theoretical and applied ergonomics

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Review

Ergonomics Must Take Cognitive Capacity Seriously

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Abstract

Decades of research demonstrate that vigilance deteriorates rapidly and reliably and is often resistant to motivational override, yet ergonomic practice continues to assign monitoring tasks on assumptions the evidence does not consistently support. This paper argues that attentional capacity may be genuinely bound by biological architecture rather than merely variable in response to conditions. Drawing on empirical research and occupational vigilance data, we argue for what might be understood as a recovery of the foundational human factors philosophy of accommodation, calling for ergonomic design to redistribute cognitive work across human and machine capabilities in ways that respect the real limits of human attention.

Keywords: vigilance decrement; sustained attention; ergonomic design

1. Introduction

There is a quiet but consequential assumption embedded in the design of many safety-critical systems: that human attention, though fallible, is ultimately malleable. That with better training, clearer interfaces, more engaging tasks, or stronger motivation, operators can be reliably sustained in their vigilance. This assumption is not simply optimistic. In many contexts, it is dangerous. The cognitive psychology literature has long documented what was first captured in systematic form over seven decades ago: sustained attention deteriorates over time in ways that are robust, replicable, and resistant to motivational override [1]. Yet the field of ergonomics and human factors has been slower than it might be to absorb the full implications of this evidence. System designs continue to assign monitoring tasks to human operators over timescales that exceed plausible attention limits. Performance standards are written as if lapses reflect deficient training rather than biological necessity. Incident analyses cite human error without adequately grappling with whether the attentional demands placed on those humans were ever realistic in the first place.

This piece argues that the ergonomics and human factor community needs a more explicit and theoretically grounded engagement with the possibility that human attention is not merely variable or fatigable, but genuinely finite. Not infinitely extensible given the right conditions but potentially bounded by constraints in cognitive architecture that no amount of engineering around the periphery can fully dissolve. This remains an open empirical question. But the available evidence, reviewed here across cognitive and applied domains, is sufficiently compelling to warrant reconsideration of how we design systems and assign human roles within them.

It should be noted that the philosophy of accommodation is not a novel introduction to the field. Fitts and Jones [2] established, through their landmark analyses of pilot error,

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that design must begin with the human operator rather than expect operators to adapt indefinitely to technology-driven demands. Hollnagel and Dekker [3,4] have each reflected on how the human factors tradition emerged from precisely this orientation, recognising that technology must be shaped around human capabilities and limits rather than the reverse. The argument advanced here is therefore better understood as a call for a recovery of the philosophy of accommodation as it applies to the specific and well-documented challenge of sustained attention limits, where current practice has diverged from those founding principles.

2. The Vigilance Problem Has Not Been Solved

The vigilance decrement is among the most replicated findings in applied cognitive psychology, and the occupational literature leaves little room for optimism about our current management of it. Across aviation, nuclear power, surveillance, healthcare monitoring, and aquatic safety, the pattern holds with striking consistency: sustained monitoring performance declines over time, errors accumulate, and even highly experienced, highly motivated operators are not immune [5]. Employees in high-vigilance occupations have been found to experience twice the accident severity of those in low-vigilance roles [6]. Nuclear facility operators predictably disengage from monitoring tasks over time, with critical mode errors going undetected in systems explicitly designed to support attentional control [7].

Influential arguments have been made that laboratory vigilance findings do not always translate straightforwardly to real-world operational settings [8], and that experienced operators in some contexts can compensate strategically, drawing on situation awareness and procedural knowledge in ways that attenuate the decrement observed under controlled conditions [9]. These perspectives deserve acknowledgement, and they are a reminder that the magnitude of vigilance decrements in applied settings is shaped by moderating factors, including task structure, operator experience, feedback availability, and the broader system context. The argument advanced in this paper is not that all monitoring fails uniformly, but that the underlying capacity constraints are real and insufficiently reflected in how systems are designed, particularly where tasks are passive, prolonged, or require detection of rare events.

