RSA FG
Research Studios Austria
Forschungsgesellschaft

SOMAREALITY

WHITEPAPER

Cognitive Load

Introducing a real-world capable assessment of Cognitive Load levels based on empiric modeling on pupillometric data

What is Cognitive load...

Introducing a real-world capable assessment of Cognitive Load levels based on empiric modeling on pupillometric data

Background

There is a wide range of definitions of attention and Cognitive Load. Claudia Roda proposed attention as 'the set of different mechanisms that allows the allocation of cognitive resources, which are assumed to be limited'[1]. When following this focus on the mental processing capacity, the term of Cognitive Load is often used as a synonym for attention, describing the ratio of attention resources that are required for the accomplishment of tasks, whereas Working Memory represents a cognitive subsystem for the transient holding, processing, and manipulation of information[2].

Cognitive Load Theory (CLT), developed by John Sweller, focuses on the limitations of cognitive resources and how they are allocated to process information efficiently. It provides insights into instructional design and learning by considering the Cognitive Load imposed on learners.

The Multiple Resource Theory (MRT) extends the Cognitive Load Theory by proposing that individuals have multiple cognitive resources specialized for processing different types of information. These resources are thought to operate in parallel:

- Visual/Pictorial Resource: Visual and spatial information.
- Auditory/Verbal Resource: Processing auditory and linguistic information.
- Motor Resource: Handling motor tasks and coordination.
- Spatial Resource: Spatial relationships and orientation.
- Temporal Resource: Managing timing and temporal aspects.

MRT acknowledges that individuals may differ in their resource capacities and preferences. Some individuals may be more visually oriented, while others may excel in auditory processing.

In summary, CLT and MRT provide a valuable framework for understanding how individuals allocate their cognitive resources. It has implications for instructional design, task analysis, and the effective presentation of information to optimize learning and performance.

Types of Cognitive Load

Intrinsic Load

how difficult the problem is

Intrinsic Cognitive Load is the inherent difficulty that's just "built into" a topic.

Extraneous Load

the way the information is presented

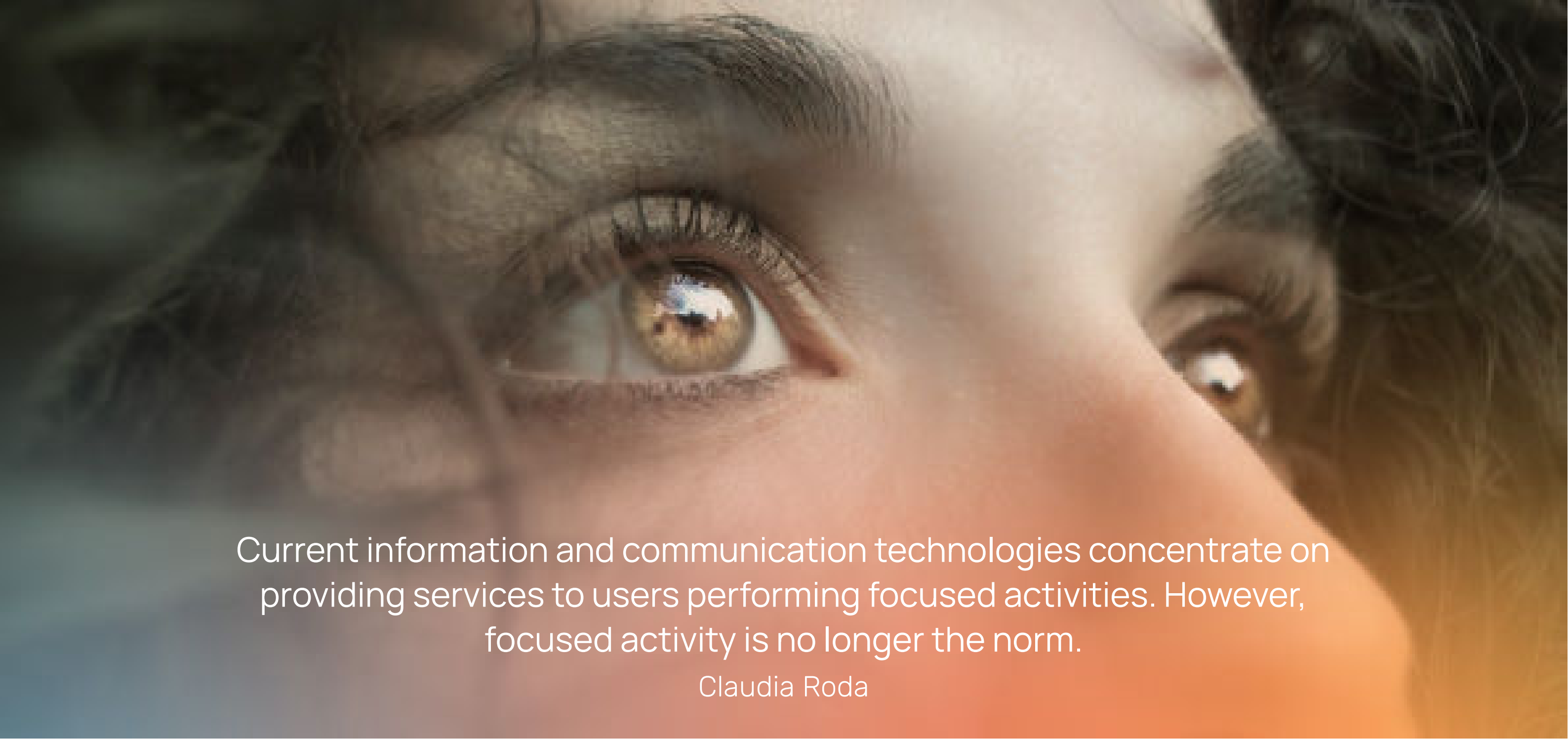
Conditions that make the learner actively process stuff without contributing to learning.

