A Comprehensive Analysis of the Influence of Cognitive Load on Physiological Signals in Virtual Reality

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Universidad Zaragoza

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What is cognitive load

What is cognitive load

$14 + 7 = 21$
$21 + 7 = 28$
$28 + 7 = 35$

What is cognitive load

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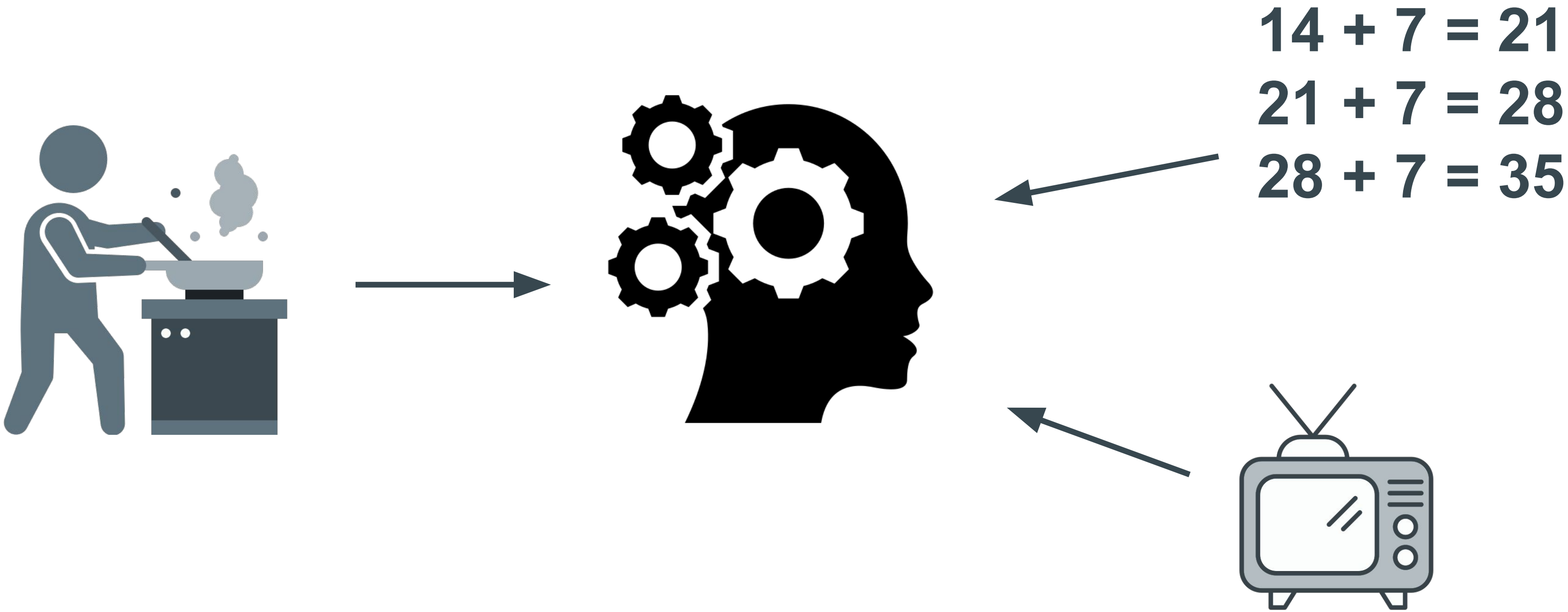
What is cognitive load



What is cognitive load

Understanding and managing CL can be highly beneficial:

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Understanding and managing CL can be highly beneficial:

- Avoid performance decrease

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Understanding and managing CL can be highly beneficial:

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- Improve user experience

What is cognitive load

Understanding and managing CL can be highly beneficial:

- Avoid performance decrease
- Improve user experience
- Allow for longer VR experiences reducing exhaustion

Interpreting cognitive load

Traditionally, CL has been studied through **subjective** evaluation (NASA TLX[1])

[1] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139–183). North-Holland.

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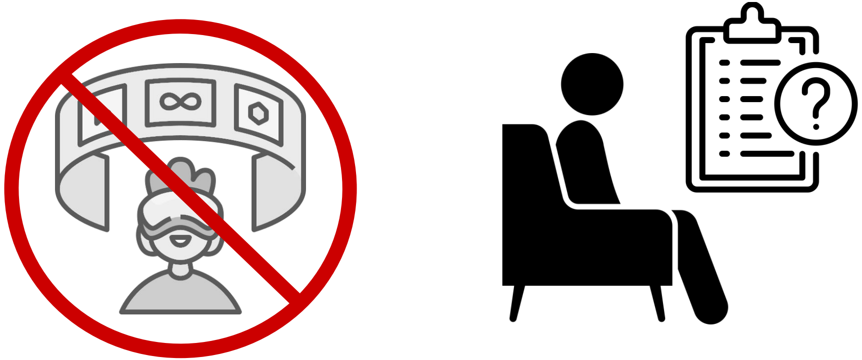

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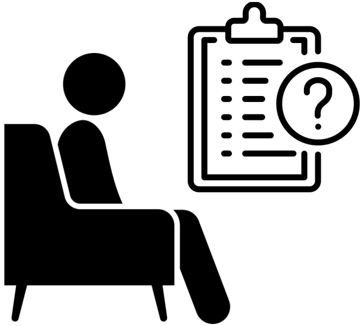
- Temporally inaccurate



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Interpreting cognitive load

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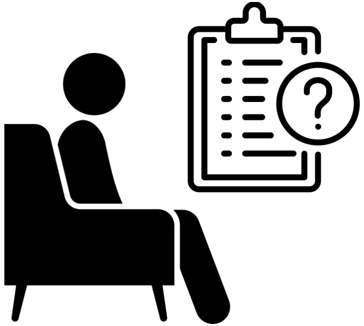
- Temporally inaccurate
- Could be biased



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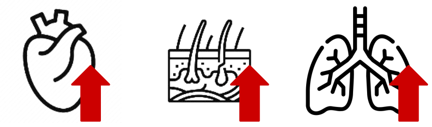
Using physiological signals

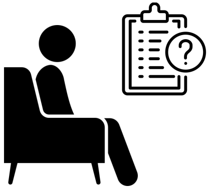
Using physiological signals

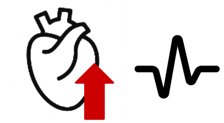
Strongly related to activations of the sympathetic and parasympathetic systems

