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Understanding Assembly Process Quality through Product Complexity and Cognitive Demand: Preliminary Experimental Evidence

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***Abstract*— This paper investigates how psychophysiological and attentional demands vary across the different phases of manual assembly processes with different levels of product complexity. Within the Industry 5.0 perspective, understanding when operators experience higher mental demand is essential for improving assembly process quality in terms of design, instructions, training, and human-centered support systems to avoid errors and defects. An experimental study was conducted on two assembly processes: a mechanical equipment and a tile cutter, representing lower and higher complexity products, respectively. Participants performed the assemblies while multimodal data were collected through eye-tracking, electrodermal activity (EDA) biosensor, and functional near-infrared spectroscopy (fNIRS). Each assembly process was decomposed into macro-phases, and psychophysiological metrics were analyzed separately for each one. Results showed that the simpler product exhibited limited differences among macro-phases. In contrast, the more complex product revealed clearer heterogeneity, with some phases emerging as attentional and cognitive bottlenecks, particularly through eye-tracking measures. These findings confirmed that assembly complexity is not uniformly distributed across process steps and demonstrate the value of a multimodal, phase-based analysis for identifying critical moments where targeted support interventions, such as improved instructions, cognitive assistance, or collaborative technologies, may be most beneficial for process quality improvement.**

Keywords – Industry 5.0, Cognitive ergonomics, Assembly process quality, Quality engineering.

I. Introduction

In assembly processes, operators must optimally allocate their attention, cognitive resources, and motor control to achieve a specific objective while adhering to constraints related to sequence, precision, time, and quality (Calzavara *et al.*, 2023; Gervasi *et al.*, 2023; Vitti *et al.*, 2025). Within the context of Industry 5.0, analyzing the involvement of mental resources becomes of fundamental importance for improving process quality (Bartolomei *et al.*, 2026). Understanding which steps in the process are most costly from a psychophysiological perspective is crucial for reducing errors, improving product and instruction design, optimizing training, and, more generally, increasing safety and efficiency (Gervasi *et al.*, 2024; Gualtieri *et al.*, 2022; Hollnagel, 1997). However, what makes an operation challenging is not always visible from the outside: two phases may appear similar in terms of manual actions, but differ markedly in terms of mental load, arousal, attentional demands, or decision uncertainty (Calzavara *et al.*, 2024; Wang and Jiao, 2025). For this reason, in recent years there has been growing interest in multimodal approaches that combine psychophysiological and behavioral signals, capable of capturing subtle and dynamic changes during task performance (Capponi *et al.*, 2024a; Villani *et al.*, 2020).

The objective of this paper is to explore how psychophysiological and attentional demands vary within assembly processes of products with different product complexity, in order to better understand where and when support interventions may be needed to improve process quality from a cognitive perspective. In the proposed study, assembly processes of two products of different complexity were observed through three families of psychophysiological measures: (i) Electrodermal Activity (EDA), a sensitive indicator of sympathetic nervous system activation and therefore of arousal and activation; (ii) functional Near-Infrared Spectroscopy (fNIRS), with estimation of aggregate oxyhemoglobin (Oxy-Hb) and deoxyhemoglobin (Deoxy-Hb) in frontal, fronto-central, and temporo-central brain regions, to capture variations in cortical activation associated with executive control, planning, and monitoring; (iii) Eye-tracking, using oculomotor and pupillary metrics (i.e., fixation duration, number of fixations per second, pupillary dilation, peak velocity, and saccade amplitude), to describe the dynamics of visual attention and, indirectly, aspects related to visual search, cognitive load, and exploration strategies.

The most interesting methodological aspect is that assembly is not treated as a single event, but as a sequence of macro-phases. In particular, the simplest product (i.e., a mechanical equipment) was segmented into three macro-phases, while the most complex product (i.e., a tile cutter) was segmented into six macro-phases. Psychophysiological metrics were calculated separately for each macro-phase, enabling a fine-grained analysis aimed at identifying when activation peaks, changes in attention, and signs of increased mental demand emerged.

This approach aims to highlight how operational complexity can be not uniform: in an assembly process, there are typically preparation and orientation steps, repetitive assembly phases, and critical moments that require alignment, verification, decisions, and quality control. Analyzing the psychophysiological signals within the assembly macro-phases therefore allows to

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go beyond an overall average difference and produce more useful results for targeted interventions (e.g., improving instructions, redesigning components, inserting checks or supports in the most critical steps) to improve process quality.

The paper is structured as follows. In Section II, the methodology implemented in the conducted for an exploratory case study is described. Section III presents the results obtained. Finally, discussion, conclusions, and directions for future research are provided in Section IV.

II. Methodology

The present study consisted in the assembly of two products of different product complexity: a mechanical equipment (Fig. 1) and a tile cutter (Fig. 2). Each assembly process was divided into macro-phases according to the following criterions: (i) each macro-phase had to represent the complete joining of two types of components (i.e., involving elementary tasks of identification, handling, alignment, and joining), thus engaging the same executive and cognitive functions (i.e., planning, working memory, monitoring, inhibitory control, response regulation, sustained attention, visuo-motor coordination) (Balconi *et al.*, 2023; Diamond, 2013), albeit with varying degrees of intensity; (ii) each macro-phase had to last at least 15 seconds to ensure a sufficient amount of data from slower psychophysiological signals, such as fNIRS and EDA. The mechanical equipment assembly process was decomposed into the following macro-phases:

- MMP1: positioning of Base, and assembly of the first oval flange (EF1) using two screws B1 and two nuts N1.
- MMP2: assembly of the square flange (SF) using two screws B1 and two nuts N1.
- MMP3: assembly of the oval flange (EF2) using the two screws B2 and two nuts N1, and final tightening check of all bolts.