Germane Load

creating schemas

The demands of getting the content stored in memory.

1. Human attention in digital environments. Cambridge University Press, 2011.
2. A. Diamond, "Executive functions," Annual review of psychology, vol. 64, p. 135, 2013.



...and what to do with it?

01 Our Vision

Cognitive Load represents one of the most crucial parameters of cognitive performance. It provides vast opportunities to advance innovations, e.g. in the fields of cognitive assessments and early diagnosis in healthcare, optimization of learning and training in education, or adaptive, individualized interaction technologies.

02 Our Mission

The mission of SOMAREALITY and Research Studios Austria lies in enabling these innovations and innovative services and applications by making eye tracking-based cognitive insights available for real-world applications, releasing the full potential of both humans as well as their current and future assistance technologies.

Key Benefits with Cognitive Load by SOMAREALITY & RSA FG

Real-Time Analytics

Real-time analysis and interpretation of Cognitive Load based solely on eye tracking data.

Compensation of Brightness Effects

Extraction of Cognitive Effects from pupillary behavior by compensating brightness-related effects (Pupillary Light Reflex Modeling).

Adaptive, Live Calibration

Adaptive, on-the-fly calibration of algorithms for optimal compensation of individual differences in physiology.

Transparency & Validation

Scientifically validated and published white-box approach based on empiric models instead of intransparent AI black box solutions.

How to measure Cognitive Load

Attention cannot be measured directly but must be inferred via interpretation of correlating effects, representations, and expressions of attention. To enable such interpretations, indirect measurements need to comply with several requirements:
(i) Sensitivity to changes in cognitive activity, (ii) Validity, (iii) Reliability, (iv) (Un-)obtrusiveness, (v) Temporal Resolution and (vi) Comfort.

Psycho-physiological measures of attention exploit the physical reaction of the human body in the preparation of, execution of, or as a reaction to cognitive activities. Most representations of attention are directly related to physiological arousal levels. Arousal represents the overall physical and psychological activation of the individuum and is directly linked to the state of the autonomic nervous system.

Pupillometry

Since the 1960's, pupil dilation has been investigated as an indicator of cognitive activities, emotion and decision making, triggering the start of the so-called cognitive pupillometry, identifying the human eye as the most promising indicator of cognitive state. Besides light incidence control, the pupil is also sensitive to psychological and cognitive activities and mechanisms. The 'Task-Evoked Pupil Response (TEPR)' is a pupillary response caused by a Cognitive Load in the execution of a task as a result of the decrease in parasympathetic activity in the peripheral nervous system [167]. Since then, this approach towards deducing Cognitive Load from pupil dilation has found application in various fields of applications in laboratory environments.