Active periods ⟷ Resting periods

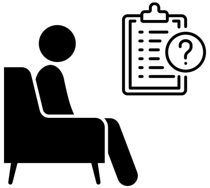


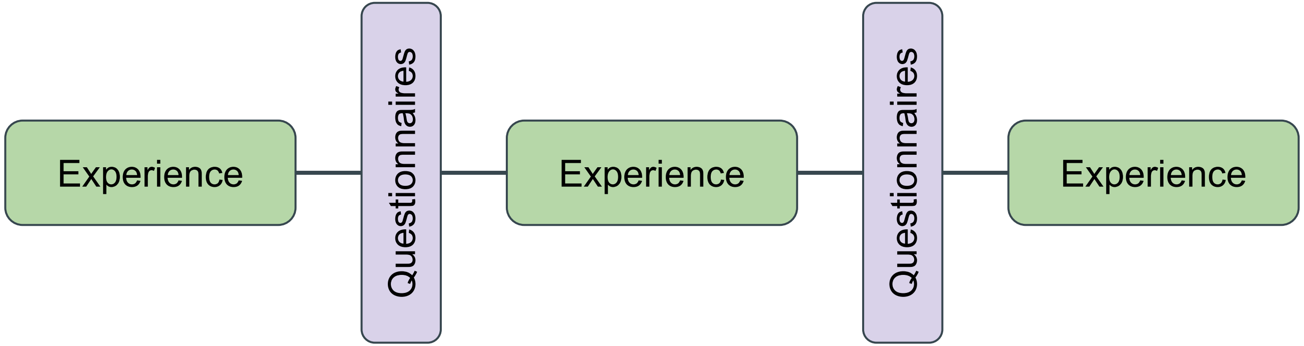
Using physiological signals

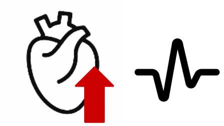




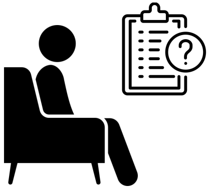
Using physiological signals

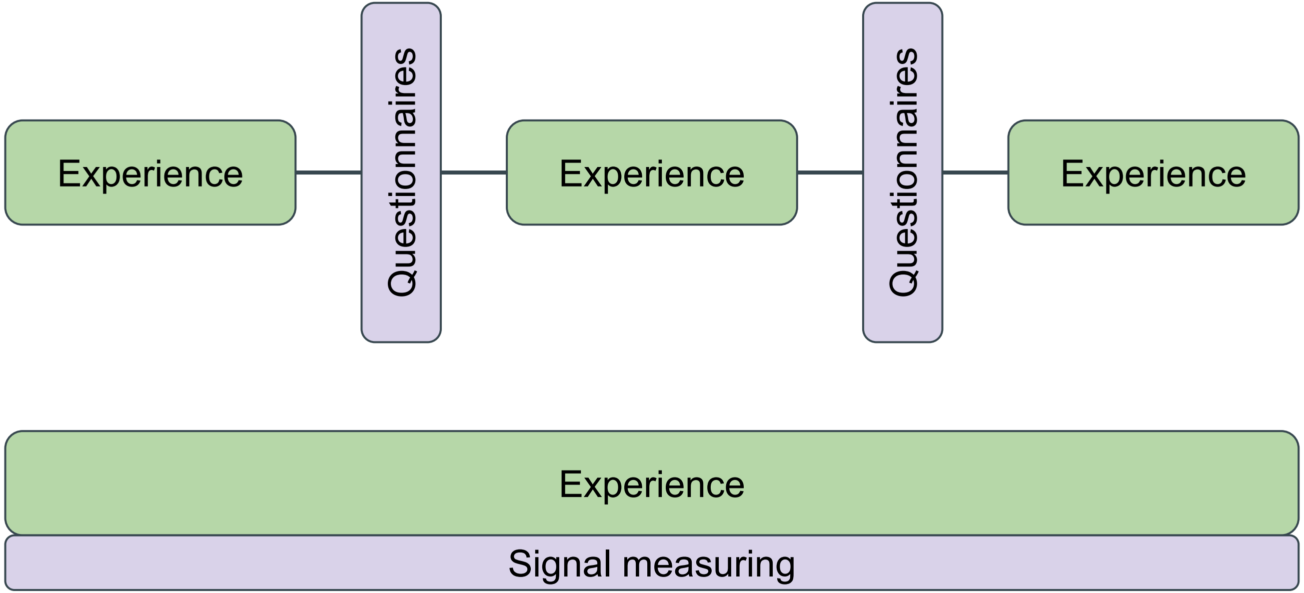


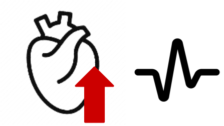




Using physiological signals







Our goal

Create a **comprehensive dataset** focused on Cognitive Load levels and **perform an analysis** to fill the gaps in literature:

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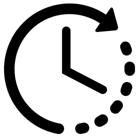

Temporality

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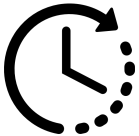
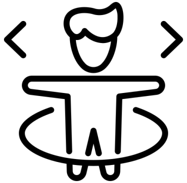


Temporality



Movement

Our goal

Create a **comprehensive dataset** focused on Cognitive Load levels and **perform an analysis** to fill the gaps in literature:

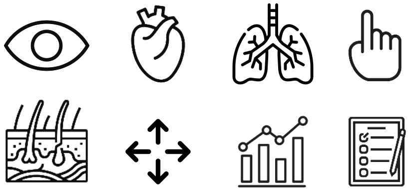
Temporality

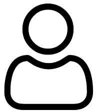
Movement

Multimodality

Our contribution

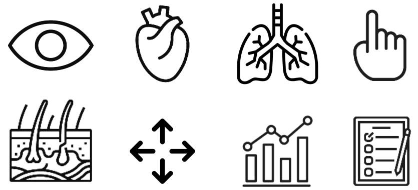
Dataset

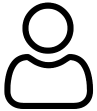


 × 36

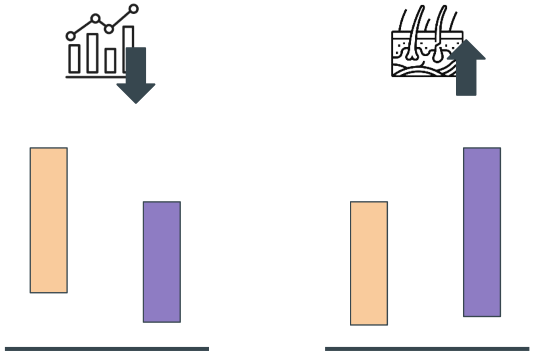
Our contribution

Dataset



 × 36

Effect of CL



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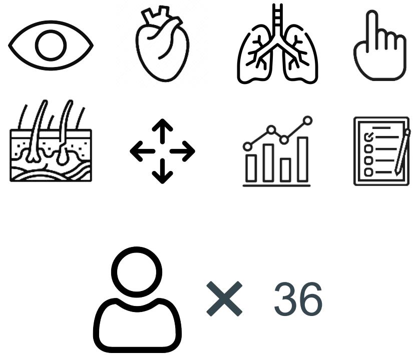
Dataset



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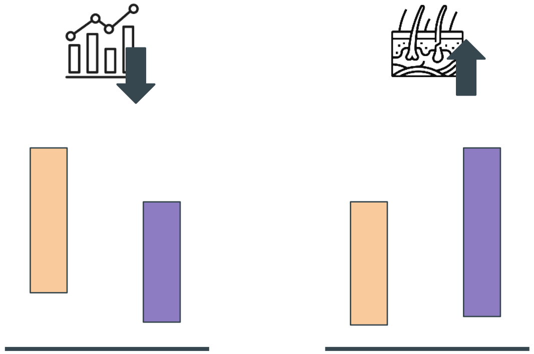
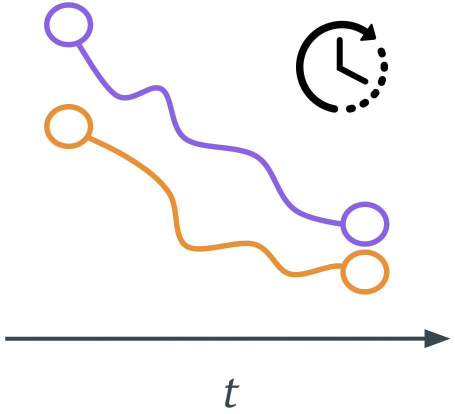
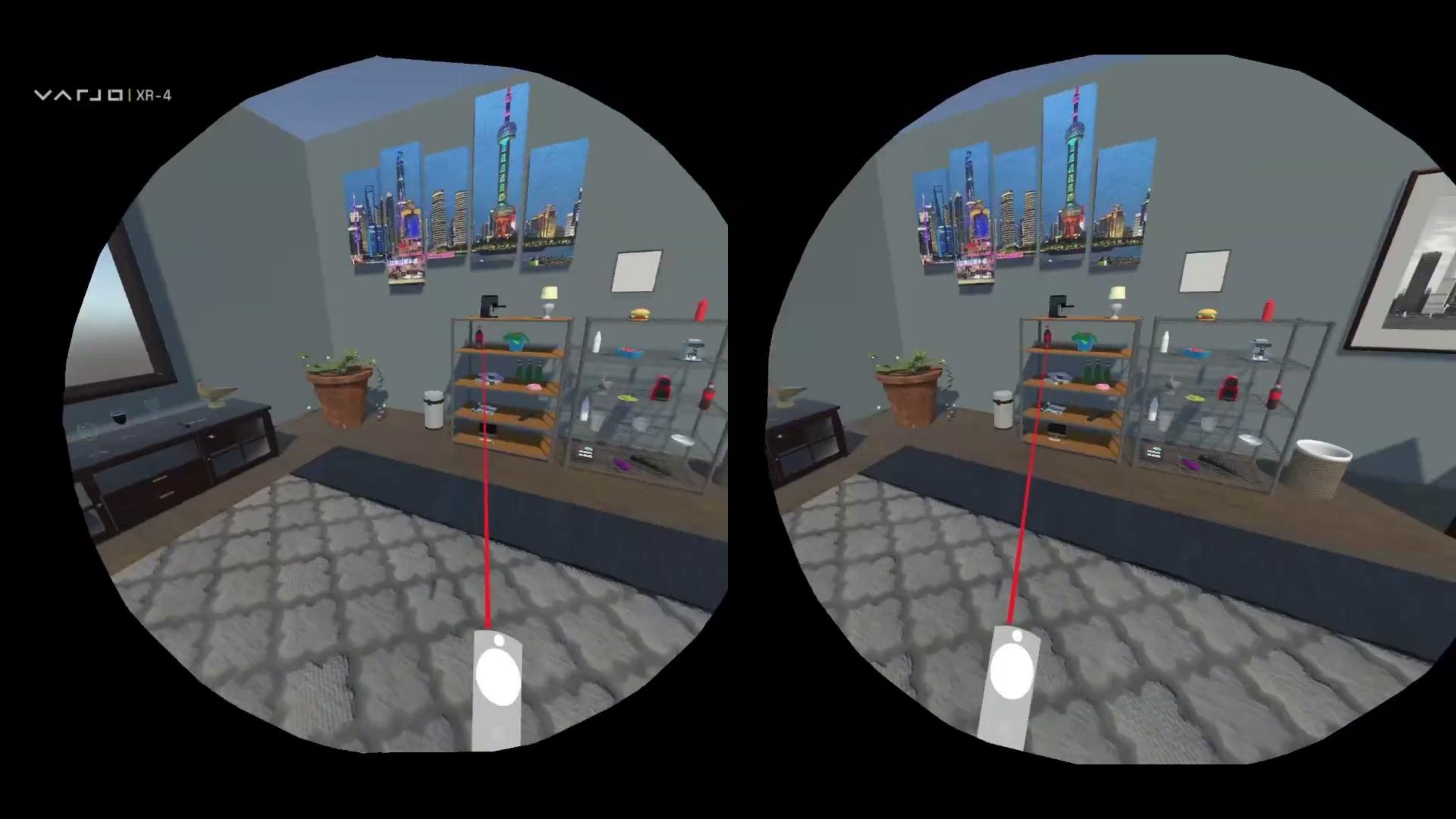