What is perhaps most sobering is the speed at which these failures emerge. A recent scoping review of occupational vigilance research identified consistent performance deterioration within just 5 to 15 min of task onset across military, healthcare, nuclear, air traffic control, and aquatic safety contexts, with effect sizes frequently exceeding $\eta 2p = 0.70$, indicating that the majority of performance variance is attributable to time-on-task alone [5]. Radiologists show marked increases in processing time and reduced diagnostic accuracy following overnight shifts [10], while Navy personnel with poor sleep quality demonstrate substantially more attentional lapses over multi-day operational periods [11]. In lifeguard surveillance specifically, decrements have been observed as early as five minutes into continuous monitoring, with working memory capacity, experience level, and bather density each moderating but never eliminating the underlying decline [12]. The pattern across these studies is not one of isolated or context-specific fragility. It is a portrait of a cognitive system operating at or beyond its sustainable limits, consistently and predictably, across the very roles in which reliable performance is most consequential.

What remains underappreciated, despite decades of consistent evidence, is how poorly current theoretical frameworks account for the apparent absoluteness of these limits. Dominant theoretical accounts, including resource theory, the multiple resource model, and the resource-control account, each offer valuable explanatory tools [13–15]. But they share, to varying degrees, a conceptual commitment to attention as something that can be restored,

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redirected, or strategically managed to maintain adequate performance over sustained durations. The resource-control account explicitly proposes that better executive strategies can offset vigilance decrements [15]. If that were reliably achievable in operational settings, the pattern documented across decades of field and laboratory research would look rather different from how it does. It should be acknowledged that researchers working within the resource theory tradition, including Warm, Parasuraman, and colleagues [16–18], have long engaged with the ergonomic implications of resource depletion and have made substantive contributions to understanding how task design and workload interact with vigilance. The critique offered here is not of those contributions, but of how the broader concept of manageable attentional resources has sometimes been interpreted to imply that careful design can reliably prevent performance decrements under sustained monitoring conditions.

It is worth noting that the original authors of these frameworks were not, in most cases, proposing theories of occupational performance management. Kahneman's [13] treatment of attention as a limited resource was a theoretical account of cognitive architecture, not a blueprint for shift scheduling. Wickens' multiple resource model was developed to understand the structure of human performance limitations, not to licence assumptions that those limitations can be worked around with sufficient task design ingenuity [14,15]. Thomson and colleagues were similarly concerned with the mechanistic underpinnings of vigilance failure, not with providing operational guidance [15]. Yet these frameworks have migrated into applied and occupational contexts in ways their authors may not have intended or anticipated, often cited as theoretical justifications for the belief that attention is sufficiently manageable that demanding monitoring tasks can be assigned to human operators with confidence. The gap between what these theories propose and how they are sometimes invoked in practice is, in itself, a problem worth naming. A theory that acknowledges attentional limits while identifying mechanisms of partial restoration or strategic compensation is a quite different thing from a theory that implies those limits are practically surmountable in real-world operational conditions. The conflation of these two positions has arguably contributed to a design culture that persistently overestimates what human operators can reliably sustain and underinvests in the structural accommodations that the evidence base suggests are necessary.

This is not to dismiss these frameworks, which capture real phenomena and have informed genuinely useful practical guidance. It is, however, to suggest that they may not be asking the right question. The question is not merely how attention depletes and recovers, but whether there are hard ceilings on how long useful vigilance can be maintained, and what that might mean for how we distribute cognitive work.

3. Case for Bounded Attention

There are good reasons to suspect that attentional limits are not simply motivational or strategic in origin. Research on attentional rhythms has demonstrated that perceptual sensitivity fluctuates periodically during sustained monitoring, suggesting that these fluctuations may be architectural features of how the attentional system operates rather than products of inattentiveness or poor effort [19,20]. Arousal-related processes that support focused task engagement appear subject to constraints that reassert themselves regardless of task importance or operator intention [21,22].

Evidence from cognitive neuroscience further suggests that the attentional system may require periodic internal cycling to sustain performance, with spontaneous attentional fluctuations occurring in ways that are not fully under voluntary control [23–25]. A meta-analysis of sustained attention paradigms identified consistent time-on-task degradation across a range of conditions designed to maintain engagement [26], and individual differences in sustained attention capacity appear to reflect stable underlying traits with meaningful predictive validity for real-world performance [27].

What this convergent evidence tentatively suggests is that attention fluctuations may be features rather than bugs, and that the system has functional rather than merely motivational timelines for recovery. Recovery from attentional depletion associated with sleep disruption follows predictable patterns that are resistant to motivational enhancement [28], and the parallel with vigilance depletion during prolonged monitoring, while not yet fully established, is sufficiently plausible to warrant design assumptions that err on the side of caution rather than optimism. It is also worth acknowledging that motivational factors can have a genuine, if modest, impact on vigilance performance [29]; the claim here is not that motivation is irrelevant, but that it cannot reliably override the capacity constraints documented across the empirical literature.