The tile cutter was decomposed into the following macro-phases:

- TMP1: positioning of Base, and assembly of the two side supports (C1a and C1b) using a screw B1 and a nut N1 for each.
- TMP2: assembly of the first component of the cutting mechanism (C2) with the component C3 using the screw B2 and the nut N2.
- TMP3: assembly of the round blade (L1) with the component C3 using a screw B3 and a nut N3.
- TMP4: assembly of the component C4 with component C3 using a screw B3 and a nut N3.
- TMP5: inserting the two rail rods (P1a and P1b) into the holes of component C2 and assembling them to the side supports C1a and C1b.
- TMP6: assembly of the handle with component C3.

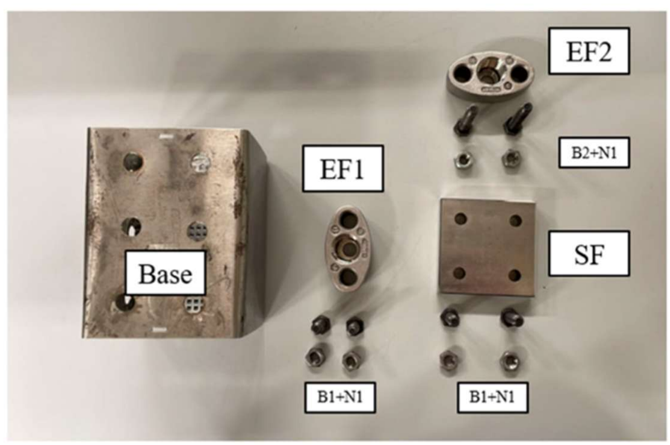


Fig. 1. The mechanical equipment and its components.

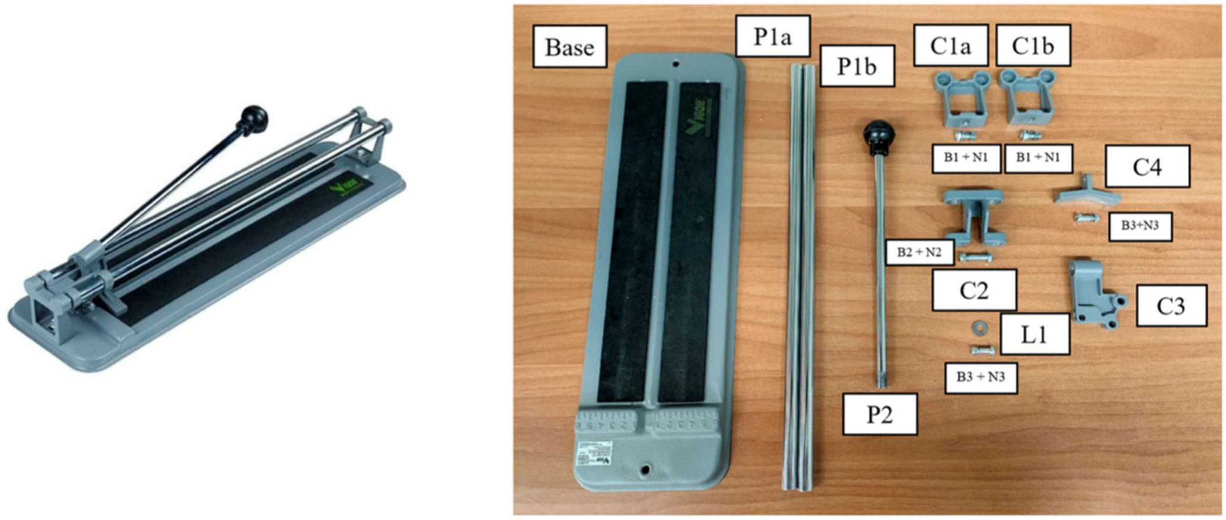
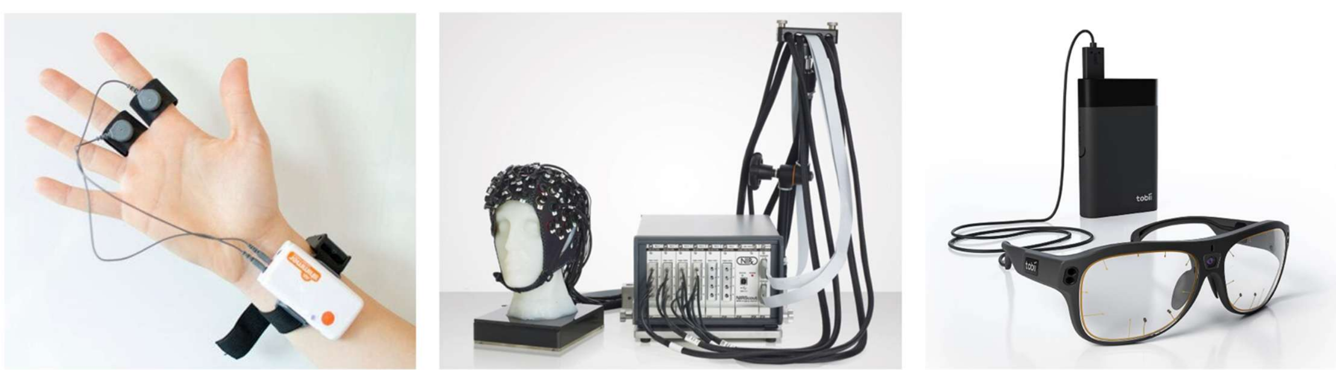


