Non-Invasive Cognitive Workload Assessment in Robotic Teleoperated Surgery Using Eye-Tracking

Candidate: **Alice Carcone**

Advisor: **Prof. Elena De Momi**
Co-Advisor: **Alberto Rota, Stefano Pomati**

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Clinical Context

Robotic Surgery

increased precision

increased technique and interface complexity

+ **38%** errors due to higher workload [1]

+ **34%** workload due to flow disruptions [2]

Workload Monitoring

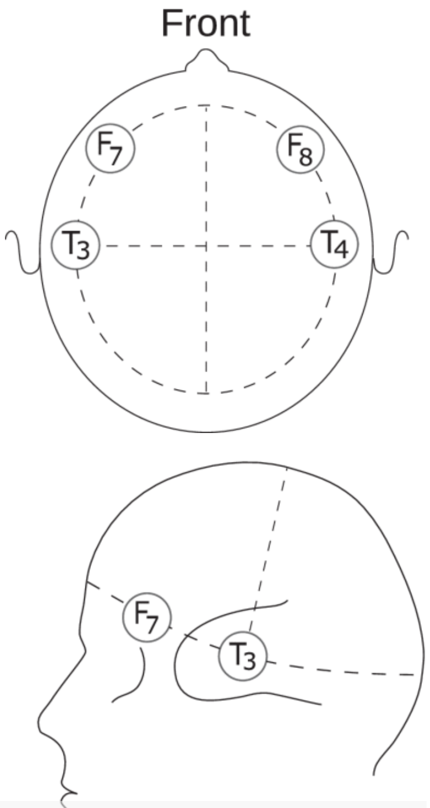
Prevents cognitive overload

Varying data interpretation

State of the Art

Traditional methods [3] → subjective
not real-time
disrupt surgical workflow

Physiological parameters monitoring [4] → invasive



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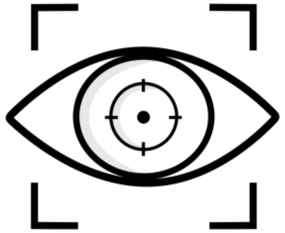
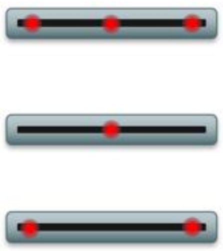
State of the Art



Eye-Tracking derived parameters [5]

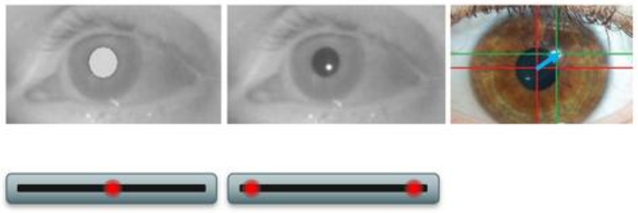
objective
continuous
real-time
not invasive



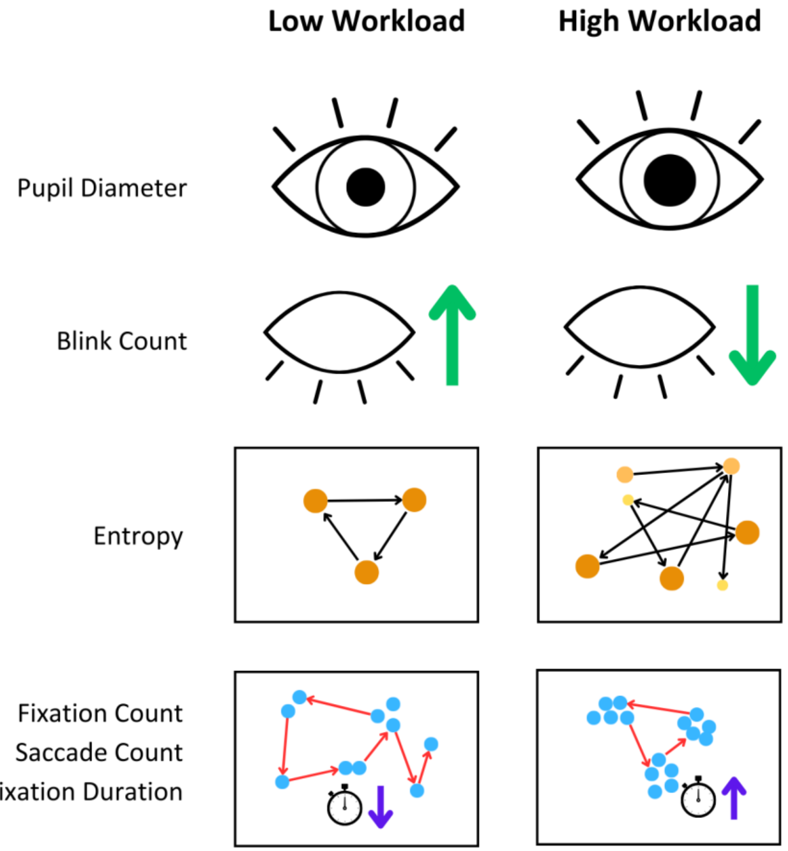
Set of **infrared emitter-receiver pairs**