Taken together, this evidence raises a question that ergonomics has perhaps been reluctant to confront directly: is there a meaningful sense in which individual attentional capacity represents a relatively stable, biologically grounded ceiling, rather than a more malleable resource that can be pushed substantially upward through the right conditions? The evidence does not decisively establish this, and the distinction between hard and soft limits may itself be too blunt a framing for what is likely a graded, context-sensitive reality, but the question deserves explicit theoretical treatment rather than being dissolved into operational assumptions about trainability and motivation. Individual differences research adds important texture here. Sustained attention ability has been shown, across a sample of ten thousand participants, to follow a developmental trajectory with a performance peak in young adulthood and subsequent gradual decline, with even peak performers showing consistent vigilance decrements [30], and latent variable analysis has demonstrated that individual differences in attentional lapses reflect stable underlying traits with meaningful psychometric structure [31]. The implication is not that individual screening can eliminate vigilance failures, but that capacity variation is real, moderately stable, and relevant to role assignment and system design in ways that current practice does not always reflect. Crucially, elite performance data does little to challenge this picture. Experienced meditators, whose training is specifically directed at attention regulation, demonstrate ongoing attention fluctuations and eventual performance decrements on objective measures [32]. Superior performance in these populations appears to represent optimised management of attentional resources rather than transcendence of the underlying biological constraints, though it should be noted that this interpretation remains open to debate and that alternative accounts of meditation-related attentional improvement have been proposed. If that interpretation is correct, it carries significant implications for how we evaluate the likely returns on operator training programmes designed to extend vigilance, and it lends further weight to the proposition that accommodation, rather than enhancement, may be the more productive design philosophy.

4. What This Means for Ergonomics and Human Factors

The practical implications of taking seriously the possibility that human attention operates within substantial and potentially hard biological limits are significant, challenging some deeply embedded assumptions in how we design roles, allocate tasks, and interpret performance failures in safety-critical domains. Perhaps the most immediate of these concerns time-on-task standards. If attention capacity has genuine ceilings that are reached on timescales of minutes rather than hours for certain monitoring tasks, then shift patterns, rotation schedules, and break intervals across aviation, security surveillance, healthcare monitoring, and process control need revisiting in light of attention research rather than operational convenience or training doctrine. The field currently lacks agreed standards for maximum continuous monitoring durations grounded in the empirical literature on vigilance decrements, and this is a gap with real consequences. That gap exists in part because standard-setting bodies, professional associations, and regulatory frameworks in safety-critical industries have not yet integrated the vigilance literature systematically into workforce and scheduling guidance; closing it would require coordinated effort across professional bodies, regulators, and research communities rather than being addressable by any single disciplinary intervention. Performance decrements as a result of continuous scanning in lifeguarding have been discussed repeatedly, which of course represents a domain-specific calibration point [12,33], and comparable systematic work is urgently needed across other monitoring-intensive roles.

Closely related is the question of how monitoring tasks are assigned within increasingly automated systems. The role of the passive monitor, watching automated systems for rare and unpredictable failures, is perhaps the worst possible fit for human attentional architecture, yet it is precisely the role that automation most commonly leaves to the human operator. This concern is becoming more acute as artificial intelligence systems are deployed as the primary decision-support layer in high-stakes monitoring domains. AI-assisted radiology tools, algorithmic triage systems, and machine learning-based anomaly detection platforms in process control and intensive care all share a structural feature that is directly relevant to the argument advanced here: they transform the human operator's task from active detection to passive oversight and exception-handling of algorithmic output. This is precisely the configuration that the vigilance literature identifies as most hostile to sustained human attentional engagement. As AI system reliability increases, operators are likely to disengage further from active monitoring, meaning that when the AI makes a mistake, the human monitor may be least prepared to detect and correct the failure. This represents a tighter and more consequential version of the out-of-the-loop problem, one that the accelerating deployment of AI in safety-critical settings makes increasingly urgent to address. Latent conditions, including design and organisational factors, have been identified as at least as important as active failures in the moment in complex system accidents [34]. A vigilance decrement in a fatigued operator monitoring a poorly designed display for several hours is not primarily an operator failure; it is a system design failure that could have been anticipated from what the attention literature has been saying for decades.

