A Pilot Study on the Validity of Mobile Pupillometry in Manual Assembly

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ABSTRACT
As Industry 4.0 requires operators to engage more in cognitive processing, objective mental workload (MWL) measurement is highly needed in order to optimize work settings. The presented work explored the external validity of pupillometry, a renowned MWL lab measure. 21 participants performed two manual assemblies while wearing eye-tracking glasses for mobile pupillometry. Results show that some key steps are imperative in order to cope with a complex set of confounding variables such as natural work station luminance, mental overload and underload.

Keywords
mental workload, pupillometry, external validity, assembly, industry 4.0

INTRODUCTION
The industrial workplace is going through a strong shift towards a knowledge driven Industry 4.0 workplace [6]. Because the load put on operator cognitive processing raises in parallel, work designers could benefit from having a tool gauging how MWL varies depending on specific MWL antecedents such as task complexity and instruction format [11]. Profound insight into MWL-processes can thereby help in optimizing work settings in terms of human error, safety and operator wellbeing.

Typically, subjective, performance and physiological measures are consulted for MWL measurement. We focus on the last category, since this realm of measures could eventually by deployed dynamically in a cyberphysical system in which automation and collaborative robots, for instance, could adapt to operator MWL.

Since wearability is the primary criterion for MWL measurement on the shop floor, electroencephalography (EEG) and functional Near-Infrared Spectroscopy (fNIRS) are part of the most promising set of gauges [12]. Since recently, also pupil size can be captured in a non-obtrusive way with eye-tracking glasses. As pupillometry has shown to be one of the most valid indicators of MWL in the lab [7], here we were among the first to explore its external validity. In an ecologically valid experiment, 21 participants (33.3% female, M_{age} = 23.3, SD_{age} = 3.25) performed an assembly of low and high complexity while wearing the SMI Eye-Tracking Glasses 2w (SMI, Teltow Germany; 47g, sampling rate of 60Hz with dark pupil tracking, automatic parallax compensation and accuracy of 0.5°) . We hypothesized that pupil size would be larger for the high complexity condition over and beyond natural changes in, e.g., luminance at the work station.

METHODS
Two assemblies were designed based on validated assembly difficulty parameters [10]. Participants performed both seven-step assemblies in a counterbalanced and randomized within-subjects design under stable artificial lighting (550 lux measured on the work table). Subjective measures were completed at the end of both assemblies and pupil size was averaged (after linear interpolation for blinks and a 20Hz low-pass filter) over both assemblies, but also per step over the entire assembly execution, from viewing instructions to selection and screwing the components together. Individual differences in self-reported dexterity and tested visual-spatial intelligence were also accounted for, though could not adjust the statistical models reported below.

RESULTS
Subjectively, MWL showed to differ strongly between both conditions (Wilcoxon Signed Rank Test: *Md* = 4.67 vs. *Md* = 1.67, z = -4.02, p < .001, with a large effect size of r = .62) but a two-way repeated measures ANOVA showed no main effect of complexity for pupil size averaged over the entire assemblies, $F(1, 11) = 1.40$, p = .26, nor a main effect of the separate steps, $F(6,6) = 1.90$, p = .09, or an

interaction effect between Complexity and Step, $F(6,6) = .82$, $p = .56$.

Exploratory analyses on only attending to the instructions (thus without physical load) showed to provide a better signal-to-noise ratio in that viewing pictures at the very start of both assemblies as well as viewing the instructions for the last step induced larger pupil sizes in the high complexity condition ($M = 3.25$ vs. $M = 3.04$ and $M = 3.69$ vs. $M = 3.35$, respectively, *p*s < .05). The other steps did not differ however. Within both conditions, a significant effect was found between the steps (Low Complexity: $F(3.58, 53.57) = 6.28$, $p < .01$, partial eta squared of .30; High Complexity: $F(3.22, 51.48) = 5.22$, $p < .01$, partial eta squared of .25), showing that the lasts steps induced larger pupil sizes, hence suggesting a possible cognitive fatigue effect [4].

DISCUSSION AND CONCLUSION

Although subjective measures differed strongly, no significant differences in pupil size were found except when taking into account the instruction phases only. Some confounding conditions could help explain the non-conclusive results of this pilot study. First, the natural luminance coming from, e.g., the parts and work table, could contaminate the signal as suggested by [8]. Excluding this variance could be achieved by taking this natural luminance into account beforehand [9]. Intriguingly, mental overload could lead to smaller pupil sizes [3], while mind wandering during low complexity could yield larger pupil sizes [2]. As suggested by our exploratory analyses, physical effort might affect pupil size as well, even in both directions [1,5]. Our sample size, finally, might not be adequate to cope with all confounding variance. In all, the current pilot unveiled the complexity of mobile pupillometry in manual assembly. The above insights could however help future work exploring how to make real-world mobile pupillometry a robust MWL-measure of the future.

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