Time Ev.



Virtual environment

Virtual environment


XR-4

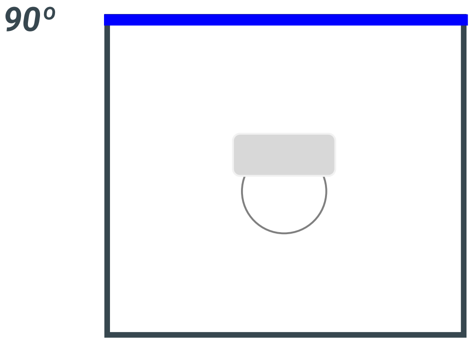
Experimental design

Search area

Cognitive load

Experimental design

Search area

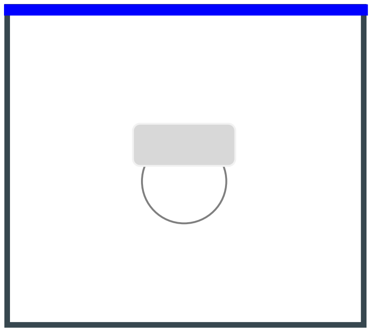


Cognitive load

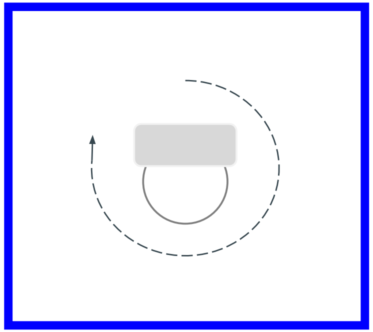
Experimental design

Search area

90^o

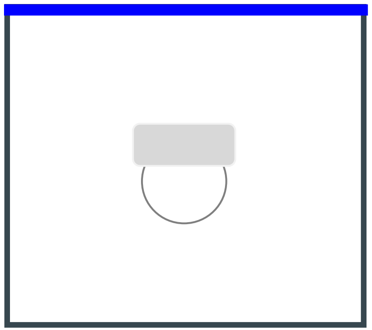
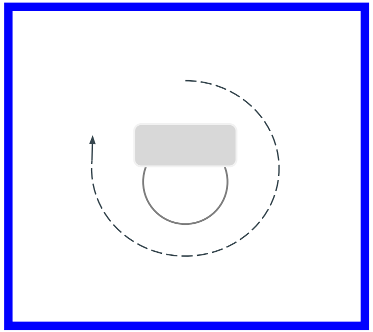


360^o



Cognitive load

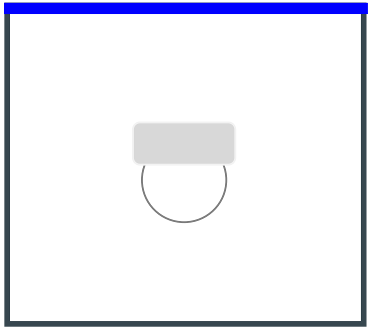
Experimental design

Search area	*90°* 	*360°* 
Cognitive load	*Low (only visual task)* 	

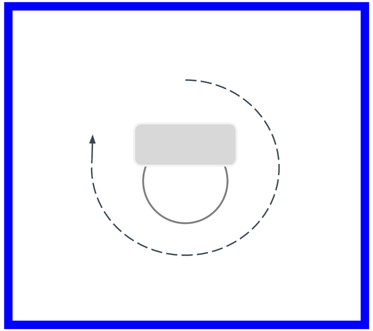
Experimental design

Search area

90°



360°



Cognitive load

Low (only visual task)

High (auditory + visual task)

Auditory task

Users listen to an audio narrating a story filled with numbers

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Users listen to an audio narrating a story filled with numbers

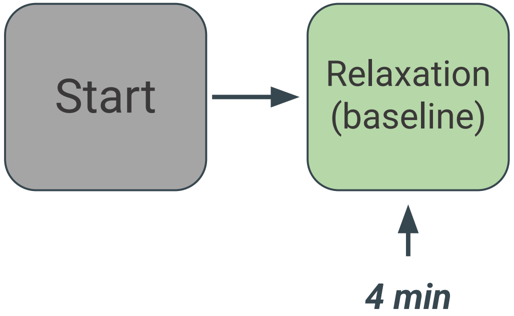
"It was a nice summer evening, fourteen, or even fifteen years ago. I remember looking at the sky and seeing seven herons flying above me with my two eyes…"

Auditory task

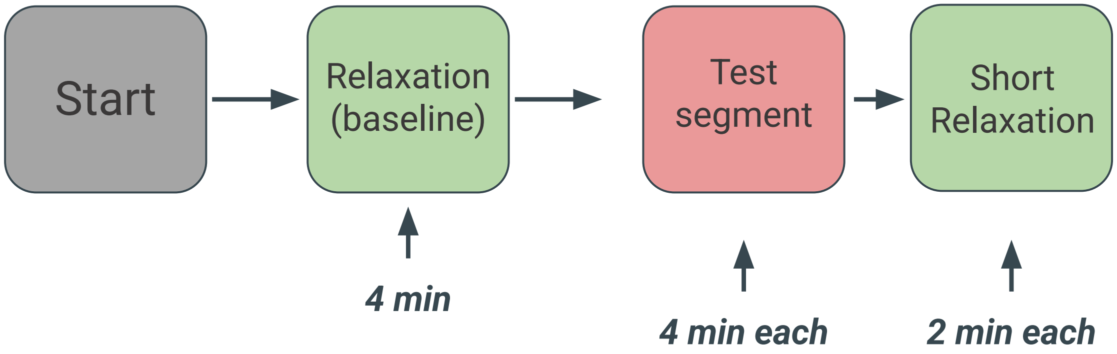
Task: Press the A button at each **odd number** as fast as possible

“It was a nice summer evening, fourteen, or even fifteen years ago. I remember looking at the sky and seeing seven herons flying above me with my two eyes…”