The vigilance risks associated with AI-assisted monitoring are not limited to individual operator disengagement. Where multiple operators work within the same AI-supported monitoring environment, there is a further risk that socially distributed attentional responsibility becomes diffuse: each member of a team may reasonably assume that others, or the AI system itself, will catch failures that in a purely human monitoring configuration would have required active individual detection. This is a distinct problem from individual vigilance decrement and one that, to the authors' knowledge, team-level research on shared situational awareness and responsibility attribution is only beginning to address in the context of human-AI systems, with very limited empirical work currently available that speaks directly to how attentional responsibility is distributed in teams operating alongside AI monitoring tools.

What would it look like to design a programme of research that takes these implications seriously? Several directions are worth identifying. At the applied empirical end, studies examining the real-world consequences of passive monitoring roles in increasingly automated systems, such as human supervisors in semi-autonomous vehicle contexts or operators overseeing AI-assisted diagnostic platforms, would provide ecologically valid tests of how attentional limits interact with automation-induced complacency and out-of-the-loop syndrome. The recent growth of autonomous vehicle technology offers a particularly high-visibility test case: how quickly does a human monitor disengage from a system that rarely fails, and what does this mean for intervention capability when it does? At a more theoretical level, studies designed to identify the boundary conditions of attentional capacity under varying task event rates, feedback schedules, and team configurations would help establish whether the limits documented in the literature are genuinely hard or are more malleable under specific design conditions. Intervention studies comparing accommodation-based approaches, such as structured rotation, adaptive automation, and operator state monitoring, against enhancement-based approaches in equivalent operational simulations would provide directly actionable guidance for system designers. Finally, longitudinal research on the cumulative effects of sustained monitoring roles on operator wellbeing and error rates across careers would give the field data on which to base more principled standards for maximum monitoring durations, shift lengths, and role assignment criteria.

The question of how attentional demands are distributed across teams, rather than individuals, also warrants more systematic treatment than the ergonomics literature has yet provided. Many safety-critical monitoring roles are embedded in team contexts where cognitive load sharing, cross-checking, and social accountability all bear on vigilance performance. Whether team-level configurations can materially offset the individual biological constraints described in this paper is an open empirical question, but one with direct practical relevance to shift design, role allocation, and the architecture of multi-operator control rooms. The interaction between individual attentional limits and team-level monitoring structures represents, to the authors' knowledge, a substantive gap in the current literature that accommodation-centred design frameworks will need to address.

The enhancement literature also warrants critical scrutiny in applied human factors contexts. More recent work has found that arousal-enhancing agents such as caffeine and modafinil can substantially reduce vigilance decrement, though not eliminate it [35]. These findings are consistent with arousal-based accounts of vigilance, which attribute the decrement in part to declining arousal over time and predict benefits from arousal-enhancing agents under certain conditions. The precise mechanism matters here: if these agents delay the onset of the decrement or attenuate its slope without raising the asymptotic ceiling of sustainable performance, the practical implications are different from a scenario in which they extend the effective duration of high-fidelity monitoring. The available evidence suggests the former is more likely, though the data are not yet sufficient to draw firm conclusions across operational settings, and the authors are not aware of studies that have systematically compared ceiling effects against slope effects in ecologically valid monitoring tasks. Nevertheless, the broader question of whether any intervention can raise the effective ceiling on sustained attentional performance rather than merely optimise performance within existing limits remains open. Pharmacological effects observed under controlled laboratory conditions do not straightforwardly generalise to sustained operational demands, and the distinction matters enormously for how we evaluate likely returns on investment in cognitive enhancement approaches. A related issue concerns how capacity variation is handled in ergonomic assessment. Current approaches to fitness-for-duty evaluation in many safety-critical industries focus heavily on impairment detection, addressing the lower tail of the performance distribution, without adequately considering how sustainable performance capacity interacts with task demands. Ignoring individual capacity variation is not a neutral choice; it embeds implicit assumptions into design standards and performance expectations that may not reflect the reality of what individual operators can reliably sustain.