Frontal Emitter: detects center of pupil

Lateral Emitters: detect corneal reflection



Output vector determines gaze direction



[5] Wu et al. (2019)

Open Issues and Objectives

Open Issues:

1. Not established **non-invasive method** to monitor surgeons' workload
2. No clear strategy on **how to apply workload estimation** to optimize surgical performance and decision-making
3. No defined **threshold** to classify high vs. low workload

Objectives:

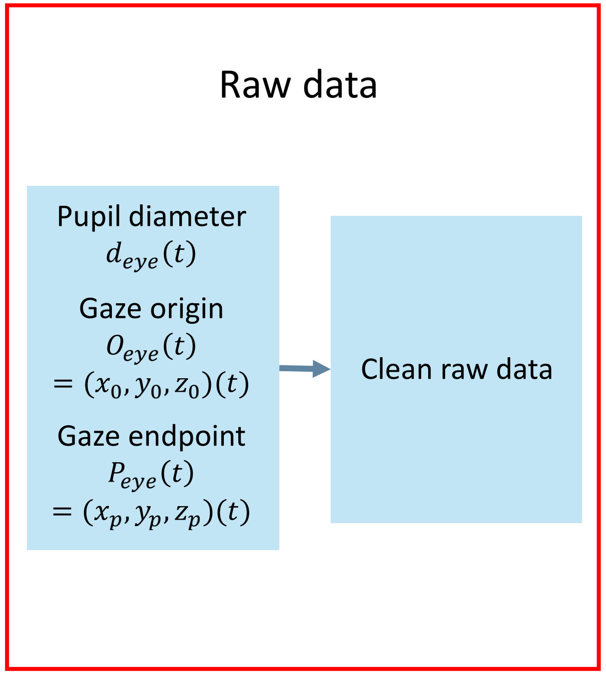
1. Leverage eye-tracking data to derive an **objective workload metric**
2. **Validate the tool** by correlating workload with surgeons' subjective phase difficulty ratings
3. Analyze **workload variations** and establish trends across different surgical phases.

Aim: Develop a post-operative non-invasive eye-tracking-based tool for cognitive workload estimation during robotic-assisted surgery.

Workload Metric Construction Pipeline

Preprocessing → Metrics Extraction → Workload Computation

Preprocessing



Preprocessing

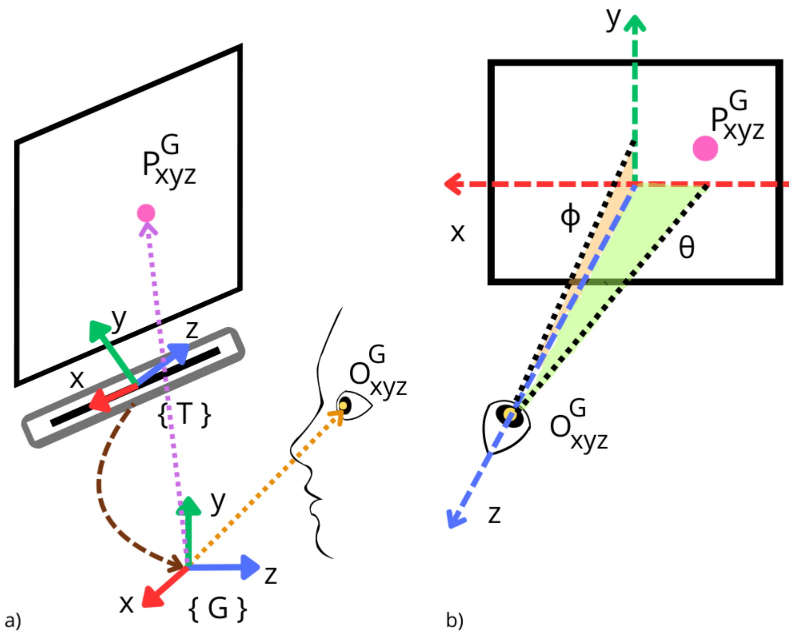
1. Invalid value handling
2. Gap interpolation (< 75 ms)
3. Median filter
4. Transformation from tracker's reference system {T} a to the global one {G}:

$$p_G = R_x(\alpha) \cdot p_T$$

5. Computation of visual angles:

$$\theta = \arctan\left(\frac{P_x - O_x}{|P_z - O_z|}\right) \cdot \frac{180}{\pi}$$

$$\phi = \arctan\left(\frac{P_y - O_y}{|P_z - O_z|}\right) \cdot \frac{180}{\pi}$$



$\boldsymbol{p_G}$ = gaze point in {G}
$\boldsymbol{p_T}$ = gaze point in {T}
$\boldsymbol{R_x(\alpha)}$ = rotation matrix
$\boldsymbol{\alpha}$ = rotation angle
$\boldsymbol{P_x, P_y, P_z}$ = coordinates of gaze endpoint