Fig. 2. The tile cutter and its components.

A. Physiological signals and behavioral data

The Shimmer3R GSR+ biosensor (Fig. 3a) was used to record EDA by placing the two electrodes on the first phalanges of the non-dominant hand according to standard procedures to minimize artifacts. Tobii Pro Glasses 3 device (Fig. 3c) was used to collect eye-tracking data (i.e., fixations, saccades, and pupil dilation) during the assembly process. Cortical hemodynamic activity was recorded using the fNIRS NIRScout system (Fig. 3b) with a 24-channel array of optodes (8 light emitters and 16 detectors) (Fig. 4) with a sampling rate of 6.25 Hz (Balconi and Vanutelli, 2016). The emitters were placed on positions AFp1, AFp2, CFC3, CFC4, CCP5, CCP6, PCP7, and PCP8. The detectors were placed on positions FAF5, FAF6, FAF1, FAF2, FFC3, FFC4, CFC5, CFC6, CCP3, CCP4, CCP7, CCP8, PCP5, PCP6, PCP9, and PCP10. The emitter-detector distance was 30 mm for contiguous optodes, and near-infrared light of two wavelengths (i.e., 760 and 850 nm) was used. Positioning was performed with respect to cranial references of the 10-5 system (Oostenveld and Praamstra, 2001) to cover the frontal (F) (channels 1, 2, 13, and 14), fronto-central (FC) (channels 3, 4, 5, 6, 7, 15, 16, 17, 18, and 19), and temporo-central (TC) (channels 8, 9, 10, 11, 12, 13, 20, 21, 22, 23, and 24) regions (Fig. 4). The relative concentrations of Oxy-Hb and Deoxy-Hb were derived.



(a) (b) (c)

Fig. 3. The implemented biosensor: (a) Shimmer3R GSR+ (Shimmer, 2026), (b) NIRScout system (NIRx, 2026), (c) Tobii Pro Glasses 3 (Tobii, 2026).

