Designing for human attention

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On a February morning in 2013, a train driver in New York failed to reduce speed approaching a curve, resulting in a derailment that killed four passengers and injured dozens more. The investigation revealed no mechanical failure, no substance impairment, no deliberate recklessness. Instead, the driver had simply experienced what investigators termed a 'daze': a momentary but catastrophic lapse in sustained attention.

Such incidents underscore a fundamental truth that psychology has long established, but society continues to resist: perfect sustained attention is not merely difficult, but theoretically impossible. This presents us with a stark choice. We can continue demanding the impossible from human operators in safety-critical roles, designing systems that require flawless vigilance and then expressing surprise when attention inevitably fails. Or we can accept what the evidence clearly shows and redesign our workplaces, technologies, and expectations around the cognitive architecture we possess.

Psychology has spent decades documenting why sustained attention fails. The time has come to focus on what we do about it.

Understanding the mechanisms of attention failure

The impossibility of perfect sustained attention stems from fundamental properties of neural architecture, rather than individual weakness or insufficient training. Research demonstrates that attention operates through rhythmic oscillations in brain networks, with enhanced and diminished processing occurring several times per second (Fiebelkorn & Kastner, 2019), rendering truly continuous attention impossible even at the millisecond scale. The locus coeruleus-norepinephrine system, crucial for attention regulation, operates in an phasic mode during focused attention (Aston-Jones & Cohen, 2005), which is unsustainable. At the cellular level, GABAergic interneurons show adaptation effects requiring periodic recovery, setting fundamental limits on the duration over which precise attentional control can be maintained (Ferguson & Gao, 2018).

These consequences manifest rapidly in real-world settings, as established by Mackworth's seminal radar operator studies during World War II, which demonstrated that detection performance invariably declines over time (Mackworth, 1948). This 'vigilance decrement' has since been documented across countless contexts and tasks, emerging as one of the most robust findings in attention research (Warm et al., 2008). A meta-analysis of 67 fMRI studies on vigilant attention revealed consistent activation in frontoparietal attention networks during sustained attention tasks, with performance deterioration occurring even when these networks remained engaged (Langner & Eickhoff, 2013).

Most tellingly, this limitation transcends expertise and motivation, with studies of elite military personnel demonstrating that even intensive training cannot enable indefinite maintenance of high vigilance performance (Matthews et al., 2019). Research on experienced meditators reveals that whilst meditation training can enhance attention regulation, it does not eliminate basic constraints on sustained attention (Lutz et al., 2008). Even individuals with exceptional cognitive abilities show inevitable fluctuations and lapses in attention (Kane et al., 2007).

In other words, the universality of these findings across all populations, contexts, and training levels reflects biological boundaries rather than malleable resource limitations.

The mechanisms underlying vigilance decrements prove more complex than simple resource depletion, as revealed by research using the gradual-onset continuous performance task showing that attention failures involve dynamic interactions between multiple brain networks (Esterman et al., 2013). Counterintuitively, regions within the default mode network, traditionally considered 'task-negative', show increased activity during periods of stable attention performance, whilst task-positive networks in the salience and dorsal attention systems show increased activity during periods of unstable attention (Esterman et al., 2013). This suggests that maintaining optimal attention may involve a more efficient cognitive state rather than simply greater effort.

The resource-control theory proposes that executive control resources become depleted over time, compromising the ability to maintain focused attention and increasing vulnerability to mind-wandering (Thomson et al., 2015). Such a framework accounts for findings which pure resource theories struggle to explain, such as the rapid onset of performance decrements and the ability to quickly recover attention with brief breaks.

Individual differences further complicate this picture, with working memory capacity emerging as a critical factor wherein high working memory individuals show superior vigilance performance particularly under high task demands (Unsworth & McMillan, 2014). Whilst experience provides substantial benefits across occupational domains, even these advantages cannot overcome fundamental biological constraints, revealing the limitation of training-based approaches that assume cognitive boundaries can be indefinitely extended through practice or motivation alone.

Where Psychology has made a difference

The recognition that perfect vigilance is impossible need not lead to fatalism. Instead, it provides a foundation for evidence-based system design that acknowledges human cognitive architecture, rather than fighting against it. Psychology has already contributed to practical solutions across multiple domains, though much work remains.

