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DETECTION OF MENTAL FATIGUE IN CNC OPERATORS THROUGH MACHINE VISION

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Abstract
CNC (Computer Numerical Control) operators are often put through long and sustained periods of focus inspection while working in high-precision manufacturing settings that lead to mental fatigue that compromises both safety and productivity. This study investigated mental fatigue detection with a non-intrusive machine vision system that observed for behavioral and psychovisual indicators i.e., blink rate, gaze stability, head pose, micro-expressions. Ultimately, based on cognitive fatigue and vigilance theory, the study utilized video feed in real time and tried to correlate visual and behavioural patterns to psychometric states of mental depletion. The results demonstrated psychovisual trends consistent with cognitive load and the study demonstrates that machine vision can indicate early signs of operator fatigue. This study results have considerable implications with industrial ergonomics and a first step towards developing adaptive work environments that promote mental health and safety. Ultimately, it provides an opportunity to combine psychological theory with machine vision monitoring, and provide insight to a new generation of smart and human-friendly manufacturing systems that considers human in a smart system design for mental health as well as process efficiency.
Keywords: Mental fatigue, CNC operators, machine vision, cognitive load, visual behaviour, occupational psychology, fatigue detection, industrial ergonomics

I. INTRODUCTION

In today's highly automated manufacturing environments CNC (Computer Numerical Control) operators are the cognitive layer between highly complex machines and high precision output. Automation has reduced some of the physical demands of working in a machine shop, but has added significant mental workload due to the need to provide ongoing attention, error detection and decision-making under various levels of constraints [1]. Over time this iterative cognitive process can contribute to mental fatigue, a psychological state characterized by decreased alertness, reduced reaction times and lower task performance. Mentally fatigue describes a loss of attentional/executive function that impacts a worker's ability to perform their anti-task. This is manifested psychologically with increased errors and/or inattentiveness; behaviorally as a decreased ability to make decisions, actively recall working memory and perform vigilance activities; and cognitively which is described as a loss of attention/executive resources. More traditional forms of fatigue detection such as [15], self-report methods and physiological sensors, are either intrusive, lagging indicators, or impractical for use in real time in an industrial context. This creates an urgent need for monitoring mental presence or mental wellness in machine operators [14]. Machine vision has an established ability to provide nonintrusive real time analysis of facial expressions and visual behaviour which makes it psychologically meaningful, and it can also be implemented at scale to detect cognitive overload at work [2] [13].

II. UNDERSTANDING FATIGUE IN PSYCHOLOGICAL TERMS

Mental fatigue, often confused with physical fatigue, is a separate psychological construct with independent cognitive and behavioural indicators [5]. Mental fatigue, unlike physical fatigue caused by the exertion of human muscles, is derived from sustained awareness of a situation (Atten, 188) and was based on our working memory (WM) capacity [4]. Mental fatigue drains (capacity) cognitive capacity has a similar impact on reducing cognitive actions like attended information processing (Atten, 188). When mental fatigue increases, vigilance begins to

decline, and increasingly cognitive decision-making goes wrong. In attention-intensive tasks like CNC operation, this assignment of mental (thinking, processing, and assessment) tasks creates continuing costs and mental load, becoming systemic fatigue without traditional physical activity [8].
Cognitive Load theory establishes a reference point, outlining how working memory will become completely overwhelmed when performing fast-moving, coupled tasks and eventually performance begins to decline (Atten, 188). Attention Drain Theory, referring to the attention depletion from demands of task-oriented attention, exhibits the fact that attention resources will be vanishingly low in time and situation, as researchers have found. The Effort-reward imbalance or "Stress and Fatigue" model suggests consideration beyond task orientation and conceptualizes being fatigued in terms of obvious impact of the modern world, with an acknowledgement that when we perceive the mismatch between effort and reward there will be stress and perhaps ultimately mental exhaustion.
We know from precedent literature that overt fatigue often manifests behavioural changes within visual behaviours, including but not limited to increased (blink) rate, decreased gaze toward fixations, altered head pitch/lateral pose, and spontaneous micro-expressions. All of which are latent measures of, 'mentally fatigued'. Behavioural visual indicators are a very exciting pathway into cognitive states, these indicators again evaluated based on real-time, non-invasive visual measures of machine vision systems [9]. When we look to clarify cognitive behaviours with validated behavioural indicators, there are possibilities hitting potential psychological barriers.

