Pupillary activity dynamics in a multitask environment

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Synopsis

This research delves into the Index of Pupillary Activity (IPA) as a novel, real-time metric for assessing cognitive workload in multitasking environments. Traditional metrics like pupil size are influenced by external factors, making them less reliable. In contrast, IPA directly reflects mental effort and attention, offering insights into cognitive workload fluctuations. This study aims to validate IPA's sensitivity to changes in cognitive demands across various task complexities and its correlation with subjective workload measures. By emphasizing IPA, this research could significantly enhance strategies for optimizing task performance and deepen our understanding of human cognition.

Background

Effective assessment of cognitive workload is vital in various domains, demanding reliable metrics. Traditional methods, such as subjective self-reports or pupil size measurement, often fall short in precision, influenced by external factors like lighting conditions. The Index of Pupillary Activity (IPA, Duchowski et al., 2018) emerges as a robust alternative, offering direct insights into mental effort and attentional shifts, thus serving as a more sensitive indicator of cognitive workload (Fehringer, 2021, Weber et al., 2021).

Its dynamic nature enables real-time analysis of cognitive demands, which is crucial for task performance optimization. The versatile and non-invasive nature of IPA, along with its compatibility with eye-tracking systems, makes it ideal for diverse research settings. Leveraging IPA can lead to a deeper understanding of cognitive workload dynamics and foster more effective strategies for managing complex tasks.

The research questions including hypotheses are as following:

1. How does manipulation of task complexity, across varying conditions from easy to hard, influence performance metrics such as reaction time in the Multi-Attribute Task Battery II (MATB-II), hit rate in the n-back task, and physiological markers including IPA?

Hypothesis: It is hypothesized that as task complexity increases, participants will exhibit prolonged reaction times and decreased hit rates, while an increase in IPA will reflect increased cognitive workload.

2. To what extent is there a relationship between subjective measures of workload and IPA?

Hypothesis: It is hypothesized that there will be a positive relationship between subjective workload and IPA, indicating increased cognitive workload during periods of elevated IPA.

Methods
A total of 12 healthy participants (8 male, 4 female, aged 23 to 55) were selected. The experimental set-up involved a multitask environment (MATB-II, Santiago-Espada et al., 2011) designed to manipulate task load and complexity (Caldwell et al., 2004, Carlozzi et al., 2009, Molloy & Parasuraman, 1996). Task difficulties were scaled from 1 (extremely easy) to 5 (extremely hard), encompassing the psychomotor tracking, system monitoring (SYSMON) and resource management (RESMAN) subtasks, alongside an auditory n-back task.

Participants' performance was measured through reaction times in the SYSMON subtask and hit rates in the n-back task. Physiological markers, namely the Index of Pupillary Activity (IPA), pupil size, and blink rate, were recorded using an eye-tracking system to gauge cognitive workload dynamically. Following each task level, participants completed the NASA-Task Load Index (NASA-TLX), rating various workload aspects on a 7-point scale.

Data analysis utilized linear mixed-effects models to evaluate the effects of task complexity on performance metrics and eye-derived measures. Pearson's correlation was applied to examine the relationship between subjective workload assessments and physiological markers. The study adhered to ethical standards as per the Declaration of Helsinki, with informed consent obtained from all participants.

Results

The manipulation of task complexity exerted significant effects on both performance metrics and physiological markers. Analysis revealed that as task complexity increased, participants exhibited prolonged reaction times in the SYSMON subtask ($F(4,44) = 3.433$, $p = .016$), decreased hit rates in the n-back task ($F(4,44) = 2.720$, $p = .042$) and increased subjective workload ($F(4,40.025) = 16.526$, $p < .001$). These findings align with expectations, indicating a clear impact of cognitive workload on task performance. This underscores the effectiveness of our approach in inducing varying levels of cognitive workload across experimental conditions.

IPA values did not demonstrate a consistent pattern in relation to task complexity, as no significant correlation emerged between these variables. However, a Pearson's correlation analysis did reveal a positive relationship between subjective workload assessments (NASA- TLX ratings) and IPA values ($r = .337$, $p = .011$), suggesting that IPA values rose with heightened perceived cognitive workload. The difficulty level correlated significantly with NASA-TLX ratings ($r = .582$, $p < .001$), yet this did not extend to a correlation with IPA values, even after regression analysis.

These results underline the potential of IPA as a robust metric for cognitive workload assessment, albeit with room for improvement in its sensitivity to task complexity variations. This study points to the necessity of further refining IPA's algorithm for better alignment with cognitive workload changes.

Discussion

Our study aligns with the growing research validating the Index of Pupillary Activity (IPA) as an effective metric for assessing cognitive workload in multitasking environments. We found a positive correlation between subjective workload ratings and IPA, mirroring findings from

Fehringer (2021) and Weber et al. (2021). These studies highlight IPA's sensitivity to varying cognitive demands, reinforcing its value in multitasking contexts.

Moreover, the Low/High Index of Pupillary Activity (LHIPA) introduced by Duchowski et al. (2020) provides an innovative approach to measure cognitive load, especially in situations where IPA may be less effective. Fehringer's (2020) recommendation to modify the IPA threshold based on task complexity suggests a potential enhancement to our methodology for future studies.

In future research, we propose adopting Fehringer's approach to threshold adjustment and exploring LHIPA as an alternative measure. Additionally, incorporating a wider array of subjective and objective cognitive load metrics, such as the fractal dimension of pupil dilation, could enrich the assessment of cognitive workload. By observing not just when the pupils dilate, but how they do so in response to different tasks, researchers can gain deeper insights into the cognitive processes at play. This holistic approach would not only validate IPA's utility further but also advance our understanding of cognitive processes in complex task environments.

In conclusion, our study highlights IPA's potential in multitasking workload assessment, suggesting the need for further refinement and exploration of complementary measures to deepen our understanding of cognitive dynamics.

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