$\boldsymbol{O_x, O_y, O_z}$ = coordinates of gaze starting point
$\boldsymbol{\theta}$ = horizontal gaze angle
$\boldsymbol{\phi}$ = vertical gaze angle

Metrics Extraction

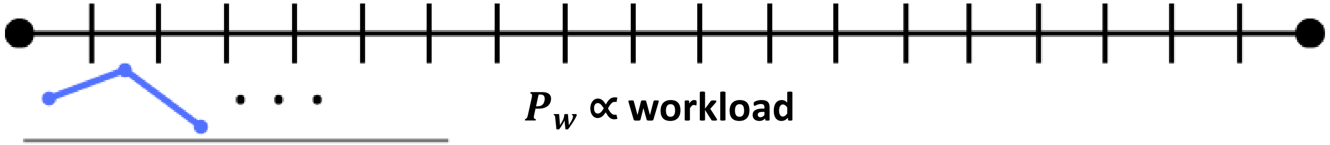
Segmented procedure

10s, 30s, 1min, 2min time windows	→	**Pupil diameter** Blinks count Gaze entropy Fixation count Saccades count Fixation duration

Metrics Extraction

1 min

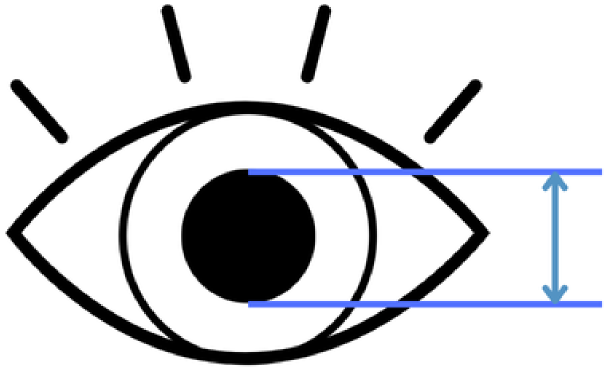
$\boldsymbol{P_w}$



$\boldsymbol{P_w} \propto$ **workload**

1. Mean pupil diameter

$$P_w = \frac{P_{r,w} + P_{l,w}}{2}$$



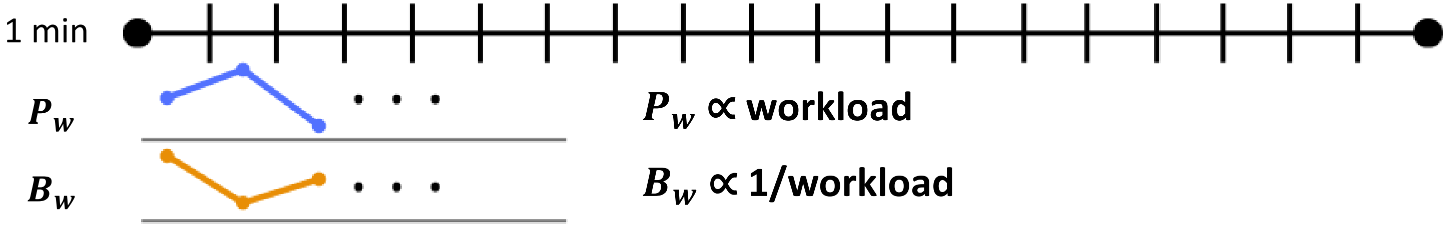
$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{P_w}$ = overall pupil diameter in w
$\boldsymbol{P_{r,w}}$ = average pupil diameter of right eye in w
$\boldsymbol{P_{l,w}}$ = average pupil diameter of left eye in w

Metrics Extraction

Segmented procedure

10s, 30s, 1min, 2min time windows → Pupil diameter, **Blinks count**, Gaze entropy, Fixation count, Saccades count, Fixation duration

Metrics Extraction

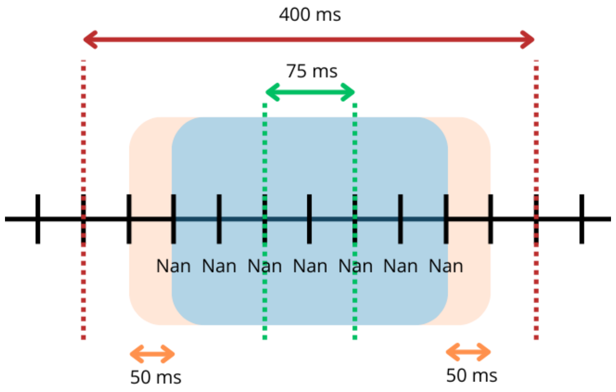


$P_w \propto$ **workload**

$B_w \propto$ **1/workload**

2. Number of blinks

$$B_w = \sum_{k \in w} 1\left(\Delta\tau_k^{cl} + 100ms \in [75{,}400]ms\right)$$