Experimental procedure



Experimental procedure



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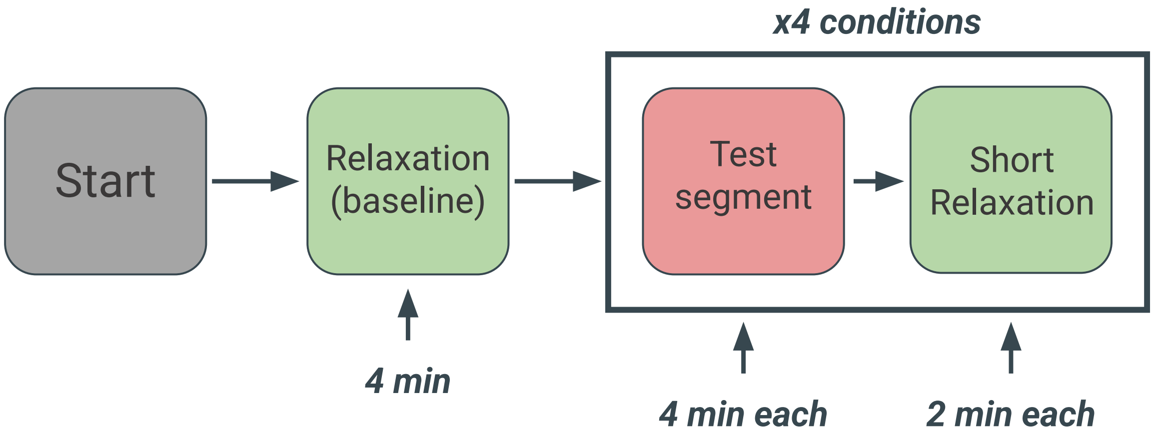

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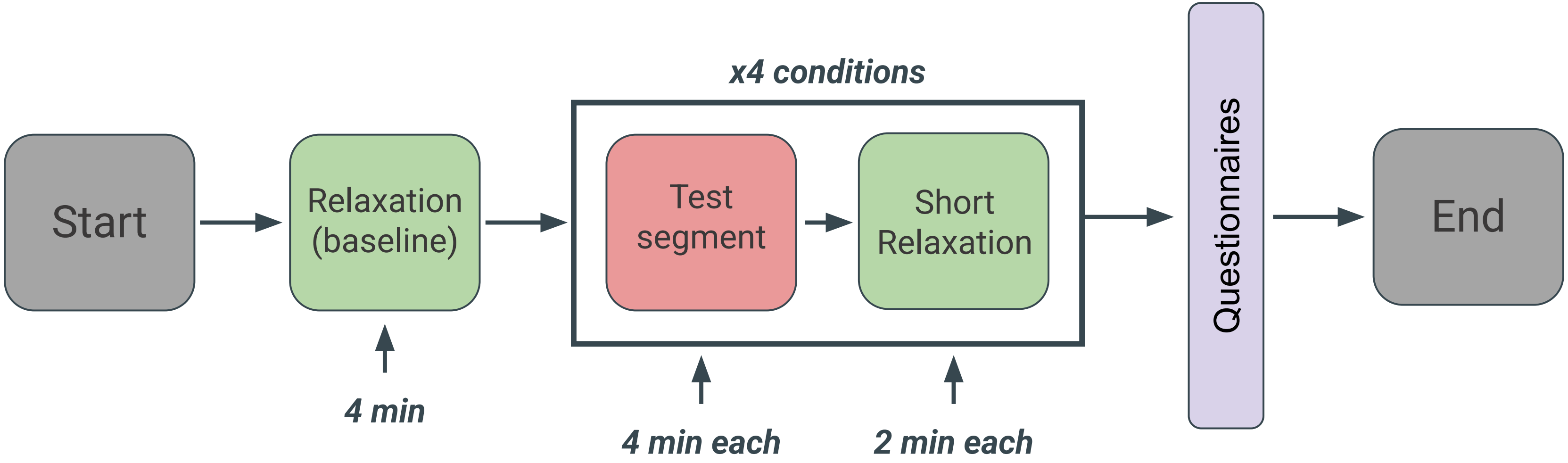

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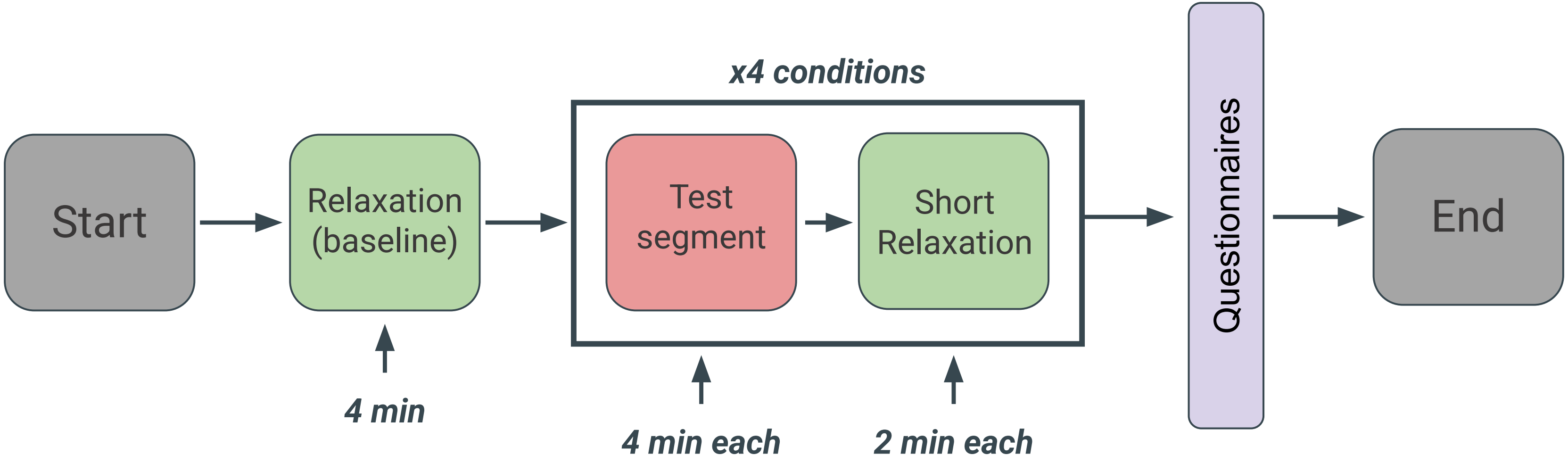
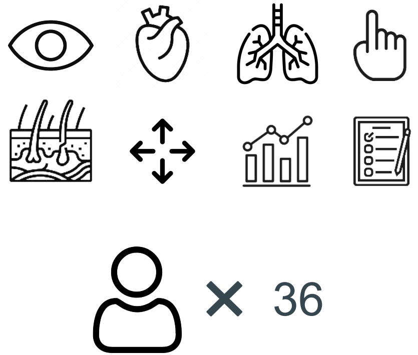


Questionnaires assessed **significant difference** in levels of CL between segments

Our contribution

Dataset



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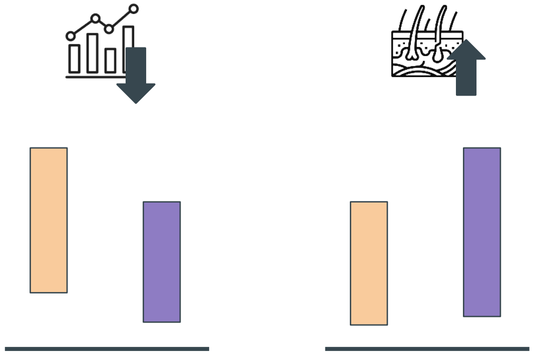

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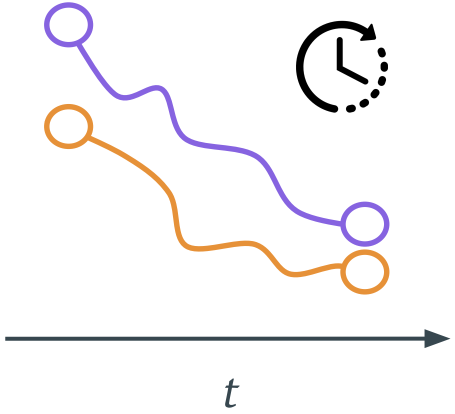


Data captured

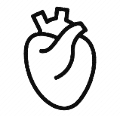
Electrocardiogram (ECG)

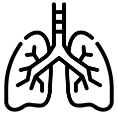
Data captured

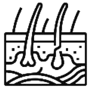
Electrocardiogram (ECG)

Respiration

Data captured

 *Electrocardiogram (ECG)*

 *Respiration*

 *Electrodermal activity (EDA)*

Data captured

- *Electrocardiogram (ECG)*
- *Respiration*
- *Electrodermal activity (EDA)*
- *Photoplethysmography (PPG)*