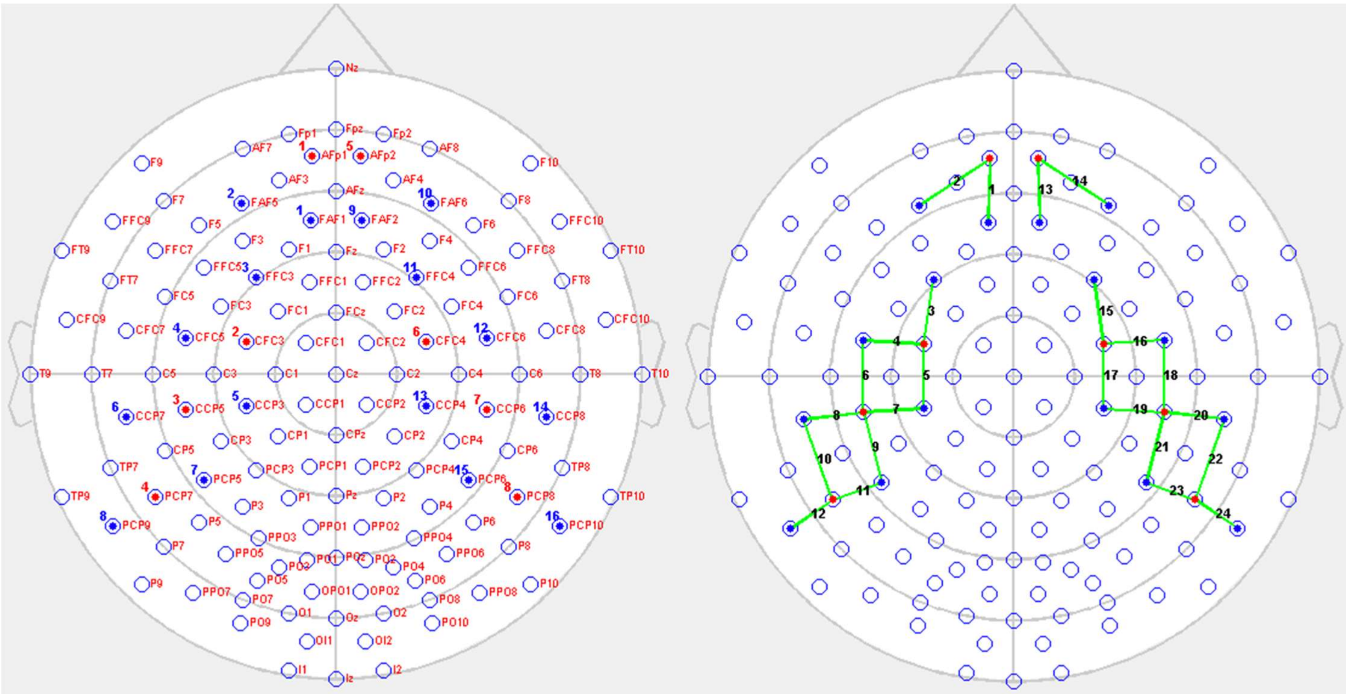


Fig. 4. On the left, position of fNIRS emitters (in red) and detectors (in blue) according to the international 10-5 system; on the right, position of the 24 channels.

B. Experimental procedure

The study was carried out in the in the "Mind4Lab" (Manufacturing Industry 4.0 Laboratory) at the "Politecnico di Torino" involving 20 participants (10 males and 10 females aged between 20 and 28 years old) without any previous experience in assembling the products.

Initially, the objectives of the study and its procedure were explained to the participant and their demographics were collected. The researcher subsequently seated the participant in the experiment location and explained the various steps of the assembly process. After any questions were discussed, the biosensors were set up on the participant. Next, the participant was invited to relax and remain still to record 2 minutes of physiological signals at rest (i.e., the baseline of the physiological signals). After this phase was completed, the participant started the assembly phase. For each product, the participant performed a training trial to learn the assembly process and then, if everything was clear, performed the assembly without any external support. Each participant performed the assembly of each product in random order. At the end of each trial, feedback from the participant was collected. The entire experimental session lasted 60 minutes on average.

C. Data processing

The software "Tobii Pro Lab" was used to elaborate eye-tracking data and extract eye-tracking metrics. Five of the most common metrics were analyzed: average duration of fixations, number of fixations per second, average pupil diameter, average peak velocity of saccades, and average amplitude of saccades. The "nirsLAB" software was used to analyzed fNIRS data and derive average changes in Oxy-Hb and Deoxy-Hb for each region. EDA data were processed and cleaned from artifacts (e.g., unusual peaks, extreme values) and average Skin Conductance Level (SCL) was computed. A summary of the response variables is reported in Table I.

TABLE I. SUMMARY OF THE INDEPENDENT AND DEPENDENT VARIABLES.

Type of variable	Variable	Description
Independent variables	Product	Product to be assembled (Mechanical equipment, Tile-cutter)
	Macro-phase	Macro-phase of the product (Mechanical equipment: MMP1, MMP2, and MMP3; Tile cutter: TMP1, TMP2, TMP3, TMP4, TMP5, and TMP6)
Dependent variables	Avg. duration of fixations	The average duration of fixations [ms]
	Nr. of fixations per second	The number of fixations per second [1/s]
	Avg. pupil diameter	The average pupil dilation [ms]
	Avg. peak velocity of saccades	The average peak velocity of saccades [°/s]
	Avg. amplitude of saccades	The average amplitude of saccades [°]
	Oxy-Hb	The average changes in oxyhemoglobin [mmol∗mm]
	Deoxy-Hb	The average changes in deoxyhemoglobin [mmol∗mm]
	SCL	Average skin conductance level [μS]

III. RESULTS

In this section, the comparison between the macro-phases for each product is analyzed based on the response variables collected. Additionally, significant differences in the response variables between macro-phases are highlighted through the Wilcoxon signed-rank test (Wilcoxon, 1945), in order to correctly manage paired data. To control family-wise error rate due to multiple pairwise comparisons, the Holm method (Holm, 1979) was implemented to obtain the adjusted *p*-values.

A. Mechanical equipment

Table II contains the resulting *p*-values of the pairwise Wilcoxon signed-rand tests among the three macro-phases for each response variable. Fig. 5 shows the comparison of the eye-tracking metrics and SCL between the three macro-phases of the mechanical equipment. Looking at the eye-tracking metrics, there were no significant differences between the macro-phases except for the amplitude of the saccades. The amplitude of the saccades significantly distinguished MMP1 from the subsequent macro-phases (i.e., MMP2 and MMP3). MMP1 included an initial setup phase, in which operators performed more visual searches by looking at and identifying among multiple components, even similar ones (i.e., EF1 and EF2), which gradually decreased in the subsequent macro-phases. This tended to produce larger saccades than in the subsequent macro-phases, where attention can remain more focused. The SCL showed significant differences between all macro-phases, highlighting a decreasing trend. This result highlights a gradual decrease in mental effort on the part of the operator due to both a decreasing variety of components to choose from and a repetitiveness of operations as the macro-phases as the macro-phases follow one another.

TABLE II. PAIRWISE WILCOXON SIGNED-RANK TEST *P*-VALUES ADJUSTED WITH HOLM CORRECTION FOR MECHANICAL EQUIPMENT MACRO-PHASES.