III. OPERATOR STATE ASSESSMENT: CONNECTING BEHAVIOUR AND PSYCHOLOGY

To evaluate the mental state of a CNC operator requires an interpretive model to first measure psychological fatigue behaviorally, and then translate into internal psychological stress. Eye movements are the most trustworthy psychological indicators of fatigue and declining attentional control due to fatigue include greater blink duration, increased blink rate, and reduced saccadic activity. It is also important for CNC operators to maintain postural stability as featuring small head movements and postural sway may indicate a disturbance in the postural control system as a result of fatigue, or lack attention meaning they are somewhat disengaged from the task. If an operator is unaware, they are losing interest in the task, they would not avoid the most dangerous and worst accidents outcome by being alert. Micro-expressions are involuntary small (milliseconds) facial movement occurring due to psychological states and can signify heightened stress, frustration, overload, etc., before the operators are aware their mental state is altered. Another behavior marker of fatigue is psychomotor slowing, which involves delayed motor responses to stimuli and slower performance of task. Fatigue is a form of attention decrement research, defined as sustained attention and situational awareness progressively being impaired over time, as fatigue increases. Both kinds of phenomena have safety and performance impacts for CNC operators.
Machine vision systems therefore provide ideal tools to uniquely capture and analyse subtle behaviours associated with fatigue in real-time [10]. This could include measuring gaze direction, blink parameters and head pose, which all represent different aspects of cognitive engagement and emotional regulation, while using the vision-based tools as a psychological mirror of changes in cognitive load. These behaviours can be interpreted as immediate signs of psychological fatigue related to theories such as cognitive load limits and depletion of attentional resources, so machine vision can provide not only a new technological method, but technically mediated ways of appraising the mental health or well-being of industrial workers in situ formally using a psychological framework [3] [7] [11].

IV. PSYCHOLOGICAL OBSERVATION AS A MEANS OF IN SITU MENTAL FATIGUE ANALYSIS USING VISION SYSTEMS

In order to investigate the observation and analysis of mental fatigue in CNC operators through a psychological lens, the study implemented a machine vision-based observation protocol in a fabricated CNC workstation setting reasonably simulated in a lab environment or integrated into a real industrial floor. The setting and tasks attempted to replicate the visual, cognitive and ergonomic stresses of a high intensity CNC operator's task, including simulated tasks typical to the work, tool changes, programming and responding to error sequences.
Participants were recruited into the project according to a specified set of inclusion criteria, including prior experience operating a machine, no diagnosed visual impairments or neurological disorders, and the capacity and disposition to remain mentally or cognitively focused for prolonged periods of time. All participants completed an initial psychological profile prior to undertaking the operational tasks, including using validated measures.

Simple Linear Fatigue Score:
Let the Fatigue Score (F) be computed as a weighted sum of key machine vision-based features:

$$F = \omega_1 \cdot B + \omega_2 \cdot G + \omega_3 \cdot H + \omega_4 \cdot M$$

Where:

Variable	Description
F	Computed Fatigue Score
B	Blink Rate (blinks per minute)
G	Gaze Dispersion (average gaze deviation)
H	Head Pose Deviation (angular shift)
M	Micro-expression frequency (per minute)
$\omega_1, \omega_2, \omega_3, \omega_4$	Weights derived from exploratory factor analysis or expert estimation

A high-definition camera system was installed at eye level and configured for the purpose of tracking the duration of blink, gaze variability, pupil dilation and head pose. These visual features were extracted in real time using computer vision algorithms so as to minimize disruption to the operator's work. Continuous video and data sampling were recorded seeking to capture variations in fatigue assemblages across task duration.
All procedures conformed to ethical requirements. Participants were provided with informed consent, and the right to withdraw participation conditions. Psychological safety was established through briefing participants in detail about the observational nature of the study, along with indicating that the participants performance would not be assessed by their mental state. The installation clearly allowed for the unobtrusive monitoring of participants which represents a balance of technological innovation with the ethical considerations required for conducting psychological research.

V. PSYCHOVISUAL DATA INSIGHTS: TRENDS AND INTERPRETATION

The analysis of visual behaviours over time allowed for the discovery of a range of trends associated with the accumulation of mental fatigue and particularly time-on-task effects. Operators demonstrated psychovisual markers as they continued prolonged CNC tasks, showing, longer durations of blink, more frequent and longer closures of eyes, lesser gaze variability, and increased head movement deviation. These observations reflect decreased attentional resources and cognitive slowing, supporting the premise of using visual behaviour as a reliable adjunct of mental state.
Fatigue measures exhibited a nonlinear trajectory, generally increasing after participants worked continuously for approximately 20–30 minutes, indicating a potential threshold for cognitive endurance that may be relevant to the task. Visual indicators of disengagement (displacement of gaze or irregular fixation) were significantly more obvious when the tasks administered were in a plateau stage or involved the handling of errors.
The state spaces of visual behaviour for the participants were loaded into a cluster analysis. Participants were categorized based on their behaviour into categories such as resilient operators (stable visual behaviour throughout tasks) or depleted operators (who exhibited rapid psychovisual decay). Each cluster category indicated individual variability in fatigue resistance and sustained attention behaviour, which may have ties to psychometric measures of conscientiousness, cognitive flexibility or stress resilience.
For each cluster, where appropriate, exploratory factor analysis (EFA) was conducted on the visual metrics dataset to identify latent psychological constructs related to fatigue response. The preliminary results revealed two main factors accounting for a huge amount of covariance in behaviour: degradation of attentional control and sensorimotor instability. These study findings support the significant value of vision-based monitoring as real-time, psychologically-informed risk management approach to fatigue assessment in industrial settings.