Data captured

Electrocardiogram (ECG)

Respiration

Electrodermal activity (EDA)

Photoplethysmography (PPG)

Eye tracking

Data captured

Electrocardiogram (ECG)

Respiration

Electrodermal activity (EDA)

Photoplethysmography (PPG)

Eye tracking

Performance metrics

Data captured

- *Electrocardiogram (ECG)*
- *Respiration*
- *Electrodermal activity (EDA)*
- *Photoplethysmography (PPG)*
- *Eye tracking*
- *Performance metrics*
- *Subjective measurements*

Data captured

- *Electrocardiogram (ECG)*
- *Respiration*
- *Electrodermal activity (EDA)*
- *Photoplethysmography (PPG)*
- *Eye tracking*
- *Performance metrics*
- *Subjective measurements*
- *Inertial measurements*

Data captured

- *Electrocardiogram (ECG)*
- *Respiration*
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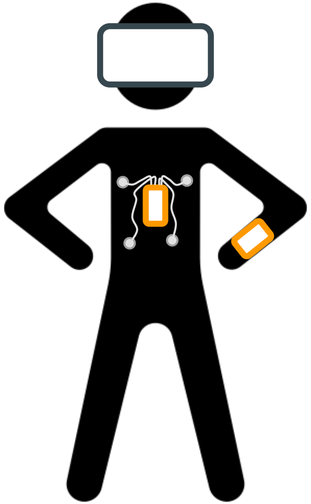
× 36

Data captured



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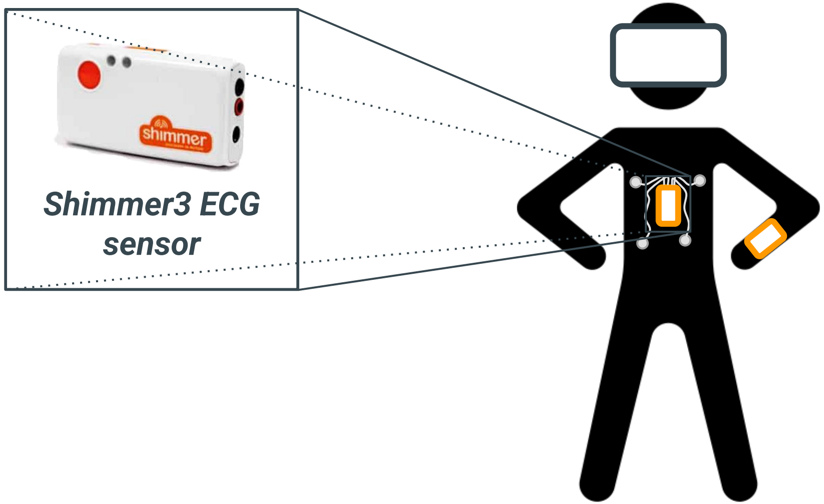

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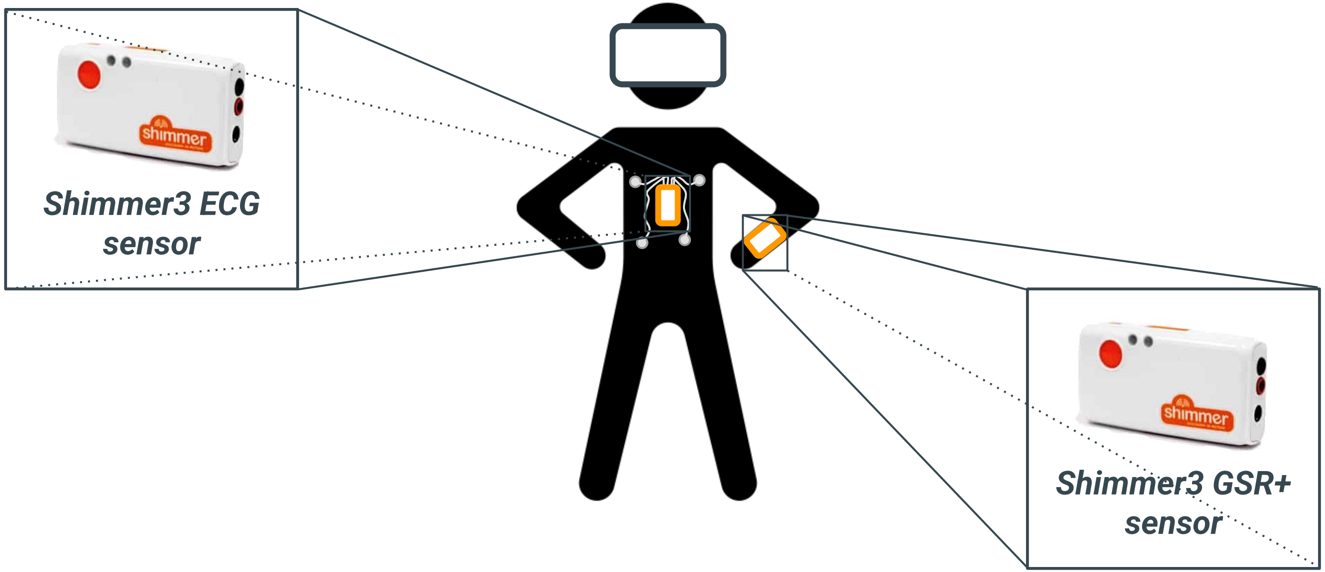

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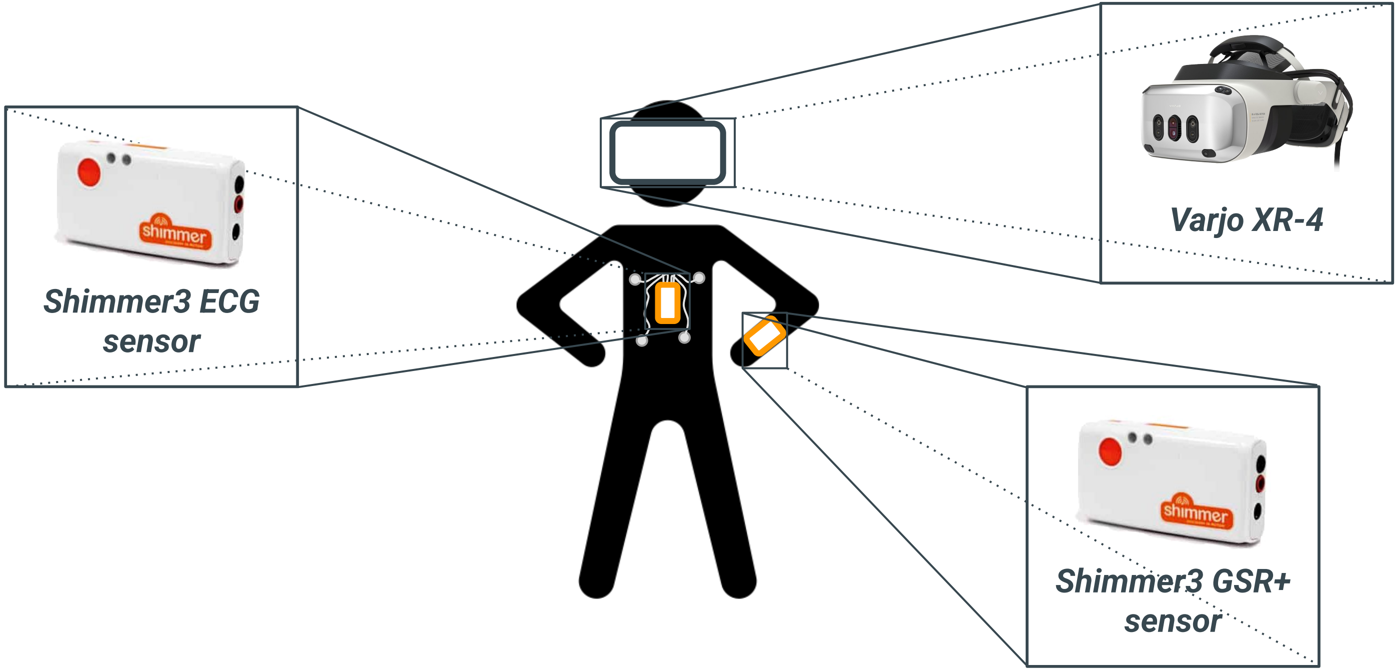
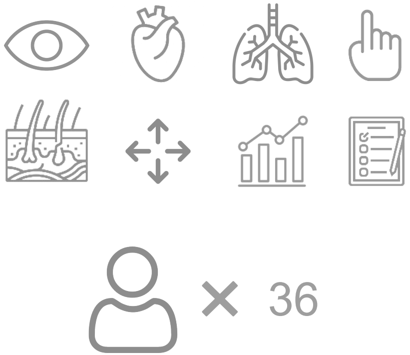
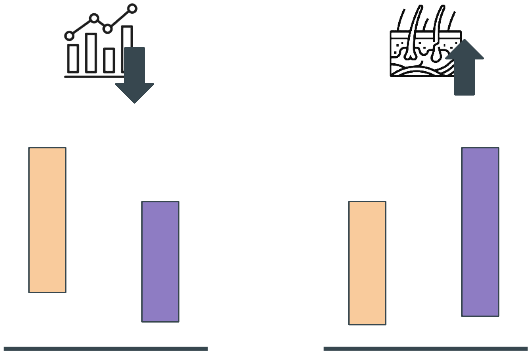