Pairwise comparison	***p*-value**											
	Avg. duration of fixations	**Nr. of fixations per second**	**Avg. pupil diameter**	**Avg. peak velocity of saccades**	**Avg. amplitude of saccades**	**SCL**	**Oxy-Hb (F)**	**Oxy-Hb (FC)**	**Oxy-Hb (TC)**	**Deoxy-Hb (F)**	**Deoxy-Hb (FC)**	**Deoxy-Hb (TC)**
MMP1-MMP2	0.792	0.846	0.696	0.958	0.020*	<0.001***	0.579	0.504	1.000	1.000	1.000	1.000
MMP1-MMP3	0.854	0.202	0.585	0.327	0.001**	<0.001***	0.579	0.046*	1.000	1.000	1.000	1.000
MMP2-MMP3	0.854	0.165	0.696	0.592	0.208	<0.001***	0.579	0.669	1.000	1.000	1.000	1.000

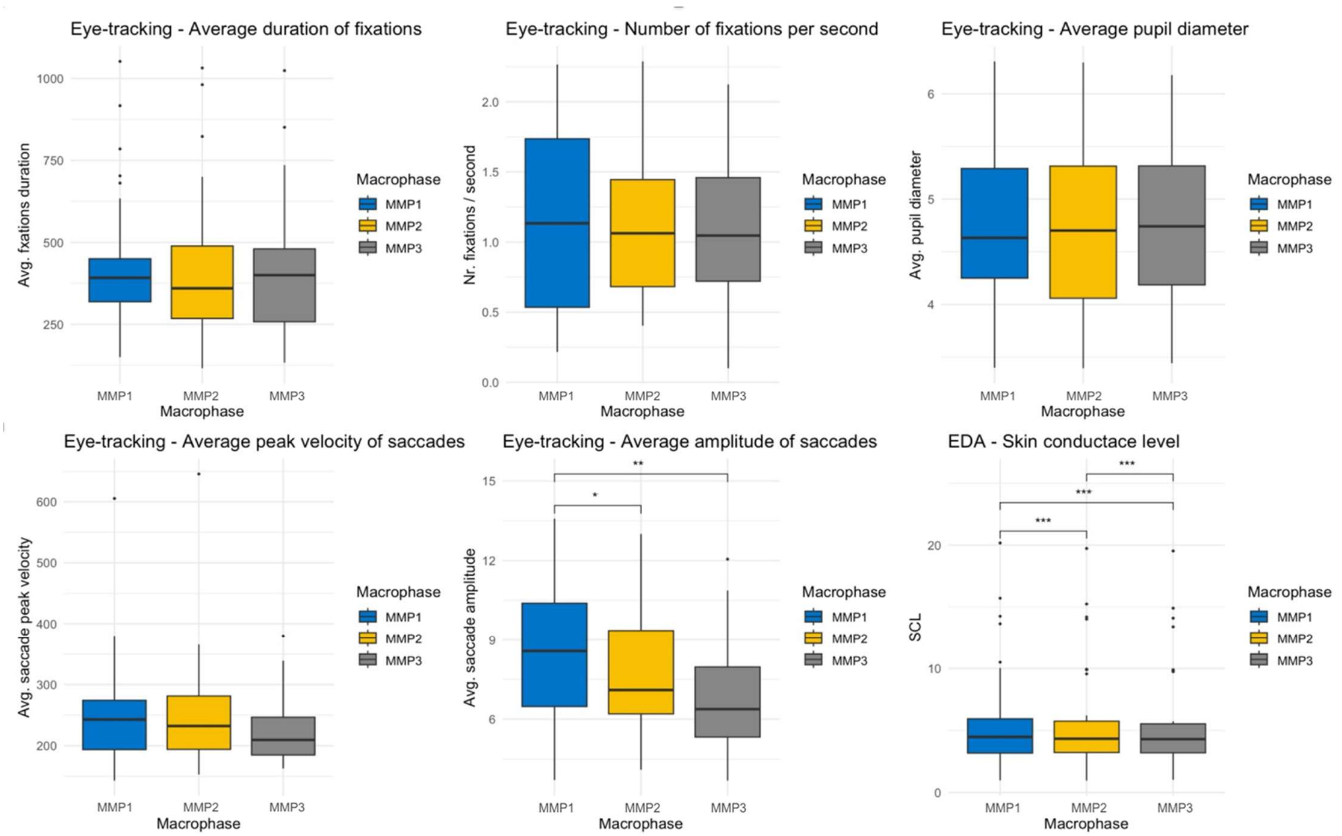


Fig. 5. Boxplot comparison of the eye-tracking metrics and EDA between the macro-phases of mechanical equipment ('*' p<0.05; '**' p<0.01; '***' p<0.001).