The aviation industry provides perhaps the most mature example of attention-informed design, where psychological research identifying optimal rotation periods for air traffic controllers has directly influenced operational protocols (Parasuraman & Davies, 1977). The National Transportation Safety Board has documented that vigilance failures contribute to approximately 20 per cent of aviation incidents, even with multiple crew members present (NTSB, 2017). Rather than expecting controllers to maintain vigilance for entire shifts, evidence-based guidelines now mandate breaks at intervals determined by vigilance research, not arbitrary scheduling convenience. Adaptive automation systems have been developed that adjust the level of technological support based on real-time assessment of operator state (Parasuraman, 2020). Research has demonstrated that systems matching automation levels to operator workload can significantly improve performance whilst maintaining appropriate human engagement (Matthews et al., 2015). Recent studies have further shown that combining behavioural measures with transcranial Doppler and cerebral oximetry can reveal systematic relationships between blood flow velocity changes and attention performance, providing neurophysiological markers for intervention (Nelson et al., 2014).

Healthcare and industrial settings have similarly begun incorporating attention science into operational practice. Research showing that sustained attention deficits are particularly pronounced during overnight shifts has influenced both shift scheduling and the implementation of decision support systems (Andrade et al., 2020). Some hospitals now use algorithms that flag cases for additional review when completed during periods of heightened vigilance risk, effectively creating a safety net that accounts for inevitable attention lapses. Studies of industrial process control have identified specific attention thresholds at which human operators should transition from direct control to technology-supported monitoring

(Warm et al., 1996). Rather than expecting clinicians to maintain constant vigilance over patient vitals, automated systems now handle routine monitoring with alerts calibrated to account for both signal characteristics and time-on-task effects. This represents a fundamental shift from demanding impossible human performance to designing systems that work harmoniously with cognitive constraints.

Security surveillance and manufacturing contexts further demonstrate how psychological research has shaped operational practices. Studies have shown that human operators should maintain primary monitoring responsibility during periods of high activity or unusual events, whilst automated systems handle routine surveillance during low-activity periods (Donald & Donald, 2015). Research on CCTV operators reveals significant decrements in threat detection performance over time, even when operators are aware of the critical nature of their task and highly motivated to maintain attention (Donald & Donald, 2015). Manufacturing environments have adopted hybrid approaches informed by the key insight that there may be one optimal way to sustain attention but many ways for it to fail, proving valuable in determining which tasks to automate and which require human judgement. Studies demonstrate that task characteristics such as signal salience significantly influence vigilance outcomes, with low-salience signals producing steeper vigilance decrements (Helton et al., 2002). Recent research in aquatic safety exemplifies how systematic psychological investigation can inform operational practice, with studies of lifeguard surveillance demonstrating that performance deteriorates rapidly, with vigilance decrements occurring within five minutes under complex conditions (Sharpe et al., 2023). Continuous eye-tracking reveals that experienced lifeguards maintain more efficient gaze strategies with consistent fixation durations, whilst novices show degraded visual scanning characterised by decreased fixation numbers and increased fixation duration over time (Sharpe & Smith, 2024).

Beyond safety-critical systems, attention science offers practical guidance extending to knowledge work and emerging technologies. The finding that attention operates in rhythmic cycles, with natural fluctuations occurring approximately every 7-12 seconds (VanRullen, 2016), suggests structuring demanding cognitive work in alignment with these cycles rather than fighting against them. Research on flow states indicates that optimal task difficulty can improve sustained engagement, though even optimal conditions do not eliminate attention fluctuations entirely (Ulrich et al., 2016). Emerging technologies offer potential for real-time attention state monitoring, with pupillometry studies showing that pupil diameter changes correlate with task engagement and can predict attention lapses, informing development of monitoring devices (Hopstaken et al., 2015). When participants were informed that remaining task duration depended on their performance, both task accuracy and stimulus-induced pupil dilation increased back to levels seen in initial task blocks, demonstrating the role of motivation in sustaining attention (Hopstaken et al., 2015).

These diverse applications illustrate how accepting cognitive limitations as design constraints, rather than deficiencies to overcome, has proven both theoretically sound and practically valuable across multiple domains.

The Psychology profession's unique contribution

Psychologists occupy a crucial position in translating neuroscience findings into practical applications, bridging domains that neuroscientists and engineers alone cannot connect. Much of the foundational work described above has indeed been conducted by psychologists or teams led by psychological researchers, from Mackworth's original vigilance studies to contemporary work on attention networks and individual differences. Even research employing advanced neuroscience methods, such as the fMRI studies of attention networks, has frequently been driven by psychologists with interests in cognitive neuroscience. Whilst neuroscientists can identify neural mechanisms underlying attention and engineers can build automated systems, psychologists uniquely understand both cognitive architecture and real-world task demands, an interdisciplinary perspective that proves essential for effective system design.

The development of ecologically valid assessment tools represents one key contribution, addressing a longstanding limitation wherein traditional vigilance tasks, whilst methodologically rigorous, often employ simplified detection paradigms with limited relevance to occupational contexts (Donald & Donald, 2015). Psychologists have pioneered approaches that maintain experimental control whilst capturing the complexity of real-world vigilance demands, exemplified by the gradual-onset continuous performance task which removes abrupt stimulus onsets that provide exogenous cues, creating a more sensitive measure of sustained attention fluctuations (Esterman et al., 2013). This methodological innovation reflects a broader shift from laboratory purity towards ecological validity, recognising that findings from oversimplified tasks may fail to generalise to the multifaceted attention demands encountered in operational settings.