Our contribution

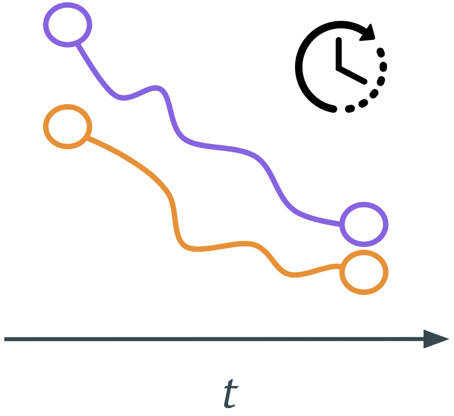
Dataset



Effect of CL



Time Ev.



Results: effect of cognitive load

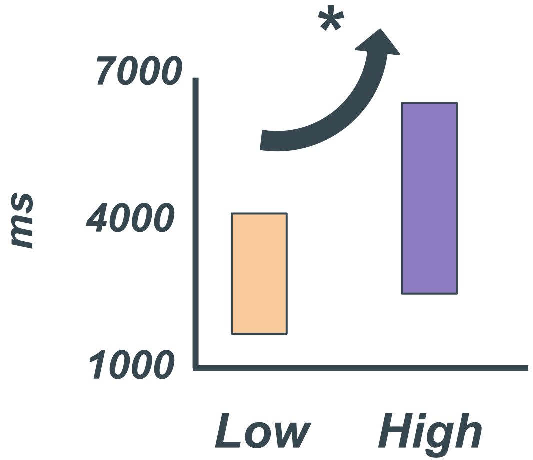
Main task performance

Results: effect of cognitive load

Main task performance

Performance **decreased** for high CL segments

Users took longer to find objects while listening to the audio



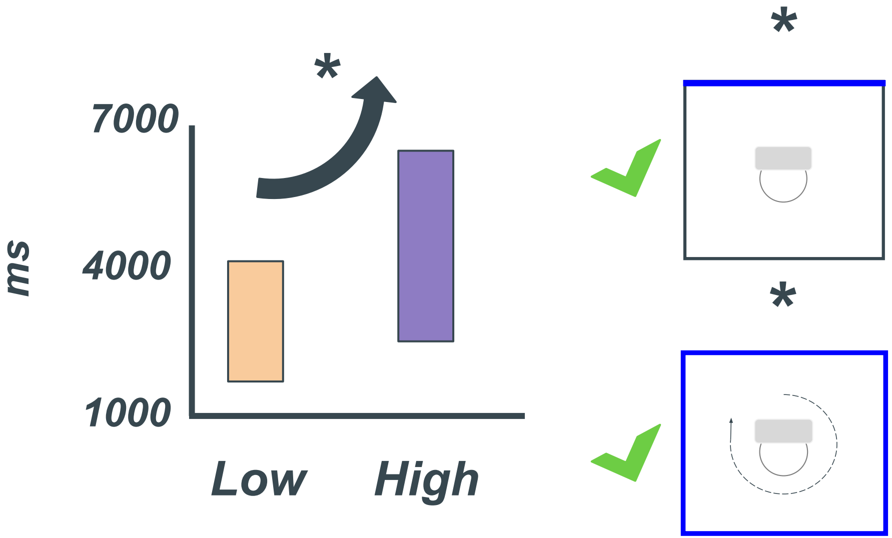
Results: effect of cognitive load

Main task performance

Performance **decreased** for high CL segments

Users took longer to find objects while listening to the audio

This was **consistent** across areas



Results: effect of cognitive load

For the analysis we focused on **four main biomarkers**:

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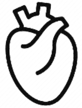
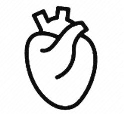
- Mean Heart Rate

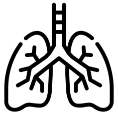


Results: effect of cognitive load

For the analysis we focused on **four main biomarkers**:

- Mean Heart Rate
- Mean Respiration Frequency

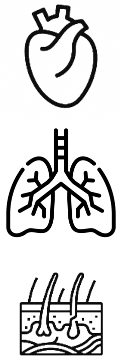




Results: effect of cognitive load

For the analysis we focused on **four main biomarkers**:

- Mean Heart Rate
- Mean Respiration Frequency
- Median EDA Tonic Component



Results: effect of cognitive load

For the analysis we focused on **four main biomarkers**:

- Mean Heart Rate
- Mean Respiration Frequency
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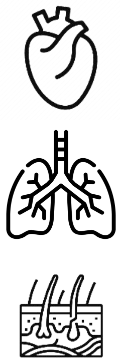
- Median EDA Phasic Component



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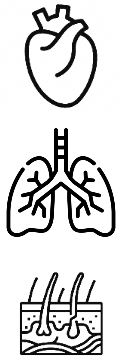
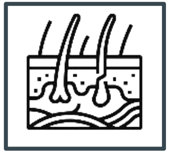


Many other remain to be properly analysed in the dataset

Results: effect of cognitive load

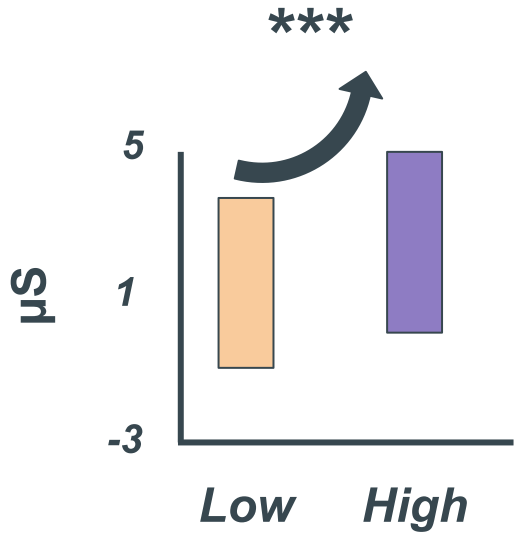
EDA Tonic

Results: effect of cognitive load



EDA Tonic

Significantly **increases for high CL** segments



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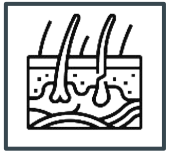
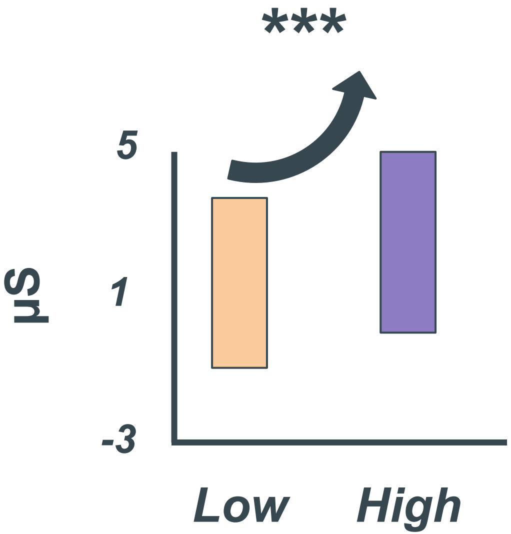