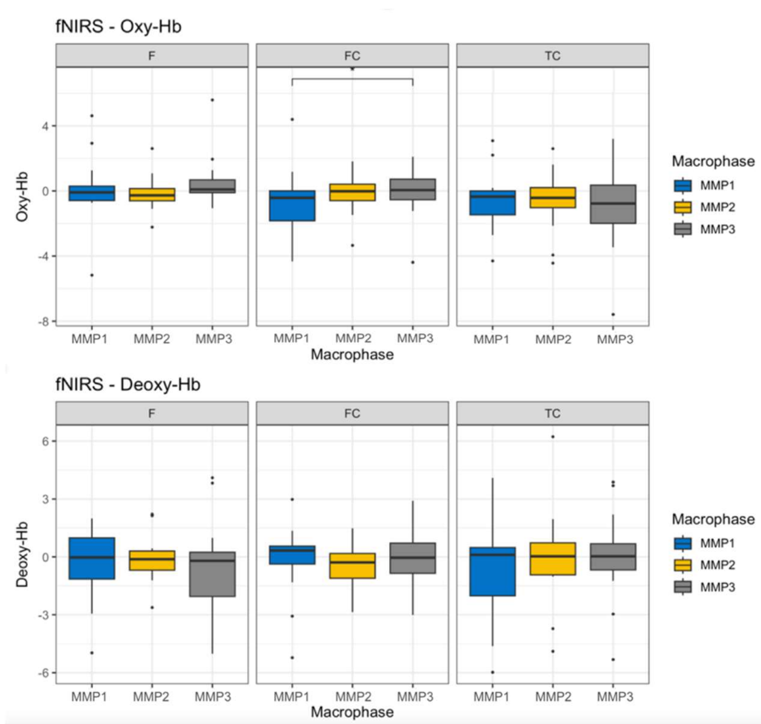


Fig. 6. Boxplot comparison of the average changes in Oxy-Hb and Deoxy-Hb between the macro-phases of mechanical equipment ('*' p<0.05; '**' p<0.01; '***' p<0.001).

Fig. 6 shows the comparison of the fNIRS metrics (i.e., Oxy-Hb and Deoxy-Hb) between the three macro-phases of the mechanical equipment. A slightly significant difference (p=0.046) emerged in the FC Oxy-Hb between the initial phase (MMP1) and the final phase (MMP3). The increase in Oxy-Hb in the fronto-central region was consistent with a greater demand for executive control in the final phase for the final tightening of all screws. However, it should be noted that there was no extensive evidence of this pattern in other ROIs, and FC Deoxy-Hb did not show a significant decrease between MMP1 and MMP3.

B. Tile cutter

Table III contains the resulting p-values of the pairwise Wilcoxon signed-rand tests among the six macro-phases for each response variable. Fig. 7 shows the comparison of the eye-tracking metrics and SCL between the six macro-phases of the tile cutter. Looking at the metrics related to saccade behavior, TMP2 emerged as significantly different from all other macro-phases. Specifically, the average amplitude and average peak velocity of saccades were lower in TMP2, highlighting greater cognitive effort compared to the other macro-phases, due to greater visual attention focused on a rather restricted area during the assembly of component C2 with C3.

Observing pupil diameter, which can be interpreted as an indicator of cognitive load and arousal, higher values are observed in TMP2 and TMP5. In particular, significant differences emerge between TMP2 and TMP1 (p=0.015), TMP5 and TMP1 (p=0.002), and TMP5 and TMP6 (p=0.045).

Focusing on the number of fixations per second, TMP5 (i.e., insertion of the two rail rods in C2 and fixing them to the supports) and TMP6 (i.e., assembly of the handle with C3) higher values than the previous macro-phases were observed, highlighting a more dynamic visual attention behavior. TMP5 differed significantly from TMP3 (p=0.016), suggesting that inserting the rods was not only more cognitively demanding (i.e., greater pupil dilation) but also more visually fragmented (i.e., more fixations per second). TMP6 differed significantly from TMP1 (p=0.017), TMP3 (p=0.016), and TMP4 (p=0.045), highlighting the presence of rapid shifts in gaze between the fastening point and the overall configuration for a final check.

No significant differences emerged between the macro-phases in terms of SCL, Oxy-Hb and Deoxy-Hb (Fig. 8), suggesting a fairly stable cortical activation throughout the process.

TABLE III. PAIRWISE WILCOXON SIGNED-RANK TEST *P*-VALUES ADJUSTED WITH HOLM CORRECTION FOR TILE CUTTER MACRO-PHASES.

Pairwise comparison	***p*-value**											
	Avg. duration of fixations	**Nr. of fixations per second**	**Avg. pupil diameter**	**Avg. peak velocity of saccades**	**Avg. amplitude of saccades**	**SCL**	**Oxy-Hb (F)**	**Oxy-Hb (FC)**	**Oxy-Hb (TC)**	**Deoxy-Hb (F)**	**Deoxy-Hb (FC)**	**Deoxy-Hb (TC)**
TMP1-TMP2	1.000	0.942	0.015*	<0.001***	<0.001***	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP1-TMP3	1.000	1.000	1.000	1.000	0.253	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP1-TMP4	0.833	1.000	0.150	0.404	0.074	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP1-TMP5	0.197	0.127	0.002**	0.264	0.052	1.000	1.000	1.000	1.000	1.000	0.866	1.000
TMP1-TMP6	0.056	0.017*	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP2-TMP3	1.000	0.161	0.238	0.038*	0.014*	1.000	0.710	1.000	1.000	1.000	1.000	1.000
TMP2-TMP4	1.000	0.92	1.000	0.035*	0.016*	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP2-TMP5	0.648	0.942	1.000	0.029*	0.004**	1.000	1.000	0.866	1.000	1.000	0.916	1.000
TMP2-TMP6	0.062	0.920	1.000	0.010**	0.002**	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP3-TMP4	0.196	1.000	0.150	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP3-TMP5	0.249	0.016*	0.073	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP3-TMP6	0.120	0.016*	1.000	1.000	0.258	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP4-TMP5	1.000	0.097	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP4-TMP6	0.754	0.045*	1.000	1.000	0.253	1.000	1.000	1.000	1.000	1.000	1.000	1.000
TMP5-TMP6	1.000	1.000	0.045*	0.268	0.088	1.000	1.000	1.000	0.664	1.000	1.000	1.000