$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{B_w}$ = total count of blinks in w
$\Delta\boldsymbol{\tau_k^{cl}}$ = duration of the k-th blink
$[\mathbf{75, 400}]\boldsymbol{ms}$ = range of blinks duration [6]

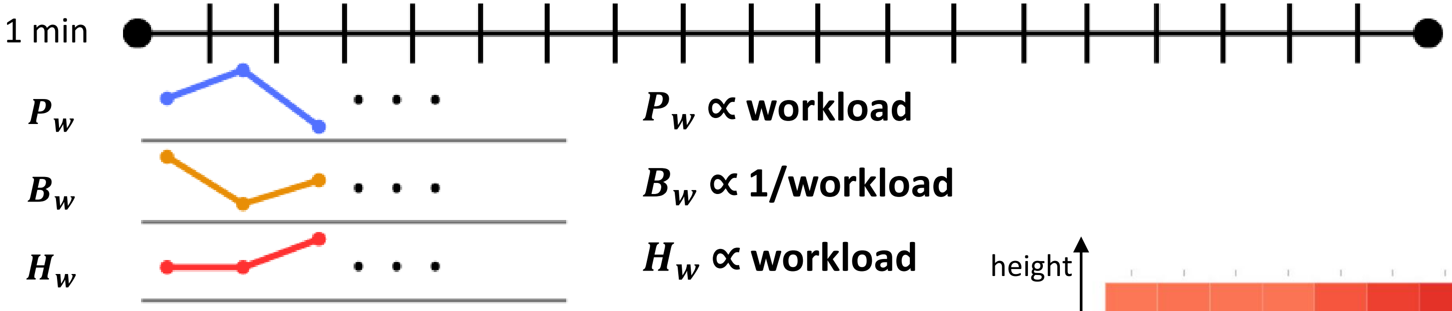
[6] Olsen et al. (2012)

Metrics Extraction

Segmented procedure

10s, 30s, 1min, 2min time windows	→	Pupil diameter Blinks count **Gaze entropy** Fixation count Saccades count Fixation duration

Metrics Extraction



$P_w \propto$ **workload**

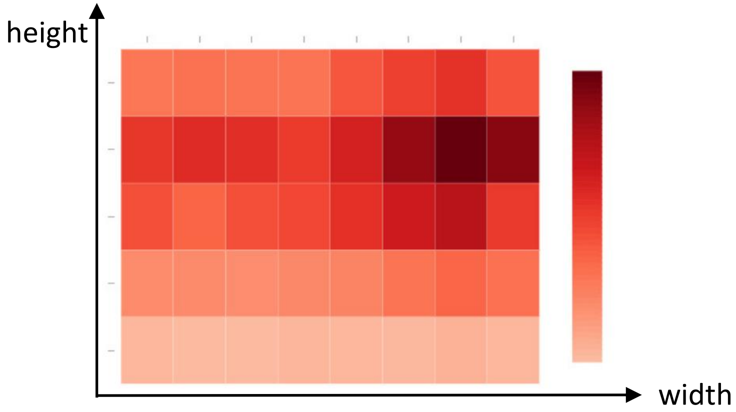
$B_w \propto$ **1/workload**

$H_w \propto$ **workload**

3. Gaze entropy

$$H_w = \sum_{i=1}^{n} p_i \cdot \log_2(p_i)$$

$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{H_w}$ = total gaze entropy in w
$\boldsymbol{p_i}$ = probability of gaze occurring in the i-th cell
$\boldsymbol{n}$ = number of cells of the field of view



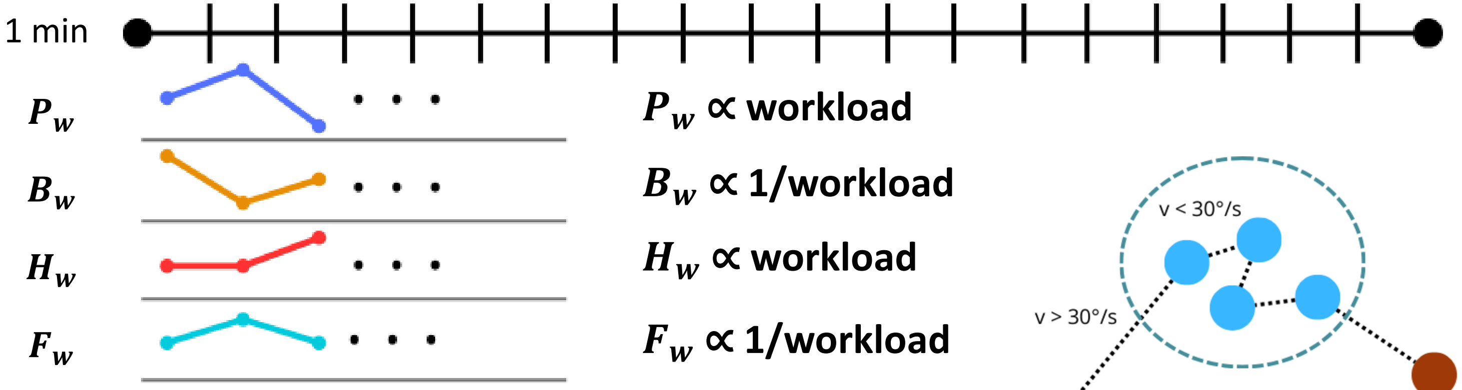
Spatial probability distribution of the gaze on the screen