However, the co-dependency of pupil dilation to light-induced effects requires a profound separation between cognitive and illumination effects to enable the dependable extraction and analysis of cognitive effects on pupil dilation.

Evaluation

⊕

- established as reliable, objective indicator of Cognitive Load via diverse academic empiric studies
- relatively unobtrusive assessment
- mobility of assessment with mobile eye trackers
- potential combination with visual attention allows detailed analysis of conscious perception and interaction

⊖

- co-dependency to environmental brightness requires separation of cognitive and brightness effects of pupillary behavior
- offline processing required for TEPR analysis (computation in the frequency domain or via brute-force curve matching)

From the Lab to Real Applications

Whereas the assessment of Cognitive Load from pupillometry has been established in controlled laboratory settings, the complexity of the analysis and modeling of cognitive effects due to the co-dependencies to brightness effects, individual physiological differences and ambiguity of psycho-physiological indicators of attention have prevented robust real-world assessments of Cognitive Load. The research group at the Research Studio Pervasive Computing Applications has succeeded in realizing the next step towards real-world capable analysis of Cognitive Load:

Compensation of Environmental Brightness Effects

Our Cognitive Load approach exploits standard cameras which cover the visual field of the user as a directional brightness sensor. The obtained brightness values are fed into empiric models of the human pupillary light reflex, enabling the modeling of how the human pupil reacts to current brightness values and separate cognitive from brightness-related effects.

Live Analysis and Interpretation

In contrast to established analysis methods of TEPR analysis, we have realized a solution which allows the analysis and interpretation of extracted cognitive effects live during runtime.

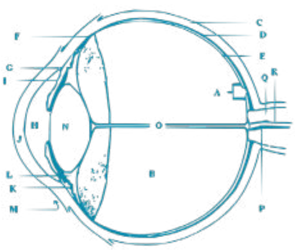
Live Calibration

To compensate and adapt to individual differences that can not be covered by generalized mathematical models, our Cognitive Load analysis performs a live calibration process which maps observed combinations of pupil dilation and brightness values to the employed empiric models.

Application of Empirical Computational Models

In contrast to other approaches, our Cognitive Load analysis is not based on purely AI-based black box solutions which lack transferability and traceability, but on empirically validated and generally applicable models of physiological behavior.

How it works

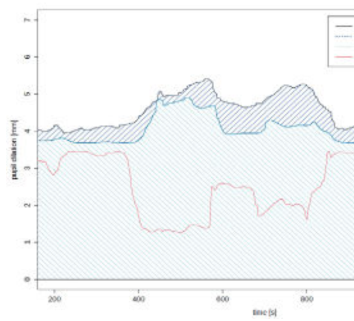


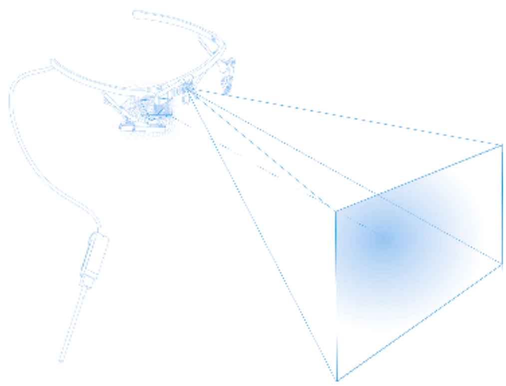
1
Calibration

Empiric models are able to describe pupillary behavior of humans in general, however, they need to be tailored to the individual and employed camera systems. Our on-the-fly calibration system allows a fast adaption of parameters to (i) current environment setting, (ii) individual characteristics, and (iii) camera specifications (aperture settings, etc.)

Brightness Compensation
2

We use the world camera data of mobile eye trackers (directed at the field of view of the user) to measure the perceived brightness in real-time. This brightness measure provides the input for an empirical model established in the literature, which describes the Pupillary Light reflex (PLR - how the user's pupil would behave when only influenced by light conditions).





