcome-based consolidation and recalibration.

SILDF's central contribution is neither the identification of stress as an important performance variable—a point understood for over a century—nor the demonstration that training can build stress-resilient performance—an established finding across many domains. Rather, SILDF's contribution lies in specifying the mechanisms through which well-designed training builds the cue-to-schema associations, regulatory capabilities, appraisal tendencies, and neurobiological preparation that together constitute genuine stress-resilient performance capacity: the ability to perform effectively, efficiently, and reliably under conditions that would devastate the unprepared.

By grounding training design recommendations in specified neurobiological mechanisms, by generating formally falsifiable propositions testable across laboratory, simulation, and field contexts, by addressing the full range of individual differences and contextual moderators that shape SILDF effectiveness, by explicitly prioritizing equity, accessibility, and learner well-being as non-negotiable design constraints, and by proposing a translational research agenda that bridges theoretical specification and practical implementation, SILDF offers the comprehensive theoretical foundation that high-stress learning environments have lacked and urgently require.

The stakes of this enterprise are high. Surgeons who lose skilled performance under intraoperative crisis conditions, pilots whose decision-making degrades under emergency stress, military operators who freeze under fire, emergency responders who become cognitively overwhelmed at mass casualty scenes—these are not failures of character or intelligence but failures of training systems that have not yet achieved what SILDF proposes is achievable: the systematic, science-based development of human beings who perform not merely despite stress, but in full integration with it.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendices

Appendix A: SILDF Conceptual Model—Expanded Diagram Description

The full SILDF conceptual model can be visualized as a **five-layer sequential processing architecture** embedded within a surrounding field of moderating influences. Reading from left to right, the model proceeds through the following components:

- **Layer 1—S* Cue Environment:** A multi-modal input field representing the range of discriminative stress cue sources—environmental/situational cues (visual, auditory, spatial), physiological/interoceptive cues (heart rate elevation, respiratory change, muscle tension), social-evaluative cues (evaluator presence, audience, supervisor observation), task-structural cues (time pressure indicators, complexity signals, consequence salience markers), and compound cue configurations (multiple simultaneous cue sources). Arrows from this field converge on Stage 1.
- **Stage 1—S* Cue Detection and Attentional Capture:** Represented as a filter and amplifier node, with efficiency parameters determined by training history and current vigilance state. Outputs include attentional capture strength, cue identification confidence, and priming signal to Stage 3. Bidirectional connections to the LC-NE system neurobiological substrate. Failed or degraded cue detection at Stage 1 feeds back to the cue environment as a missed detection signal.
- **Stage 2—Appraisal and Arousal Modulation:** Represented as a dual-process evaluation node with primary appraisal (relevance assessment) and secondary appraisal (resource evaluation) sub-components feeding into a challenge-threat appraisal outcome node. The challenge-threat outcome drives a forked arousal pathway: challenge appraisal drives adaptive cardiovascular reactivity (increased cardiac output, stable vascular resistance); threat appraisal drives maladaptive reactivity (increased vascular resistance). Both pathways feed arousal level as a parametric input to Stage 3. Regulatory intervention inputs—arousal reappraisal, stress mindset activation, paced breathing—enter at Stage 2 as modulators of the appraisal outcome and the arousal pathway selection.
- **Stage 3—Schema Retrieval and Cognitive Control:** Represented as a competitive retrieval network with multiple schema candidate nodes weighted by cue-match strength, training-determined association weights, and contextual appropriateness signals. Executive control inputs—working memory capacity, inhibitory control, cognitive flexibility—modulate retrieval competition resolution. Outputs include selected schema identity, retrieval confidence, and residual working memory capacity for Stage 4. Prefrontal-amygdalar dynamics and hippocampal-striatal competition are represented as neurobiological constraint parameters acting on retrieval competition resolution.
- **Stage 4—Action Selection, Execution, and Real-Time Regulation:** Represented as a motor and cognitive output node with parallel streams for proce-

dural/motor execution and cognitive/communicative execution, both guided by the schema output of Stage 3. Real-time monitoring loop feeds error detection signals back into the execution stream. Regulatory action sub-components—embedded within schemas as trained procedural elements—are represented as integral action nodes within the execution sequence rather than as external inputs. Team communication outputs are represented as connecting arrows to other agent nodes in collective performance configurations.