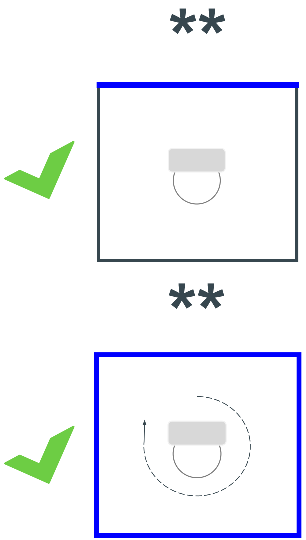
EDA Tonic

Significantly **increases for high CL** segments

Regardless of search area

Most robust indicator found





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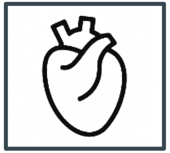
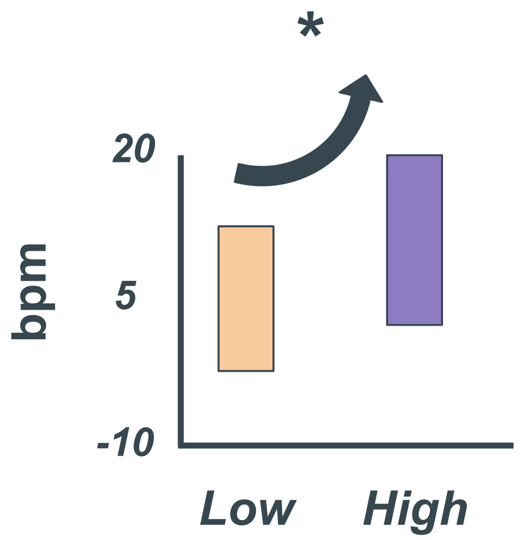


Heart Rate (ECG)

Results: effect of cognitive load

Heart Rate (ECG)

Significantly **increases for high CL** segments



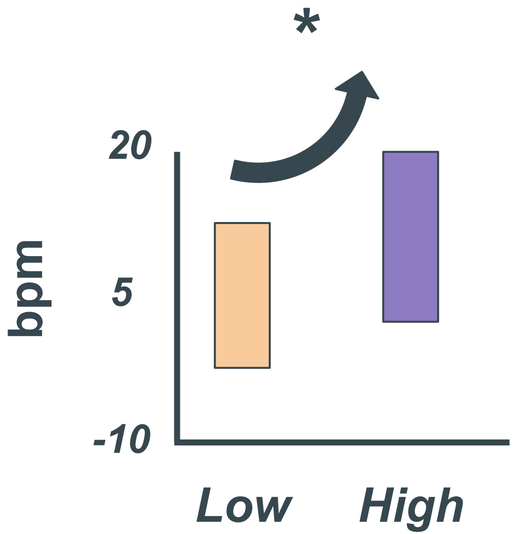
Results: effect of cognitive load

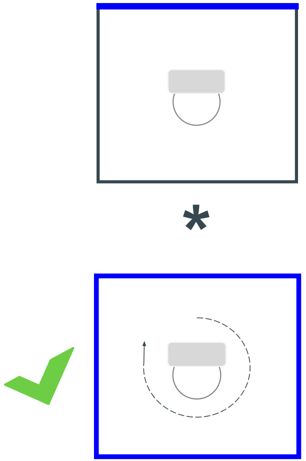
Heart Rate (ECG)

Significantly **increases for high CL** segments

Seems to be affected more by

search area





Results: effect of cognitive load

Respiration Frequency (ECG + ImP)

Results: effect of cognitive load

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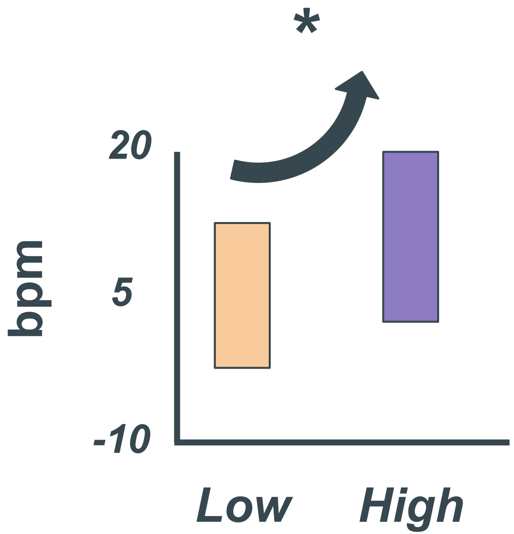


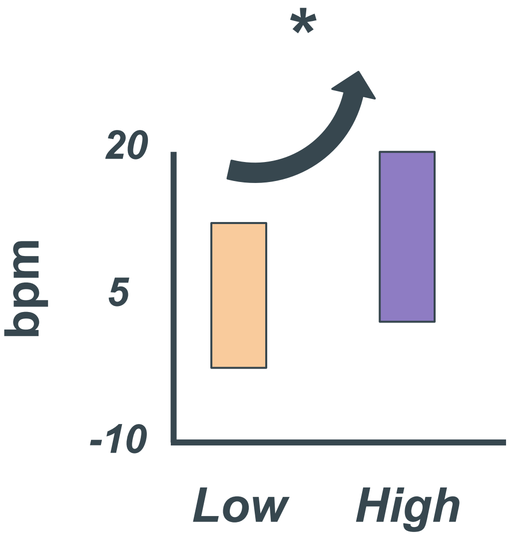
Results: effect of cognitive load

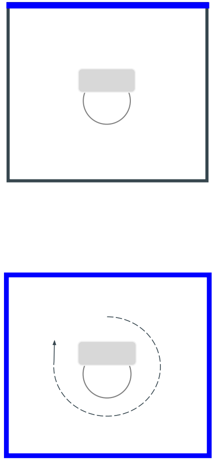
Respiration Frequency (ECG + ImP)

Significantly **increases for high CL** segments

Most sensitive to search area

Vulnerable to **movement artifacts**





Results: effect of cognitive load

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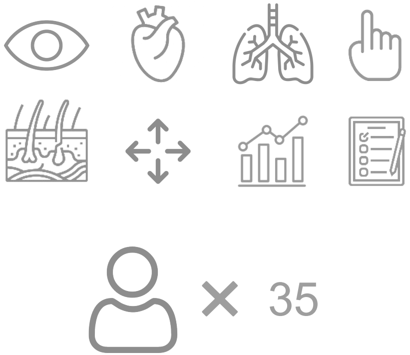
In summary:

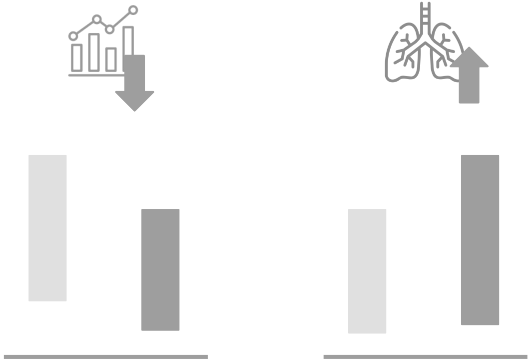
- The EDA Tonic component presented as the most robust indicator
- Heart Rate and Respiration Frequency were sensitive to movement
- The EDA Phasic component seemed weak for long durations

Our contribution

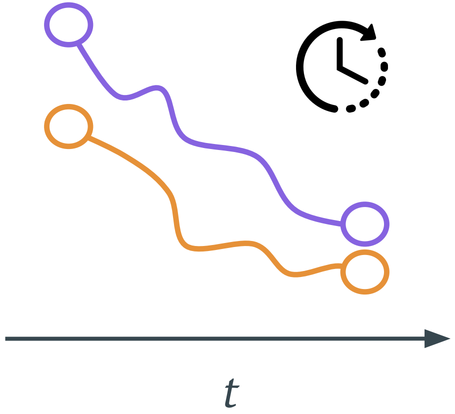
Dataset



Effect of CL

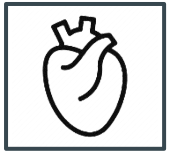


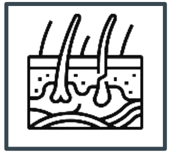
Time Ev.