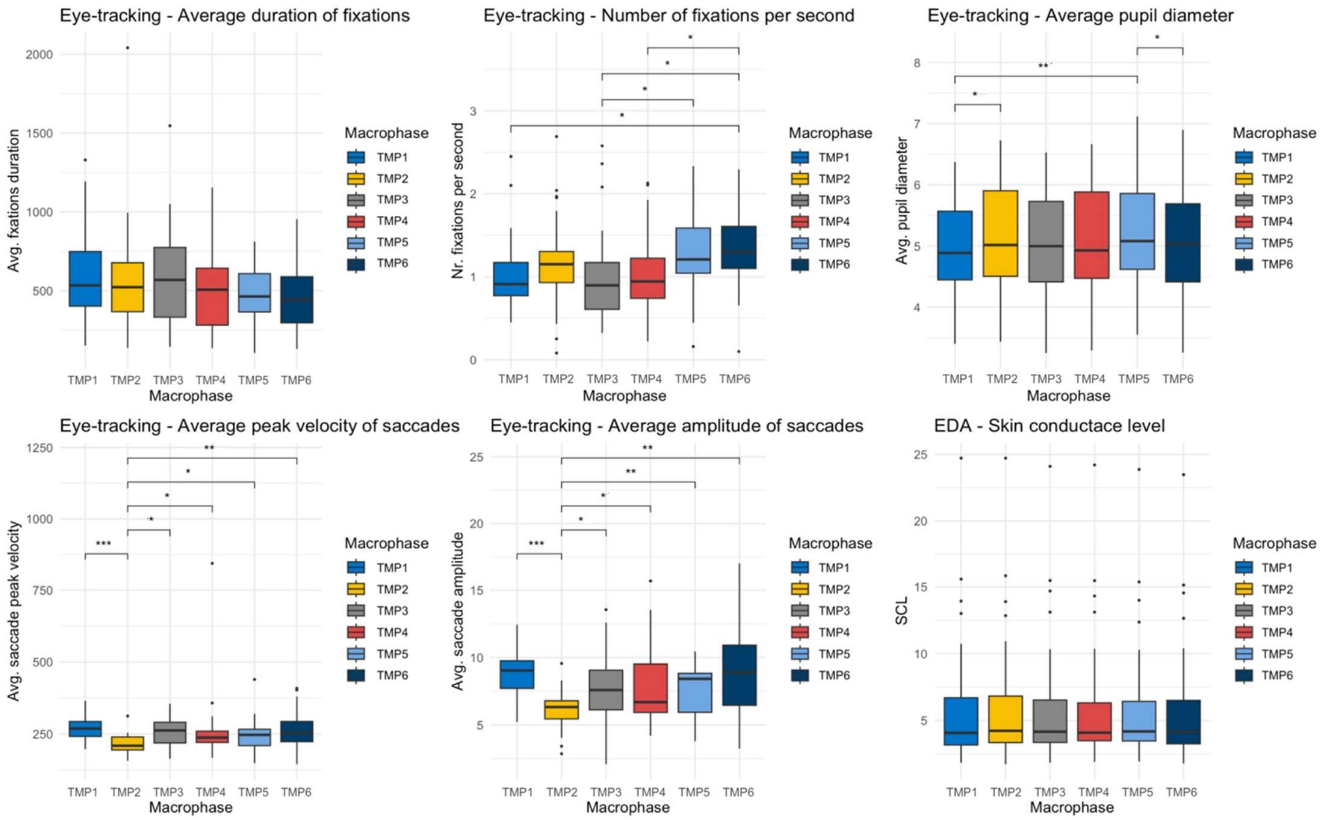


Fig. 7. Boxplot comparison of the eye-tracking metrics and EDA between the macro-phases of tile cutter ('*' *p*<0.05; '**' *p*<0.01; '***' *p*<0.001).