- **Stage 5—Feedback Integration, Consolidation, and Cue Recalibration:** Represented as a multi-process update node receiving outcome feedback from Stage 4 and from external sources (instructor feedback, objective performance data, peer assessment). Three sub-processes are shown: feedback integration (encoding performance outcome representations), stress-modulated consolidation (HPA axis influence on memory trace strength), and cue recalibration (dopaminergic reward-prediction error updating of cue-schema association weights). Updated association weights feedback to Stage 3's retrieval network and updated cue salience weights feedback to Stage 1's detection filter, closing the recursive learning loop.
- **Surrounding Moderator Field:** Represented as a surrounding envelope acting on Stages 2-5, with labeled moderator arrows indicating the entry point and direction of influence for each moderator: regulatory capacity (amplifying Stages 2 and 4), training history (amplifying Stage 3), stress reactivity (constraining Stage 2 arousal modulation), appraisal tendencies (shaping Stage 2 outcomes), chronic stress and allostatic load (attenuating Stages 2, 3, and 5), group context and team dynamics (extending Stage 4 to collective outputs and Stage 5 to collective debrief), and cultural and contextual factors (shaping cue meaning throughout).

For a complete summary of the eight formal propositions and their falsifiability criteria, see Appendix B.

Appendix B: Summary of SILDF Propositions and Falsifiability Criteria

Proposition	Formal Statement (Condensed)	Falsifiability Criterion
1	Reliable S* cues that consistently predict high-stakes demands produce faster schema retrieval, higher accuracy, and smaller performance decrements under stress than matched performance demands presented without S* cue marking.	Disconfirmed if reliable S* cue training produces no significant reduction in decision latency or improvement in accuracy under matched stress across at least two independent domains with adequate power, or if benefits disappear when controlling for total practice time.
2	Pairing S* cues with successful schema execution during training produces stronger, more stress-robust cue-to-schema associations than equivalent training volume without explicit cue-outcome pairing.	Disconfirmed if explicit cue-success pairing produces no advantage over equivalent practice without pairing in at least two pre-registered replication studies using matched practice volume controls.
3	Individual differences in emotion regulation capacity, stress mindset, and trait challenge-versus-threat appraisal significantly moderate SILDF training effectiveness and stress-resilient performance outcomes.	Disconfirmed if these moderators show no significant moderating effects on training outcomes across three or more well-powered independent pre-registered studies with adequate measurement fidelity.
4	Multicontext S* cue exposure (varying environmental, task, social, and arousal features) produces superior transfer of stress-resilient performance to novel high-stress contexts compared to single-context training of equal volume.	Disconfirmed if multicontext training produces no significant transfer advantage over single-context training in novel high-stress contexts across two or more pre-registered replications with adequate transfer-versus-retention assessment.
5	The effectiveness of S* cue-driven schema retrieval is a nonlinear (inverted-U) function of arousal; appraisal and regulation interventions widen the effective arousal range, extending performance maintenance to higher absolute arousal levels.	Disconfirmed if the arousal-retrieval relationship is linear rather than curvilinear, or if appraisal/regulatory interventions produce no significant shift in the effective arousal window across two or more well-powered studies with continuous physiological monitoring.
6	Learners receiving structured metacognitive training plus systematic post-performance debriefs develop faster SILDF skills, more accurate self-assessment, and superior long-term retention compared to those without these components.	Disconfirmed if metacognitive training and structured debrief produce no significant advantage over training-only conditions in at least two well-powered pre-registered studies, or if improved self-assessment calibration does not predict superior transfer performance.
7	Higher allostatic load negatively predicts SILDF training effectiveness (slower learning, less stable retrieval under stress, greater performance decrement); reducing allostatic load prior to training enhances outcomes.	Disconfirmed if allostatic load indices show no significant predictive relationship with SILDF training effectiveness in two or more adequately powered longitudinal studies, or if allostatic load reduction interventions produce no enhancement of subsequent training outcomes.
8	In team contexts, shared cue recognition (consistent team representations of S* cue identities and response schemas) predicts collective performance under stress beyond individual members' training; team-level SILDF training produces superior collective performance compared to aggregated individual training.	Disconfirmed if team-level SILDF training produces no significant collective performance advantage over aggregated individual training in two or more well-powered team studies, or if shared mental model quality does not mediate the relationship between team training and collective outcomes.

Note: Full mechanistic rationales, testable predictions, experimental designs, and proposed analytic approaches for each proposition are provided in Sections 6.1 through 6.8 of the main text.