3
Extraction
Cognitive Ef

The aforementioned modeli
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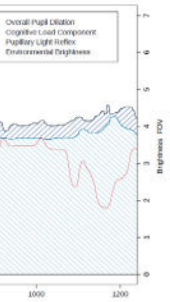
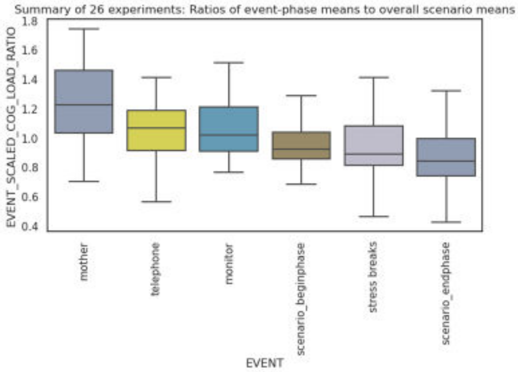
the separation of light-relat
and cognition-related (~20%
pupillary behavior.



The extracted cognitive effects are analyzed via a second established empiric model of Cognitive Load (Task-evoked Pupil Response - TEPR). This traditionally offline analysis has been transformed into a live modeling and analysis algorithm which provides continuous, normalized Cognitive Load data and timestamps of underlying stimuli.



Live Modeling Cognitive Load

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Analysis & Adaptive Solutions

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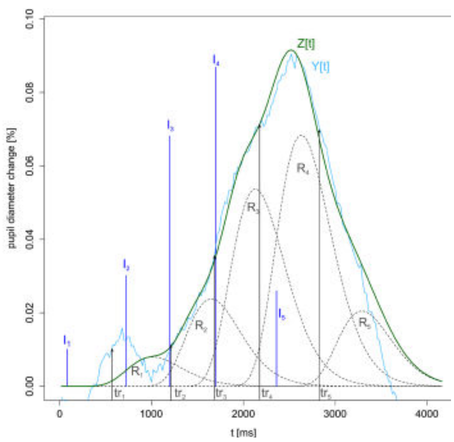
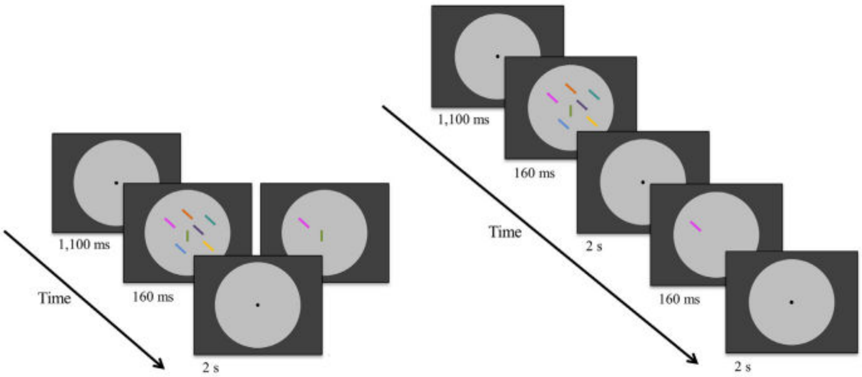


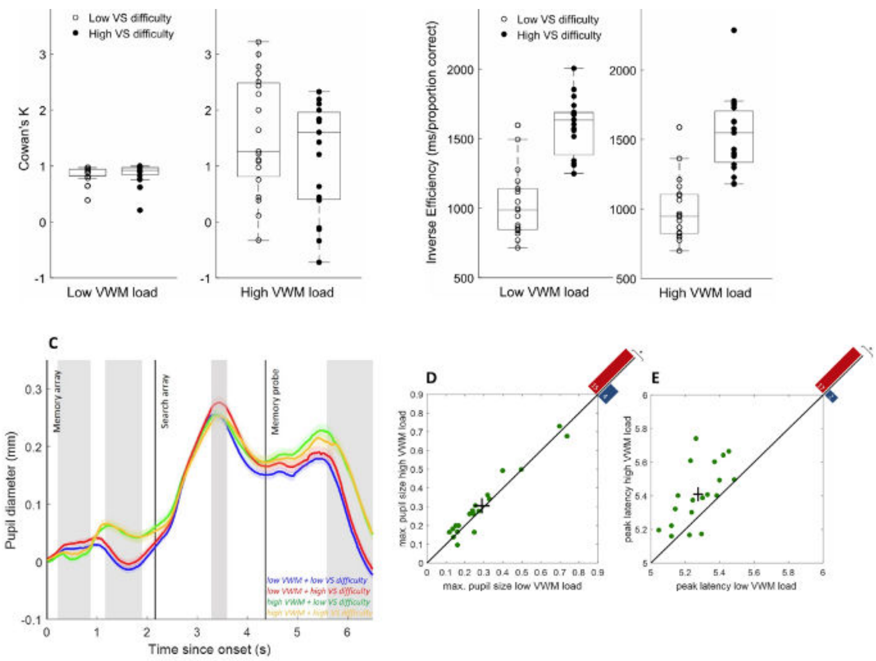
The provided data allows both (i) analyzing individual time series to identify peaks of Cognitive Load and relating them to events and (ii) averaging Cognitive Load data over longer time periods to compare performances between performances and between individuals.