Beyond assessment tools, psychologists contribute expertise in individual differences that enables personalised rather than one-size-fits-all approaches to managing attention limitations. Research demonstrates that working memory capacity, attentional control, and fluid intelligence all correlate with vigilance performance (Unsworth & McMillan, 2014), suggesting that psychological assessment can identify individuals at higher risk for attention failures in specific contexts, enabling targeted support strategies rather than assuming uniform cognitive limitations across populations. Studies using the gradual-onset CPT have revealed that sustained attention abilities develop throughout childhood and young adulthood, not beginning to show age-related declines until one's mid-40s (Fortenbaugh et al., 2015), a developmental perspective with implications for age-appropriate task allocation and training approaches that challenge assumptions about peak cognitive performance.

Perhaps most critically, psychologists can advocate for system-level changes that accommodate attention limitations, requiring a fundamental shift beyond deficit-focused models that view attention lapses as failures requiring remediation towards approaches that accept cognitive boundaries as design constraints. Successfully implementing such approaches often requires organisational culture change, a domain where psychological expertise in behaviour change and implementation science proves invaluable, as resistance to accepting imperfect vigilance frequently stems not from technical obstacles but from deeply held beliefs about human capability and professional standards that only sustained psychological intervention can address.

Looking forward

The translation of attention research into practice requires coordinated efforts across different psychological specialisms. Researchers should prioritise developing attention-aware assessment tools feasible for operational settings, identifying biomarkers that predict attention failures before they occur, and conducting long-term studies examining vigilance demands over shifts and careers. The field requires more ecologically valid research conducted in actual work environments with time scales reflecting real occupational demands.

Practitioners should routinely assess sustained attention deficits across clinical populations, recognising that attention impairments often exacerbate other cognitive difficulties. The resource-control theory (Thomson et al., 2015) suggests that attention failures reflect failed executive control rather than depleted resources per se, a conceptualisation with significant treatment implications. Interventions might focus on strengthening control mechanisms through focused attention meditation training, which consistently shows improvements across various populations (Lutz et al., 2008), whilst computer-based cognitive training programmes targeting cognitive control have also demonstrated benefits (Anguera et al., 2013).

Applied psychologists should advocate for system designs that work with cognitive constraints, challenging unrealistic expectations for human vigilance, promoting evidence-based rotation schedules, and ensuring automation supports rather than replaces human operators. The goal is to deploy human attention strategically on tasks requiring contextual understanding, pattern recognition, and adaptive decision-making whilst allowing technology to handle continuous monitoring.

Educators should emphasise attention-aware design principles, integrating human factors psychology, cognitive neuroscience, and applied ergonomics to provide students with tools for addressing real-world attention challenges. Psychologists must also inform policy development around working time regulations and safety standards, educating stakeholders about attention limitations, particularly as many leaders view acknowledging imperfect vigilance as defeatist rather than evidence-based.

The sustained attention paradox, that maintaining focused attention is both essential and impossible (Sharpe & Tyndall, 2025), need not remain a paradox if we accept cognitive limits as design constraints, creating systems where imperfect attention is sufficient. This requires shifting from asking 'How do we achieve perfect vigilance?' to 'How do we maintain safety given inevitable attention lapses?' The universality of vigilance decrements indicates we are confronting biological boundaries, not training deficits. Recent work shows that functional connectivity patterns can predict individual differences in performance (Rosenberg et al., 2016), providing potential biomarkers for early intervention. Emerging approaches show promise, including transcranial direct current stimulation reducing vigilance decrements (Nelson et al., 2014) and neurofeedback training enabling voluntary attention regulation (de Bettencourt et al., 2015). These technologies may provide additional tools for managing attention limitations.

The path forward requires psychologists to move beyond documenting limitations towards actively designing solutions. Perfect sustained attention is theoretically impossible due to fundamental neural properties. The next decades must focus on what we do about it, with psychology's unique position bridging neuroscience, behaviour, and application proving essential. We need more psychologists translating research into real-world solutions.

The train driver who experienced that fatal lapse was neither incompetent nor negligent but human, subject to the same cognitive architecture we all possess. The tragedy lay not in his attention failure, which was inevitable given sufficient time on task, but in a system designed as though such failures were impossible. Psychology can help us design better systems that acknowledge our cognitive reality and work harmoniously with it, reframing the question from whether we can achieve perfect vigilance to whether we will finally accept we cannot, and act accordingly.

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