Appendix C: Recommended Measurement Battery for SILDF Research

Cognitive and Performance Measures

- Operation Span Task (OSPAN)—working memory capacity
- Reading Span Task—working memory capacity (alternative)
- N-Back Task—updating component of executive function
- Domain-specific performance rubrics (expert-validated per domain)
- Transfer assessment batteries (near and far transfer, domain-specific)
- Error detection and correction rate protocols

Self-Report Measures

- Stress Mindset Measure—Brief (SMS-4) (Crum et al., 2013, 2017)
- Emotion Regulation Questionnaire (ERQ) (Gross & John, 2003)
- State-Trait Anxiety Inventory (STAI) (Spielberger, 1983)
- Cognitive Appraisal Questionnaire (challenge-threat) (Jones et al., 2009)
- Maslach Burnout Inventory (MBI) (Maslach et al., 2016)
- Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989)
- Recovery-Stress Questionnaire (REST-Q) (Kellmann & Kallus, 2001)
- Perceived Stress Scale (PSS-10) (Cohen et al., 1983)
- Metacognitive Awareness Inventory (MAI) (Schraw & Dennison, 1994)

Physiological Measures

- Salivary cortisol (ELISA or luminescence immunoassay)—HPA axis
- Salivary alpha-amylase—sympathetic/noradrenergic activation
- Heart rate variability (RMSSD, LF/HF ratio)—autonomic regulation
- Impedance cardiography (cardiac output, total peripheral resistance)—challenge-threat cardiovascular profiling
- Electrodermal activity (skin conductance level and response)—sympathetic arousal
- Pupillometry (task-evoked pupil dilation)—LC-NE activation and cognitive load
- Eye-tracking (fixation duration, saccade patterns, AOI transitions)—attentional behavior

Neural Measures

- EEG: N2 and P3 ERPs—cue detection and attentional allocation
- EEG: Frontal theta power—prefrontal cognitive control engagement
- EEG: Alpha power suppression—cortical activation
- EEG: Error-related negativity (ERN)—error detection efficiency
- fNIRS: Prefrontal oxygenation—cognitive control under naturalistic stress (portable, simulation-compatible)

Team-Level Measures

- Shared Mental Model Questionnaire (SMM-Q; adapted per domain)
- Team communication coding scheme (expert-developed, domain-specific)
- Team performance rubrics (expert-validated, domain-specific)
- Collective efficacy scale (adapted from Riggs et al., 1994; Riggs & Knight, 1994)
- Psychological safety scale (Edmondson, 1999)

Appendix D: SILDF Training Program Implementation Checklist

The following checklist is provided as a practical implementation guide for training designers and program directors seeking to develop SILDF-informed training programs across high-stress learning domains. Items are organized by implementation phase.

Phase 1: Needs Analysis and Program Design

- Conduct systematic S* cue identification through structured expert interviews, critical incident analysis, and operational observation
- Validate S* cue library through expert consensus panel with inter-rater reliability assessment
- Develop domain-specific schema library with expert validation and training volume specifications
- Conduct baseline learner assessment: domain knowledge, regulatory capacity, stress reactivity, allostatic load, stress mindset
- Design graduated stress exposure arc across program duration
- Develop assessment and feedback system with expert-validated performance rubrics
- Establish learner well-being monitoring protocol and intervention thresholds
- Conduct equity and accessibility review with diverse stakeholder consultation
- Establish ethics governance framework and obtain required approvals

Phase 2: Instructor Preparation

- Train instructors in SILDF theoretical foundations and training design principles
- Train instructors in trauma-informed facilitation and distress recognition
- Train instructors in structured debrief facilitation methodology
- Train instructors in physiological monitoring interpretation for training calibration
- Establish instructor calibration and quality assurance protocols

Phase 3: Program Delivery

- Deliver stress mindset and arousal reappraisal instruction before stress exposure begins
- Implement Stage 1 cue detection training with immediate feedback
- Implement Stage 2 regulatory skill training with biofeedback support
- Implement Stage 3 retrieval practice with appropriate variability and stress exposure
- Implement Stage 4 real-time regulation and error recovery training
- Implement Stage 5 structured debrief after each significant performance episode
- Monitor cumulative well-being indicators and apply intervention protocols as needed
- Adjust individual training parameters based on physiological monitoring and performance data

Phase 4: Transfer Assessment and Longitudinal Follow-Up

- Administer standardized near and far transfer assessments at specified intervals
- Collect operational performance indicators where feasible and ethically governed
- Assess retention at one month, three months, and twelve months post-training
- Monitor long-term well-being outcomes including burnout, sleep quality, and perceived recovery
- Conduct program evaluation and iterative refinement based on outcome data