Validation & Applications

Importantly, online modeling of pupil responses was successful on three points. First, there was good correspondence between the modeled and stimulus locked pupil dilations. Second, stimulus onsets could be approximated from the derived attentional pulses to a reasonable extent. Third, cognitive demands could be classified above chance level from the modeled pupil traces in both tasks.

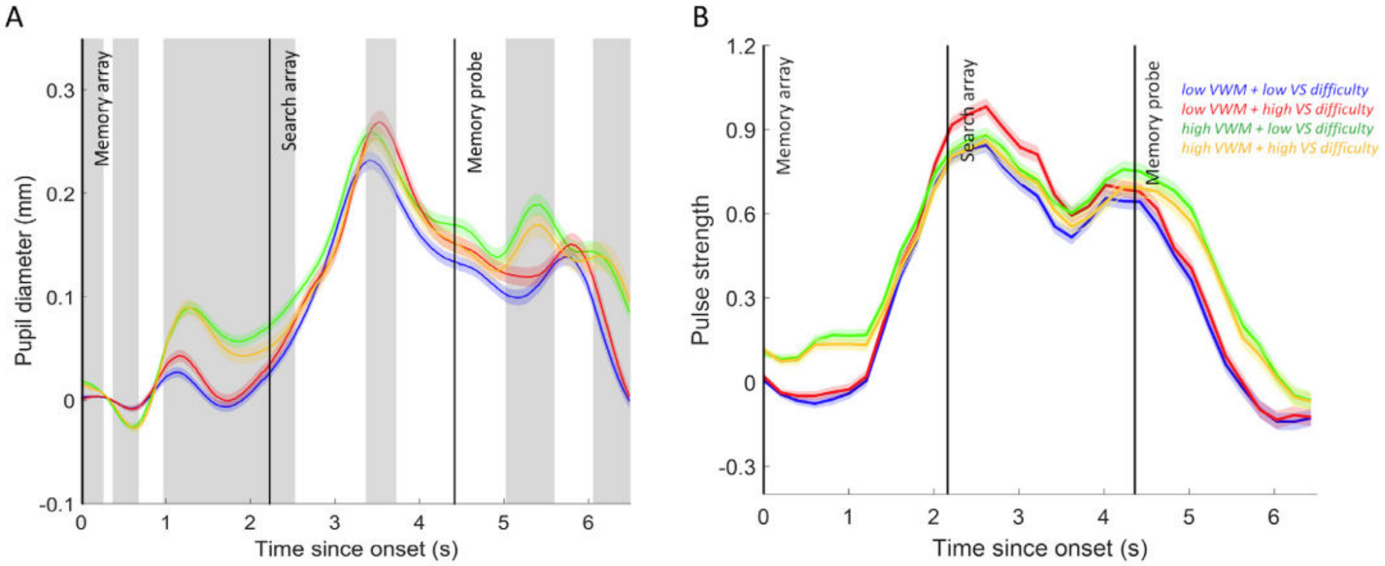


In conclusion, the pupil response in general and its modeling by an online algorithm were validated as useful indicators of Cognitive Load and of search difficulty by several experimental effects of manipulating the corresponding variables as a benchmark. As such, the use of continuous tracking of performance demands by an online algorithm that operates without prior knowledge of task onsets is a promising approach.



Study Cognitive Psychology

In Experiment 1, VS was performed during the retention interval of the VWM task to assess interactive effects between search and memory load on pupil dilation. In Experiment 2, the tasks were performed separately. The results of the stimulus-locked pupil data demonstrated reliable increases in pupil dilation due to high VWM load.