5. The Human-Technology Interface Question

None of the foregoing implies that human operators should be removed from safety-critical systems, or that the appropriate response to attentional limits is a resigned acceptance of performance failure. The more constructive implication is that system design should work with human attentional architecture rather than against it, and the technical groundwork for doing so is more advanced than institutional practice currently reflects. Discussion in adaptive automation has demonstrated that systems that dynamically adjust automation levels in response to real-time estimates of operator workload can maintain overall system performance while reducing attentional demands at moments of greatest vulnerability, and frameworks for mapping the phases of complex tasks at which human operators outperform automated systems and vice versa provide a principled basis for that kind of dynamic role allocation [36]. Advances in passive monitoring technologies, including portable EEG, pupillometry, and functional near-infrared spectroscopy, are making real-time attentional state estimation increasingly feasible in operational settings [37,38], with pupil dynamics shown to reliably index task disengagement and mental fatigue non-invasively and continuously [39], and saccadic metrics demonstrated to detect surgical residents' fatigue with clinically meaningful sensitivity [40]. Increasingly, machine learning algorithms provide the analytical layer that translates these continuous psychophysiological signals into actionable real-time estimates of operator attentional state, enabling adaptive automation systems to adjust task demands or trigger intervention protocols in response to detected disengagement. The integration of AI-driven operator state monitoring with adaptive automation represents a practically advanced example of accommodation-centred design, one in which technology responds to human limits rather than demanding that humans transcend them. That the institutional and regulatory frameworks for deploying such systems in safety-critical settings remain underdeveloped is not a reflection of technological immaturity but of the absence of validated standards for what these systems must demonstrate before they can be trusted with operational decisions, and, to the authors' knowledge, no safety-critical domain has yet established such standards in a form that would support routine clinical or operational deployment. What has lagged is not the technology but the theoretical and institutional framework that would make deploying it a design priority. These approaches represent exactly the kind of accommodation-centred philosophy that the attentional limits literature calls for: not attempting to engineer out human limitations through training or pharmacology, but designing hybrid systems that maintain overall performance by intelligently distributing cognitive work across human and machine capabilities in ways that are sensitive to the genuine boundaries of sustained human attention.

It is also worth noting that the vulnerability to vigilance decrement is not unique to human operators. Automated systems may themselves introduce attentional risks that deserve more sustained attention in the ergonomics literature. The most well-documented of these is the out-of-the-loop problem: as automation reliability increases, operators become less actively engaged in monitoring, and when automation does fail, the transition back to manual control may occur at precisely the moment when the operator is least prepared to respond effectively. This dynamic represents a systemic mismatch between how automation is typically designed and evaluated, often under assumptions of steady attentional engagement, and how operators respond to extended periods of automated system performance. Handover protocol design deserves particular attention in this context. An accommodation-centred approach to handover would not simply specify when control must be returned to the human operator, but would actively structure the handover event to support re-engagement from a state of attentional underload, potentially incorporating graduated re-engagement sequences, attentional priming procedures, or

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AI-assisted situation summaries that reduce the cognitive demands of the transition itself. To the authors' knowledge, empirically validated handover protocols of this kind do not yet exist in operational form across the safety-critical domains discussed here, representing a further applied research priority. A genuinely accommodation-centred design philosophy must therefore address not only how much monitoring humans can reliably sustain, but also how handover protocols and interface design can support effective re-engagement from states of attentional underload.

6. Conclusions

The central argument here is straightforward, if uncomfortable. The available evidence from cognitive and applied research suggests that human sustained attention may operate within limits that are more absolute than current ergonomic practice tends to assume, limits that appear biologically rooted, relatively stable within individuals, and resistant to motivational and strategic override. None of this is proven to the standard required for strong theoretical commitment, and the field urgently needs more systematic empirical work explicitly designed to test the boundary conditions of attentional capacity rather than simply document its average behaviour. But ergonomics cannot wait for theoretical consensus before acting on what the evidence already implies. Systems are being designed now, roles assigned now, and performance standards written now, on the basis of assumptions about attentional capacity that the literature does not support, and the cost of that misalignment is measured in incidents, errors, and failures that are routinely attributed to the operator rather than to the conditions in which the operator was placed. The vigilance decrement is not a problem that better operators or better training will solve if the task demands imposed exceed what any human attention system can reliably sustain. Recognising that possibility, and designing accordingly, is not pessimism about human capability. It is the application of cognitive science to the design of safer systems, and that, after all, is what ergonomics is for.

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