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Eye movement mechanisms of mind wandering in Monitoring workers: a review

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Abstract

Mind wandering (MW), as a prevalent phenomenon of endogenous attention shift, significantly impacts operational safety and decision-making efficiency in sustained monitoring tasks. This review integrates advancements in cognitive neuroscience and eye-tracking technology to systematically explore the visual characterization mechanisms of MW and its intervention strategies. Studies indicate that ocular features during MW—such as gaze fixation, nonlinear pupillary dynamics, and simplified saccadic patterns—exhibit significant correlations with declines in task performance, particularly in high-risk scenarios like driving and industrial monitoring. Real-time monitoring systems based on multimodal eye-tracking metrics (gaze entropy, pupillary fluctuation index, and saccadic velocity) have achieved 89.7% detection accuracy, while dynamic task adjustment and neurofeedback training effectively prolong sustained attention. Future research must address technical challenges like baseline drift and individual variability to advance third-generation quantum eye-tracking technologies in industrial safety. This paper provides a theoretical and technical framework for constructing attentional failure early-warning systems.

Keywords

Eye movement techniques; Cognitive mechanism; Mind wandering; Monitoring workers

1. Introduction

Mind wandering, a core feature of human consciousness, involves the unconscious shift of attentional resources from current tasks to self-generated thoughts (Smallwood & Schooler, 2015). In high-stakes environments such as nuclear power plant control rooms and air traffic control, operators experience MW episodes lasting 10–15 seconds every 4–7 minutes, increasing the missed detection rate of critical risk signals to 3.2 times baseline levels (Song et al., 2012). Traditional MW detection relying on subjective reports suffers from task interference and recall bias (Weinstein, 2018). With eye-tracking technology achieving temporal resolutions exceeding 10 ms (SR Research EyeLink 1000 Plus), objective physiological metrics—including gaze patterns and pupillary dynamics—now enable precise MW identification. This review synthesizes cognitive mechanisms, ocular characterization, and technological applications to establish a closed-loop model linking cognitive failure, ocular anomalies, and safety risks, offering cross-disciplinary solutions for cognitive state monitoring in high-risk industries.

2. Cognitive Characteristics and Behavioral Risks of Mind-Wandering

2.1.Conceptual identification: definitions and core features

The study of mind wandering originated in the 1950s. With the development of cognitive psychology, scholars have gradually recognized the important role that flexibility and variability of mind play in human adaptive behavior and mental health. Through experimental settings, neuroscience techniques, and other means, researchers have delved into the processes, mechanisms, and influencing factors of mind wandering. Mind wandering is actually an important cognitive process, which refers to the ability of individuals to flexibly adjust their attention, thinking, and behavioral strategies in the face of changes in tasks, situations, or thought patterns. It centers on cognitive flexibility and adaptability, i.e., the ability of an individual to quickly switch from one mode of thinking to another, or to switch effectively between different tasks. This concept covers a wide range of cognitive functions including, but not limited to, problem solving, creative thinking, and decision-making skills.

Distraction and mind wandering are often confused, but they are fundamentally different in terms of neural mechanisms and behavioral manifestations.Varao-Sousa's (2018) dual-path model states that distraction stems from the capture of attention by exogenous stimuli (e.g., sirens, unusual visual signals); whereas mind wandering manifests as spontaneous thought roaming. This difference is crucial in accident attribution: distraction can be mitigated by environmental optimization (e.g., noise masking), whereas mind wandering requires cognitive training interventions.

2.2.Empirical Evidence in Safety-Critical Contexts

Analysis of large-scale accidents shows that “endogenous attentional defocus” triggered by mind wandering is an important causative factor of industrial accidents. In a coal mine monitoring task, Naiwen Li (2018) found that the frequency of mind wandering of miners was significantly and positively correlated with the incidence of roof accidents ($r=0.68$, $p<0.01$); in a driving scenario, the braking reaction time to sudden obstacles in the MW state was prolonged to 1.8-2.3 seconds (normal level 1.2-1.5 seconds), and the steering wheel correction amplitude error increased by 40% (He et al. 2011). Notably, the harms of mind wandering are task-specific: in the instrument monitoring task, MW mainly leads to signal omission (False Negative rate rises to 28%), whereas in the dynamic decision-making task it manifests itself as a surge in the False Positive rate (Wickens et al., 2021). Dissociation of attention from visual and auditory perception interferes with the task at hand, especially when the task requires continuous task monitoring and sustained attention (Galéra et al., 2012), and its inward shift of attention after prolonged periods of work cannot be ignored.

3. Methods and advances in the study of mind wandering

3.1 Experimental Paradigms and Behavioral Observations

When exploring mind wandering, researchers typically employ a strategy that combines laboratory tasks with natural scene observations to fully capture the multidimensional features of this complex cognitive phenomenon. In the classical laboratory paradigm, the sustained attention response task (SART) has been widely used for its ability to efficiently elicit and detect mind wandering (Robertson et al., 1997). The task requires subjects to inhibit automated key press responses to non-targets and respond only to target stimuli by presenting non-target stimuli (e.g., the numbers "1-9") at high frequency with low-frequency target stimuli (e.g., the number "3"). Because task monotony tends to induce attentional drift, subjects' incorrect responses (e.g., key presses to non-target stimuli) or response delays (>500 ms) can be viewed as objective behavioral markers of mind wandering, the frequency of which was significantly correlated with self-reported degree of wandering ($r=0.71$, $p<0.01$).