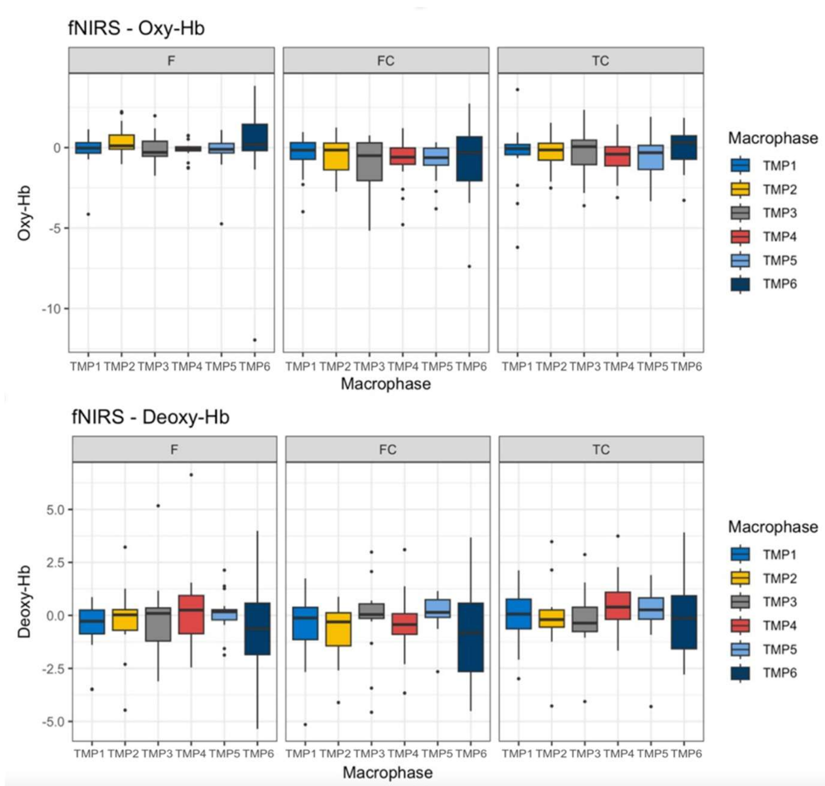


Fig. 8. Boxplot comparison of the average changes in Oxy-Hb and Deoxy-Hb for each ROI between the macro-phases of tile cutter ('*' *p*<0.05; '**' *p*<0.01; '***' *p*<0.001).

IV. Discussion and conclusions

The aim of this study was to analyze process quality from a cognitive perspective, by characterizing how psychophysiological and attentional demands vary within assembly processes, using a multimodal approach (i.e., eye tracking, fNIRS, and EDA) and comparing macro-phases within each product. The results proved to be different depending on the complexity of the product: in the simplest task (i.e., mechanical equipment), the differences between macro-phases are limited and circumscribed, while in the most complex task (i.e., tile cutter), clearly distinctive macro-phases emerge, suggesting that the complexity of the product translates into greater heterogeneity of demands throughout the process.

In the mechanical equipment assembly process, the only eye-tracking metric sensitive to differences between macro-phases was the amplitude of saccades, with MMP1 distinct from MMP2 and MMP3. From an operational point of view, MMP1 included positioning the base and starting assembly with the first oval flange, a phase in which it is plausible that operators must quickly construct a spatial representation of the work area and identify the correct components and orientations. This type of "attentive setup" is compatible with greater visual exploration and therefore with larger saccadic patterns compared to later macro-phases, which are more repetitive and focused on tightening already known elements. This effect was also observed through SCL, with gradual relaxation due to the receptiveness of the operations. At the cortical level, the difference between MMP1 and MMP3 observed on fronto-central Oxy-Hb suggests that the beginning and final phases were not equivalent in terms of executive control processes. MMP3 involved assembling the second oval flange with B2 screws (different from B1) and required greater control of the final assembly conditions (i.e., alignment and correct overall tightening). It is relevant that the fNIRS effect was selective to fronto-central region, while other indices did not differ. This may indicate that in an assembly process of a simple product the demands change more in terms of executive control in some specific steps than in terms of arousal or global visual strategies.

In the tile cutter assembly process, eye-tracking metrics revealed the heterogeneity of the macro-phases due to an uneven cognitive resource use across them. A key finding was that TMP2 (i.e., the assembly of C2 with C3) represented an attentional and cognitive bottleneck. TMP2 systematically differed from all other macro-phases in terms of saccadic metrics (i.e., amplitude and peak velocity). The pattern found was consistent with a phase of fine manipulation and concentration in a restricted area, indicating the need for greater cognitive effort to complete the macro-phase. At the same time, TMP2 showed also greater pupil diameter, suggesting that it required greater sustained attention. Participants' feedback confirmed that the alignment between the component C2 and C3 was the most difficult phase to carry out correctly, as it was not intuitive, thus requiring mental effort. TMP5 (i.e., the insertion and fixing of the rail rods) emerged as another macro-phase requiring high attention, presenting greater pupil dilation and number of fixations per second. This macro-phase required several visual checks for the correct insertion of the rods into the C2 supports and for the alignment of the rods in the C1a and C1b side supports, which contributed to increasing the cognitive effort. Surprisingly, EDA and fNIRS metrics did not reveal any statistically significant differences among the macro-phases. This may be due to the variety of component shapes and the low repetitiveness of assembly operations between macro-phases, which required a constant level of executive control involvement.

The overall pattern that emerged is consistent with the idea that in a complex task certain macro-phases represent attentional and cognitive bottlenecks (Capponi *et al.*, 2024b). From an application perspective, the paper showed how to objectively identify these situations, suggesting where support interventions (e.g., cobots, cognitive assistance systems, targeted training) should be concentrated to improve process quality and thus prevent errors and defects. For instance, concerning the tile cutter assembly process, additional cognitive support should be implemented in TMP2 and TMP5 to reduce mental effort and reduce error risk.

Future work will focus on validating the preliminary results by enlarging the experiment to include a higher number of participants and other products to be assembled, as well as characterizing the effect of different kind of cognitive support interventions in an assembly process.

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