VI. UNDERSTANDING COGNITIVE SIGNALS: WHAT THE VISION DATA INDICATES PSYCHOLOGICALLY

The patterns of visual functioning that were captured through machine vision may show surface fatigue, but also reveal deeper psychological processes that are evident in operator performance. There were more tired operators (exhibiting reduced gaze stability, more blinking, and head movement) who tended to have lower self-ratings on psychological constructs such as sustained attention and cognitive flexibility. Operators who rated higher on constructs like self-regulation, resilience, or task persistence had more stable visual behaviour across the episode indicating a psychological basis for fatigue resilience. Cognitive drift, a specific incident of slight disengagement from a focused task, was one specific thing that we observed. Cognitive drift is indicated in the data by long fixations to non-relevant areas or to off-screen gazing, and would often co-occur with lapses of vigilance (failure of the operator to respond quickly to unexpected task or to alerts) which have shown to increase the risk of errors, or accidents, in high stakes CNC operation.

The psychological ramifications are unequivocal: mental fatigue factor diminishes the dependability of task performance, decision-making accuracy, and reactively deteriorates. If sustained over long periods, mental fatigue will also decrease productivity, with potentially dangerous consequences for occupational health and safety [6]. If machine vision has been incorporated into the CNC workspace, detection of fatigue markers can proactively alert a supervisor, human operator, or system intervention to suggest microbreaks, alter task loads, and/or engage supportive alertness before a worker's mental fatigue state worsens [12]. Thus, this study highlights the preventative aspects of psychologically-oriented vision systems to not only help ensure operator wellness, but also promote industry efficiency.

VII. DESIGNING INTERVENTIONS: TOWARDS RESILIENCE IN HUMAN-MACHINE SYSTEMS

As machine vision technology progresses in fatigue monitoring and we identify various engagement and fatigue mitigation strategies, we can invent a number of interventions for operators. The nature of the engagement strategies will be shaped both by what people can do "in the field," and the efficiency of the recommendations as cognitive-centric resolutions to lagging social-economic performance. Simply put, we could have simple interventions requesting that the operators take timeout breaks, and have them surveyed in accordance to what they saw that led to any errant behaviour(s), or errors in judgment.

This machine vision data can also be used to pursue various training opportunities for workers we perceive to be fatigue pruned identified by similar visual behaviour. For example, even if fatigue is mitigated, operators could follow cognitive endurance or attention management training.

One major intervention that has been developed is a potential adaptive CNC interface which upon monitoring, could modulate complexity, speed of production, or the amount of attention directed to a range of human-operational variables based on the current cognitive state of the operator. This technology may be able to identify indicators of cognitive overload, and the level of overload would inform it to variably modulate (reduce) the amount of workload, or simplify the conceivable display format, and/or prompt guidance to guide them and limit erroneous deliveries.

Similarly, on an institutional level, our work to research fatigue monitoring contributes to establishing workplace policies that are fatigue aware.Organizations can integrate visual behavior monitoring into occupational health practices, develop research-based shift designs, and reaffirm mental well-being as an element of industrial safety. By linking technological capability with psychological understanding, such applications are enabling CNC contexts to continue their evolution to resilient human-machine systems that can sustain performance and consider mental health.

VIII. CONCLUSION

This study emphasized the effectiveness of machine vision in recognizing and interpreting mental fatigue in CNC operators in a non-intrusive, psychological way to monitor cognitive well-being in an industrial setting. The research utilized subtle visual behaviours (i.e., eye movements, blink rate, head position) to draw conclusions that took us from observation of behaviour to cognitive fatigue theory.Overall, the study makes important contributions to both engineering psychology and human-machine interaction. From an engineering perspective, machine vision could potentially provide operators a safer and more efficient work environment, without hindering the workflow process. From a psychological perspective, the study significantly contributes more detailed understanding of the type of behaviour that cognitive fatigue creates, allows for observing cognitive fatigue in real-time, and ultimately increases the ability to detect cognitive fatigue in a scalable way.In terms of future research, the focus could be on a real-time monitoring system that has an automated capability to mitigate workflow based on operator fatigue. Future research could also concentrate on combining this research on cognitive fatigue with an understanding of emotional cues (e.g., stress and frustration) to achieve better mental state evaluations comprehensively. Studies could also be directed towards the development of pressure-free/ wearable-free and ambient vision systems which is likely to enhance accessibility and likely reduce resistance to monitoring.Ultimately, this research could pave the way for a new approach to industrial mental health, in which psychological states are observable and actionable variables rather than hidden variables.

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