To enhance ecological validity, Smallwood et al. (2006) further developed the Choice Reaction Time Task (CRT), embedding a randomized thought probe in a numerical parity judgment task to quantify the frequency of wandering by instantly asking subjects whether they were "focused on the task just now". This method not only correlates behavioral performance (e.g., 28% increase in the coefficient of variation of reaction time) with subjective states of consciousness, but also reveals the effect of task complexity on mind wandering - when the rate of digit presentation was increased from 1Hz to 2Hz, the frequency of wandering decreased by 19% ($p=0.03$).

In order to break through the limitations of the laboratory environment, the researchers gradually extended the observation field to real-life scenarios, such as using multi-angle video cameras in the classroom environment to record students' gaze movement trajectories and facial micro-expressions (e.g., frequent blinking, line-of-sight deviation from the blackboard), and analyzed the spatial-temporal distribution patterns of distraction in conjunction with the post-coding.

However, although this type of naturalistic observation method can capture the characteristics of mind wandering in real operational scenarios (e.g., gaze fixation phenomenon of miners during gas monitoring), it faces challenges such as the difficulty of controlling environmental variables and the subjectivity of behavioral coding, and needs to be automated by machine learning algorithms (e.g., convolutional neural networks) to extract features from video data in order to improve the objectivity and reproducibility of the observation results (Krasich et al. 2020). The synergistic application of the three types of methods - SART/CRT to provide mechanistic explanations, and naturalistic observations to verify ecological validity - together construct a research closure loop from experimental control to reality mapping, and promote a paradigm shift in mind-wandering research from phenomenal description to predictive intervention.

3.2.Mind-wandering with Eye-tracking

Meanwhile, eye-tracking technology provides millisecond-level real-time monitoring metrics for mind wandering by capturing visual behavioral features with high precision (<0.5° error): abnormally prolonged gaze duration (e.g., from a baseline of 220 to 300 ms) is often accompanied by an attenuation of the depth of information processing, manifested as a 41% decrease in the accuracy of the response to critical dashboard signals (Schultz et al., 2020) ; decreased sweep frequency (e.g., from 4.2 to 3.3 sweeps/s) is associated with depletion of attentional resources due to cognitive overload, which is predictive of lane departure events in a driving simulator (OR=2.7, 95% CI:1.8-4.1); and nonlinear changes in pupil diameter (12%-15% dilation at low-intensity MW and contraction to 8% below baseline at high-intensity) not only mapped the gradient of activation of the blue-spot-norepinephrine system (Smallwood, 2011), but was also significantly negatively correlated with working memory load (r=-0.63, p<0.001). Notably, the real-time fusion system developed by Chen et al. (2021) multimodally coupled EEG theta wave (4-8 Hz) power with eye movement metrics (gaze entropy, sweep acceleration) to achieve an 89.7% online recognition rate of mind wandering in a nuclear power plant control room scenario, marking a major breakthrough in the technology of collaborative decoding of neural-behavioral signals.

4.Mechanisms of eye movement representations of mind wandering

4.1.Focusing pattern variants

Mind wandering significantly alters visual information processing strategies.Krasich et al.'s (2018) virtual driving experiment found that gaze points during MW, although focused on the central region of the windshield (82% of the total gaze time), reduced the number of gazes to the critical dashboard by 64%. This “gaze fixation” phenomenon is associated with low-frequency oscillations in the frontal-striatal pathway (fMRI evidence, Grandchamp et al., 2014), reflecting a failure of top-down attentional control. Further studies have shown that gaze entropy (Gaze Entropy) can be used as a quantitative metric: when entropy values fall below 2.3 bits (normal baseline 3.1 bits), the operator's risk perception accuracy drops to 71% (Schultz et al., 2020).

4.2.Pupil Dynamic Response

Pupil diameter change is a sensitive biomarker for MW monitoring.Smallwood (2011) found that low-intensity mind wandering (e.g., task-irrelevant thinking) enlarged the pupil diameter by 12%-15%, whereas high-intensity wandering (e.g., situational fantasies) resulted in a contraction of the diameter due to an overexploitation of cognitive resources. This nonlinear relationship can be fitted by a second-order derivative model (R^2 = 0.89), with an inflection point occurring at a pupil diameter of 6.2 mm (Zhu et al., 2015). The latest study utilized a 1000Hz sampling rate eye-tracker to capture the phenomenon of pupil pre-dilatation 300ms prior to the onset of the MW (increase of 0.52±0.07mm), providing a 50-80ms window of time for real-time warning.

4.3.Sweeping Dynamics Characterization

Mind wandering disrupts the plan-execute loop of sweeping movements. The reverse eye hop task showed an increase in the incidence of erroneous sweeps (toward the cued stimulus rather than the target location) in the MW state from 12% to 21%, and a 32-ms prolongation of the latency.An industrial monitoring study further found that the peak speed of sweeps during the MW decreased to 350-400°/s (normal values of 450-500°/s) and the acceleration curve showed a bimodal abnormality (normal is a unimodal Gaussian distribution), suggesting a dysfunctional motor control of the cerebellar-brainstem pathway (Chen et al., 2022).

5.Conclusion

Research on MW's ocular characterization provides quantifiable theoretical tools for attentional management in high-risk industries. By analyzing gaze patterns, modeling pupillary dynamics, and decoding saccadic paths, critical cognitive failure states can be precisely identified. Future efforts must overcome ecological application barriers to develop intelligent monitoring systems that adapt to complex environments and individual differences, ultimately achieving proactive safety through human-machine-environment synergy.

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