Metrics Extraction

Segmented procedure

10s, 30s, 1min, 2min time windows → Pupil diameter, Blinks count, Gaze entropy, **Fixation count**, Saccades count, Fixation duration

Metrics Extraction

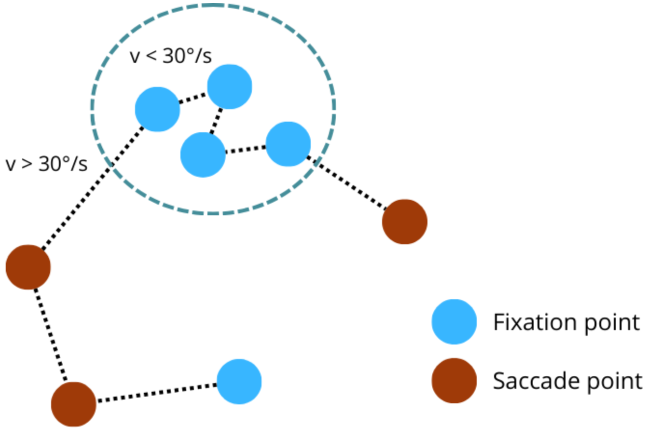


$P_w \propto$ **workload**

$B_w \propto$ **1/workload**

$H_w \propto$ **workload**

$F_w \propto$ **1/workload**



4. Number of fixations

$$F_w = \sum_{f \in w} 1\left(\max_{i \in f} \omega_i \leq 30°/s \text{ [6]} \wedge t_f \geq 60ms \text{ [6]}\right)$$

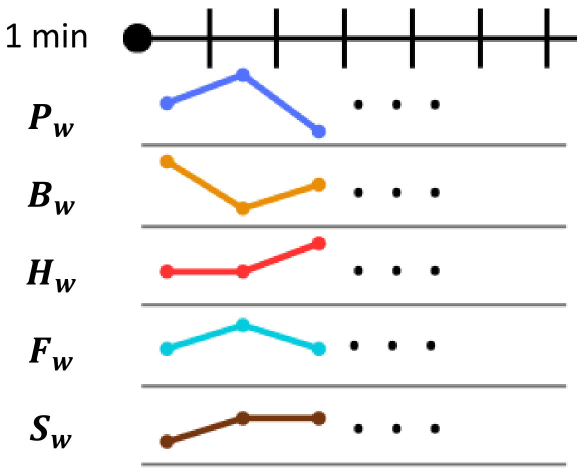
$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{F_w}$= total count of fixations in w
$\boldsymbol{\omega_i}$ = angular velocity between consecutive points
$\boldsymbol{t_f}$ = duration of fixation f

Metrics Extraction

Segmented procedure

10s, 30s, 1min, 2min time windows → Pupil diameter, Blinks count, Gaze entropy, Fixation count, **Saccades count**, Fixation duration