Results: temporal evolution

We compared the first and last 40 seconds of each segment





(Phasic)

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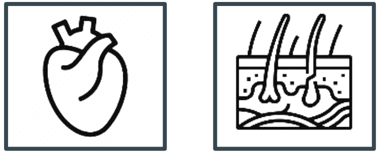
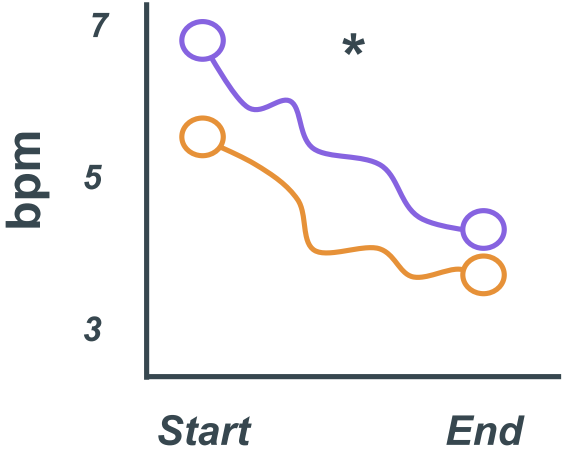
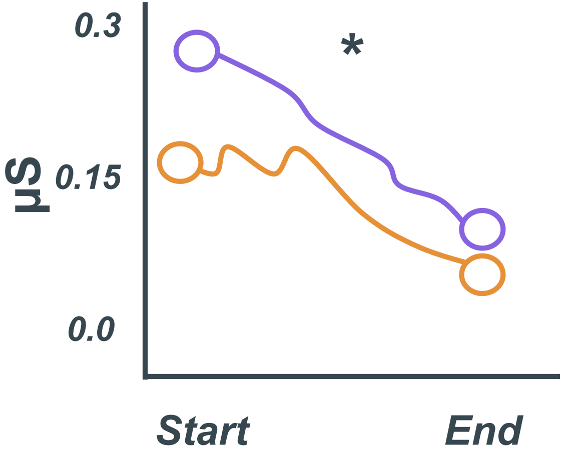


(Phasic)





Both Heart Rate and EDA Phasic **significantly decreased** along the segment duration

Results: temporal evolution

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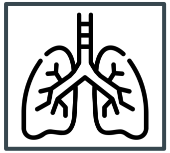

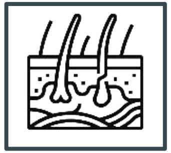

(Tonic)

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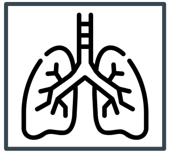
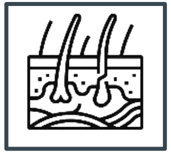
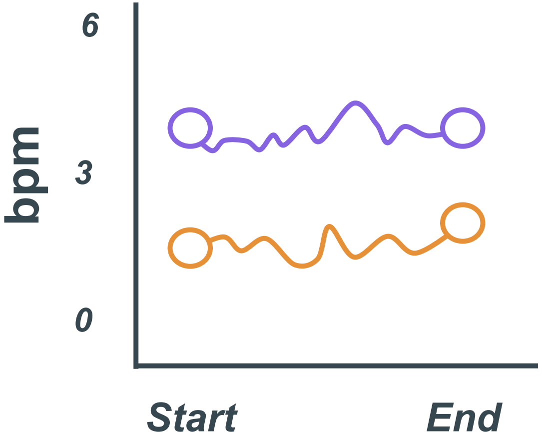
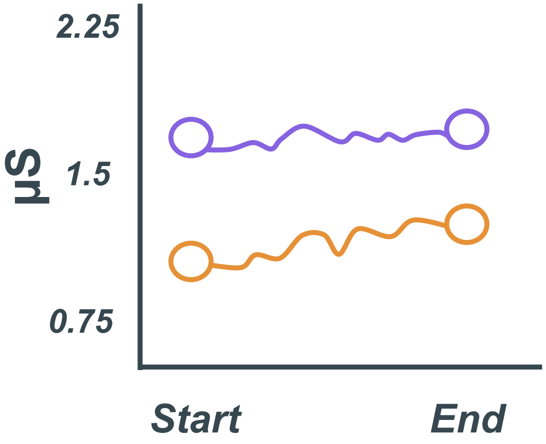




(Tonic)



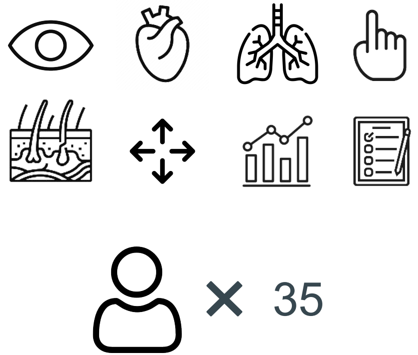


Respiration Frequency and EDA Tonic were consistent along the segment

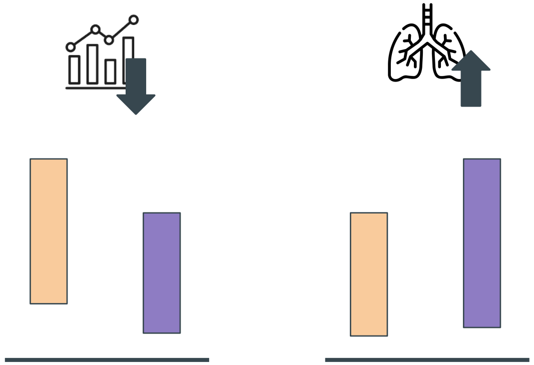
Respiration seems less reliable for the 360º search area

Our contribution

Dataset



Effect of CL



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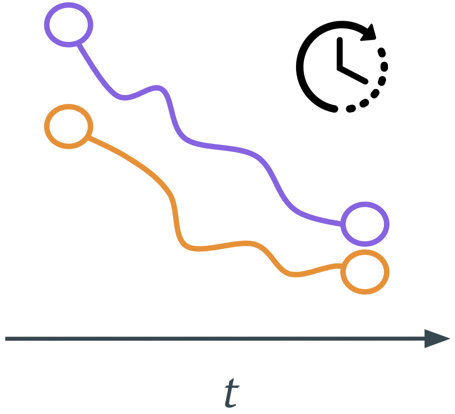

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- We offer a comprehensive biosignals dataset for different levels of **CL and movement** during search tasks in VR

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- We offer a comprehensive biosignals dataset for different levels of **CL and movement** during search tasks in VR
- We analyzed the validity of main markers as CL indicators, pointing at **EDA Tonic as the most consistent**
- We tested the reliability of main markers across time, where **EDA Tonic also proved to be the most invariant**

Future work

- Leverage further physiological markers

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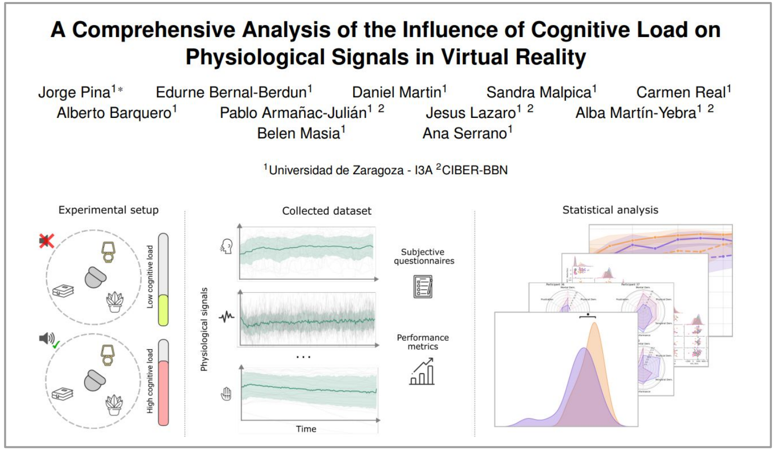
- Disentangle sources of Cognitive Load

Future work

- Leverage further physiological markers
- Disentangle sources of Cognitive Load
- Expand to more in-the-wild scenarios

Our dataset is publicly available

Visit our project page for the **full paper and dataset!**


A Comprehensive Analysis of the Influence of Cognitive Load on Physiological Signals in Virtual Reality

Jorge Pina[1*] Edurne Bernal-Berdun[1] Daniel Martin[1] Sandra Malpica[1] Carmen Real[1] Alberto Barquero[1] Pablo Armañac-Julián[1 2] Jesus Lazaro[1 2] Alba Martín-Yebra[1 2] Belen Masia[1] Ana Serrano[1]

[1]Universidad de Zaragoza - I3A [2]CIBER-BBN