Therefore, in the present study, we validated the continuously operating online algorithm that does not require prior knowledge of the time at which a demanding process begins in two controlled laboratory experiments. We investigated the effects of Visual Search (VS) demands and Visual Working Memory (VSM) load on behavioral performance and pupil responses. In Experiment 1, VS and VWM load manipulations were combined to test for possible interactions, as both types of demands often occur together in real life settings, but the tasks were performed separately in Experiment 2 to isolate specific contributions. VS demand was manipulated by changing target distractor similarity, whereas VWM load was determined by the number of items to be held in memory.

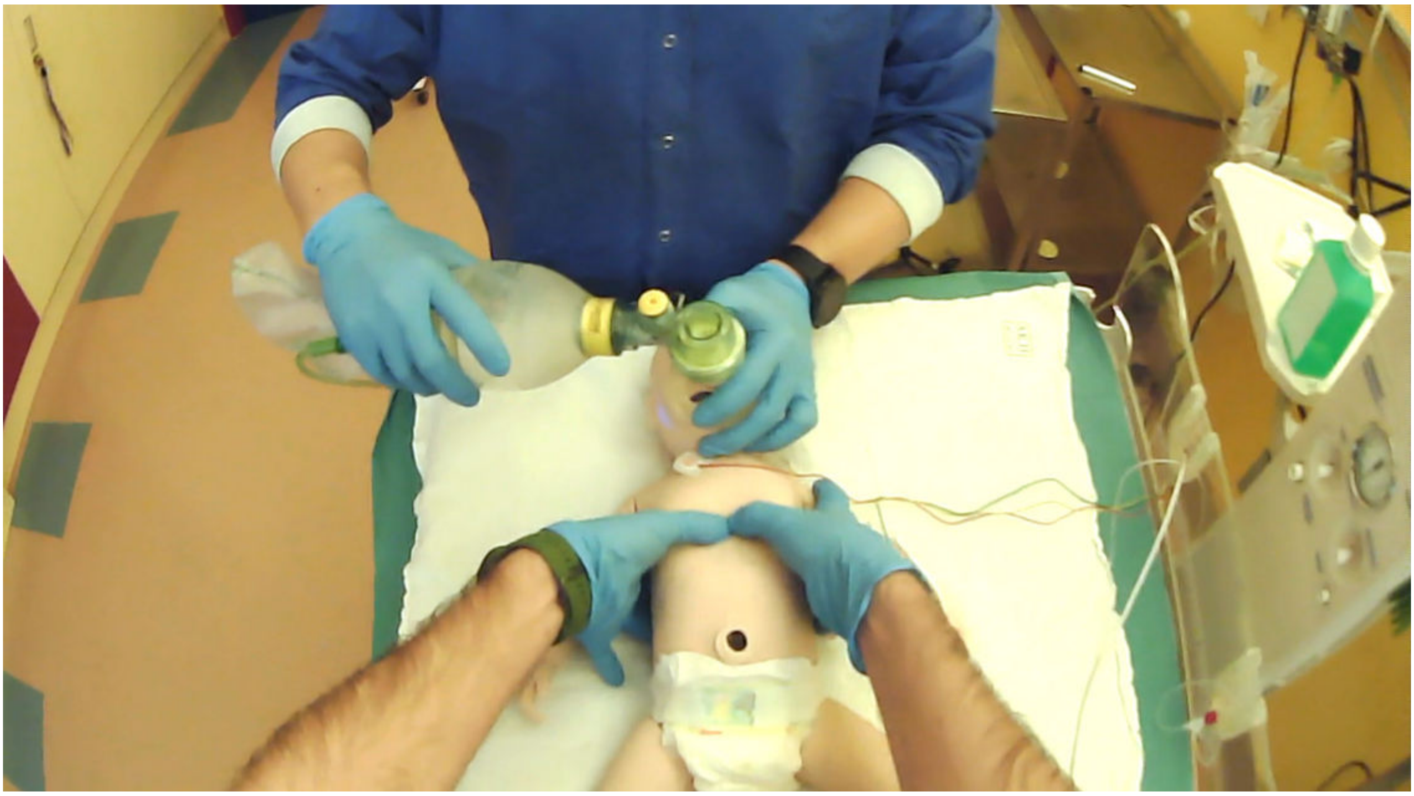
Importantly, online modeling of pupil responses was successful on three points. First, there was good correspondence between the modeled and stimulus locked pupil dilations. Second, stimulus onsets could be approximated from the derived attentional pulses to a reasonable extent. Third, cognitive demands could be classified above chance level from the modeled pupil traces in both tasks. In conclusion, the pupil response in general and its modeling by an online algorithm were validated as useful indicators of Cognitive Load and of search difficulty by several experimental effects of manipulating the corresponding variables as a benchmark. As such, the use of continuous tracking of performance demands by an online algorithm that operates without prior knowledge of task onsets is a promising approach.