Metrics Extraction



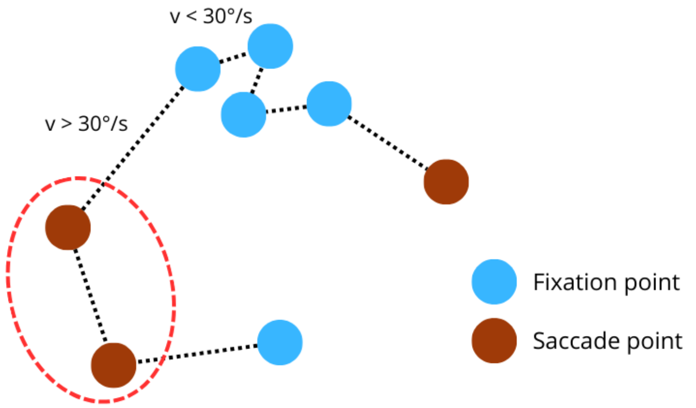
$P_w \propto$ **workload**

$B_w \propto$ **1/workload**

$H_w \propto$ **workload**

$F_w \propto$ **1/workload**

$S_w \propto$ **1/workload**



5. Number of saccades

$$S_w = \sum_{s \in w} 1(\forall i \in s: \omega_i > 30°/s \text{ [6]})$$

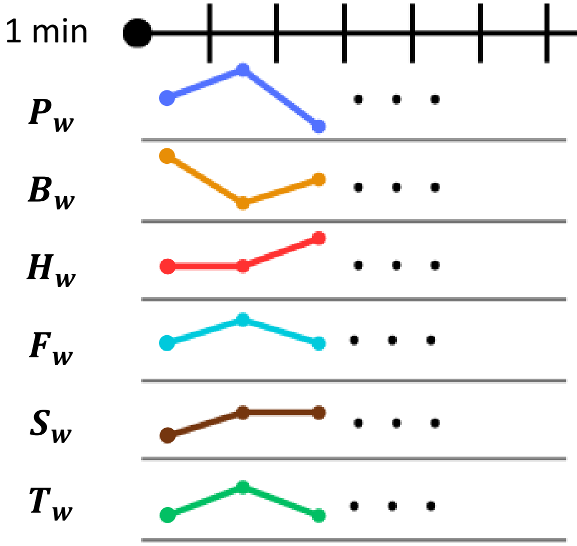
$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{S_w}$ = total count of saccades in *w*
$\boldsymbol{\omega_i}$ = angular velocity between consecutive gaze points

Metrics Extraction

Segmented procedure

10s, 30s, 1min, 2min time windows → Pupil diameter, Blinks count, Gaze entropy, Fixation count, Saccades count, **Fixation duration**

Metrics Extraction



$P_w \propto$ workload

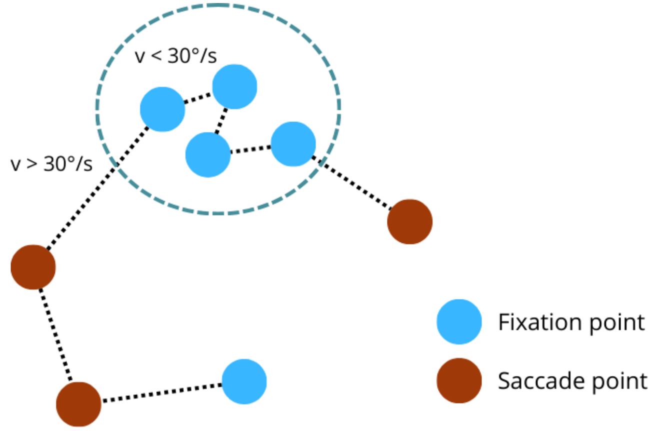
$B_w \propto$ 1/workload

$H_w \propto$ workload

$F_w \propto$ 1/workload

$S_w \propto$ 1/workload

$T_w \propto$ workload

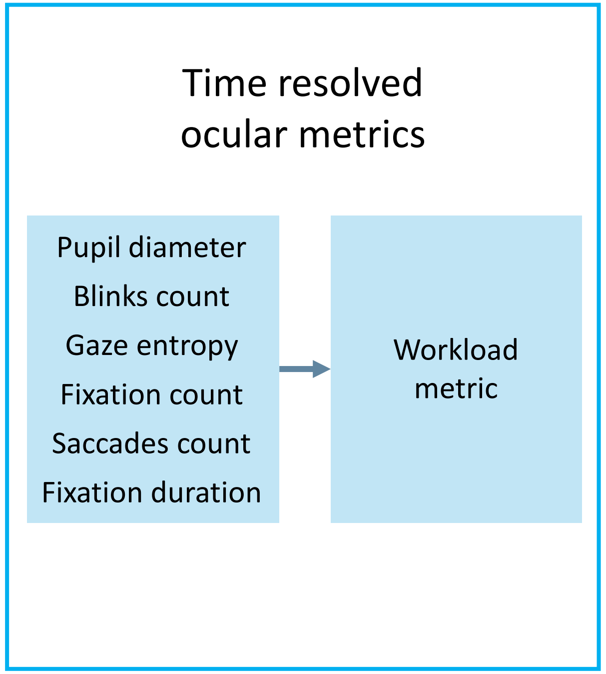


6. Mean fixation duration

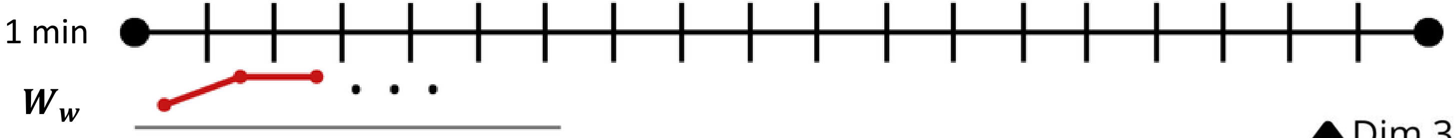
$$T_w = \frac{1}{F_w} \sum_{f \in w} t_f \cdot 1(t_f \geq 60ms)$$

$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{T_w}$ = is the mean fixation duration within w
$\boldsymbol{t_f}$ = duration of fixation f

Workload Computation

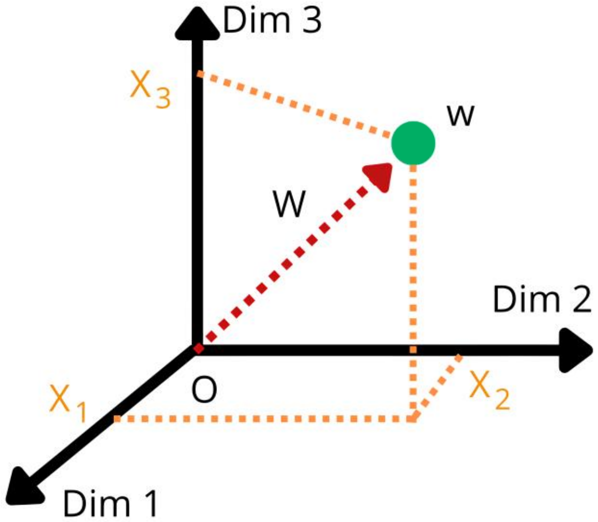


Workload Computation



1. Ocular metrics **inversion**
2. Metrics **normalization** (scale 0–1)
3. **Euclidean distance** in a multi-dimensional space

$$W_w = \sqrt{\sum_{i=1}^{6} X_{i,w}^2}$$



$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{W_w}$ = final workload metric for w
$\boldsymbol{X_{i,w}}$ = i-th coordinate of 6D point made of the six metrics corresponding to window w

Workload Validation Pipeline

Data Collection → Subjective Difficulty Annotation → Validation

Data Collection

Data Collection

Senhance® Surgical System: robotic arms, surgical console, HD vision system.

Tobii Eye Tracker 4C: records eye movements to drive the endoscope.

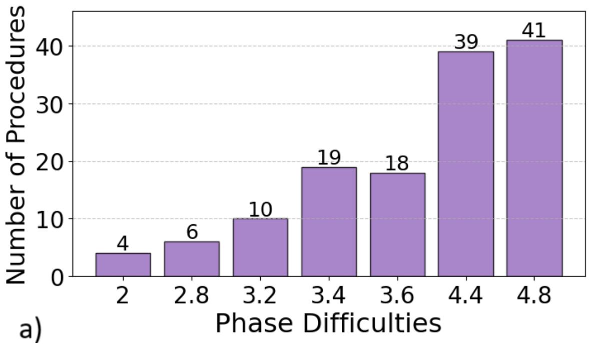
- **Data Source**: 48 robotic-assisted cholecystectomies.
- **Participants**: 13 surgeons across 6 hospital centers.
- **Data Collected**: Eye-tracking raw data, surgical phase annotations.

Subjective Difficulty Annotation

Subjective Difficulty Annotation

1. Subdivision of procedures into **phases**
2. Computation of **mean difficulty scores** (scale 1-10)
3. Computation of **weighted difficulty**

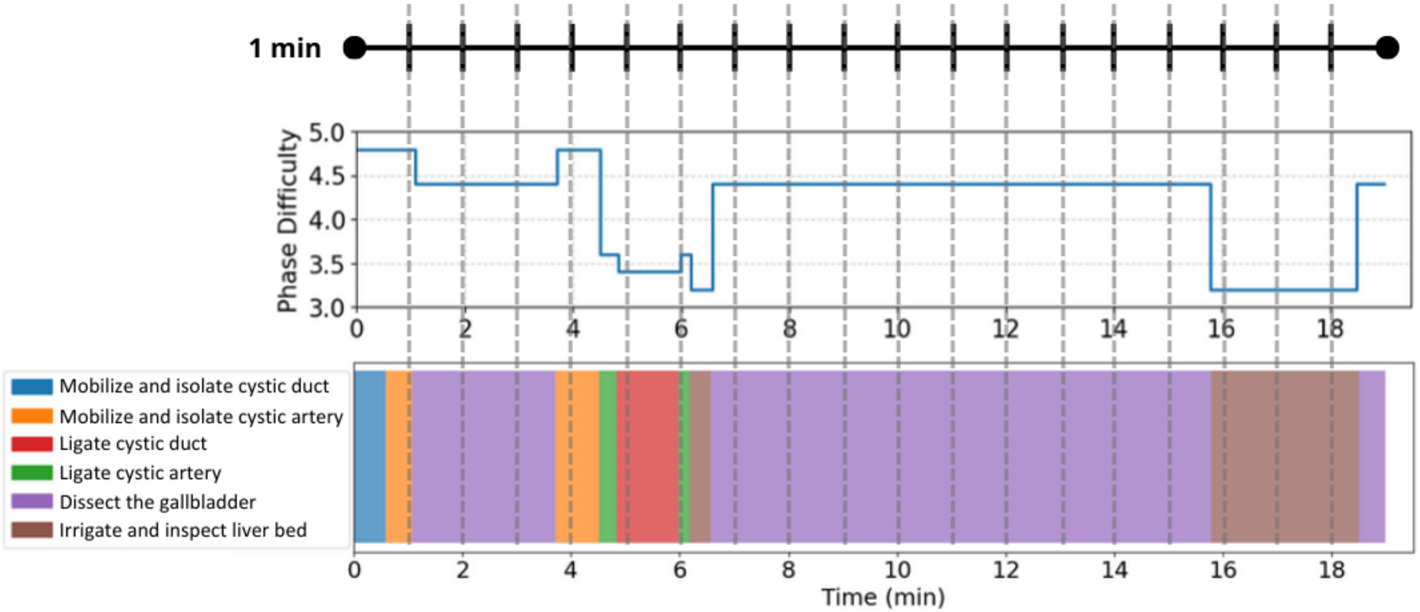
$$D_w = \sum_{p=1}^{9} \left(\frac{t_{p,w}}{t_w} \cdot d_p \right)$$



a)

$\boldsymbol{w}$ = window of length 10s/30s/1min/2min
$\boldsymbol{p}$ = surgical phase
$\boldsymbol{D_w}$ = weighted difficulty score for w
$\boldsymbol{t_{p,w}}$ = duration of phase p within w
$\boldsymbol{t_w}$ = total duration of w
$\boldsymbol{d_p}$ = difficulty rating assigned to p

Phase	Difficulty
Access intraperitoneal space	2.8
Mobilize and isolate cystic duct	4.8
Mobilize and isolate cystic artery	4.8
Ligate cystic duct	3.4
Ligate cystic artery	3.6
Dissect gallbladder	4.4
Irrigate and inspect liver bed	3.2
Remove gallbladder	3.2
Remove trocars	2



Validation and Results

Validation

$\boldsymbol{L}$ = segmentation window length $L \in$ {10s, 30s, 1min, 2min}
$\boldsymbol{\rho}^{(L)}, \boldsymbol{p}^{(L)}$ = Spearman correlation and its pvalue
$\boldsymbol{W}^{(L)}, \boldsymbol{D}^{(L)}$ = vectors of time-resolved workload and difficulty metrics

TOST test significative levels:
*(p<0.05)
**(p<0.01)
***(p<0.001)

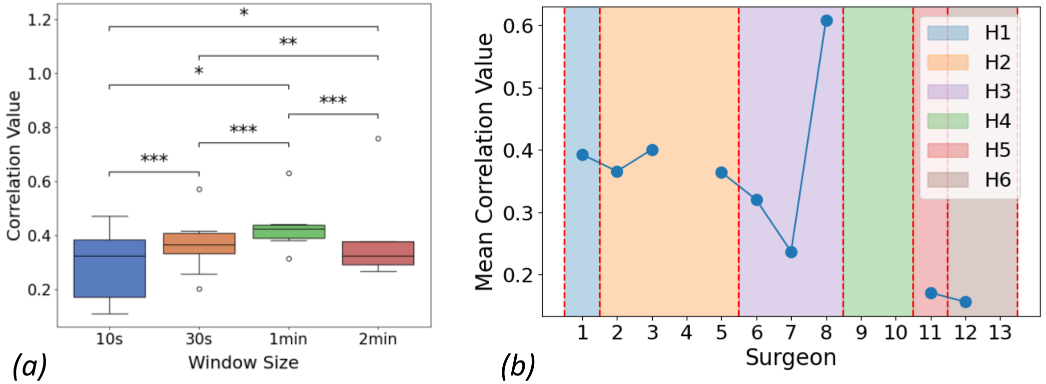
1 **Correlation** between cognitive load and self-reported difficulty → Over all surgeons and procedures:

$$\rho^{(L)}, p^{(L)} = Spearman\left(\boldsymbol{W}^{(L)}, \boldsymbol{D}^{(L)}\right)$$

→ ***(≈ 0.30 ± 0.05)*** *significant*

2 Correlation **stability** → Between different window lengths: TOST test *(a)*

Between the 13 surgeons *(b)*



(a) *(b)*

3 Influence of **procedure duration** → Kruskal-Wallis test

Window length	10 s	30 s	1 min	2 min
P-value	0.116	**0.022**	**0.032**	0.086

Discussion

Validation of the Method

- **Moderate** and **valid** correlation between objective cognitive load and surgeons' subjective assessments
- **Stability** across different time windows, with no significant impact on results.

Critical Analysis and Limitations

- Results are statistically more reliable in **longer procedures**
- **Imbalanced** surgical phases distribution
- Qualitative difficulty imputation **not validated** in literature

Possible solutions

- Refinement of the **raw data collection** process
- **Data balancing techniques** for machine learning to address dataset imbalance

Conclusions

Addressing Open Issues

Eye-tracking offers a promising **non-invasive** and **objective** way to assess surgeon workload

A **validated** workload metric can enhance decision-making and performance

Defining a **universal threshold** remains an open challenge

Future Developments

Combine eye-tracking with other non-invasive physiological signals

- real-time **alert systems** for cognitive overload
- adaptive **robotic assistance** based on workload fluctuations
- personalized training programs

Develop a more **systematic** method for self-reported workload ratings

Thank you