Validation & Applications

Human error is among the major causes of medical-related accidents. In Europe, medical errors account for more than 750,000 adverse events a year, with 95,000 being a lethal outcome, making it the third leading cause of death. In this context, together with the MedUni Vienna, we investigated the influence of cognitive, affective and biometric (e.g., stress)-related factors, especially Cognitive Load on the behavior, decision-making and acting of pediatric medical emergency staff (PMEs) under stress and in high-risk operational situations.

In this context, the Cognitive Load assessments

- increase training quality (adaption to individual requirements)
- increase in training efficiency (reduction of costs, reduction of time spent in life drills while increasing the individual training payoff)
- save lives and minimize medical errors due to lack of appropriate training



In the experiments, we introduced stress events into the medical procedures to evaluate how good the trainees react to additional stressors in already stressful situations. The stress events were: (i) failure of monitor showing vital signs, (ii) distraction by ringing telephone and (iii) disturbance by the worried mother of the child.

Training Medical Experts

Real-word Experiments

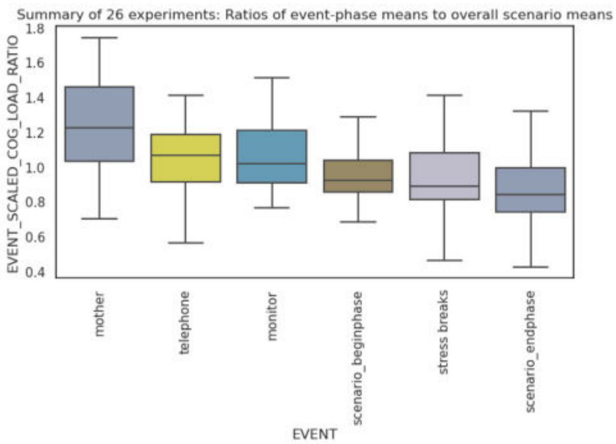
In the course of the real-world experiments we used wearable eye trackers (Pupil Labs Core) for the evaluation of Cognitive Load levels from pupil dilation.

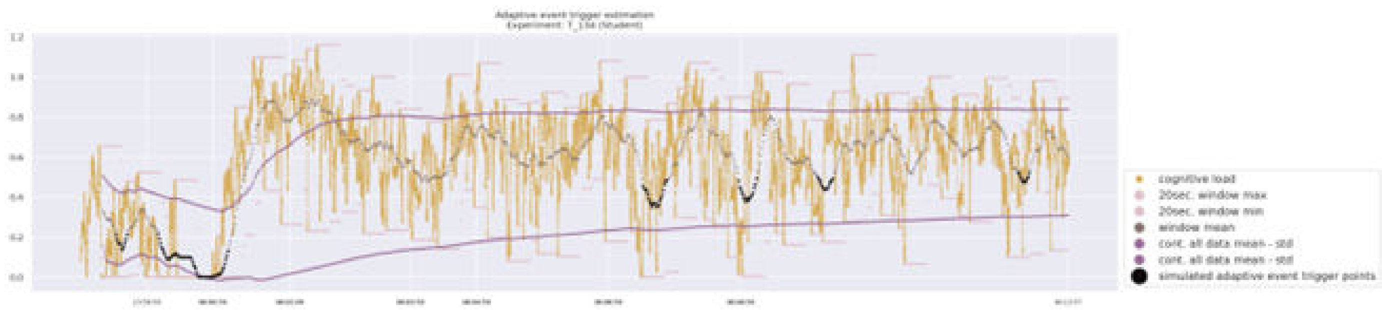
The aggregated event phase mean ratios for all selected experiments show the overall high effect on Cognitive Load during the event "mother" in the scenario, with a significantly higher mean-ratio than all other event phases.

For the two other stress events "telephone" and "monitor" we can also show a statistically significant difference to the other phases. The p value obtained from ANOVA analysis ($p = 3{,}21*10^{-9}$) is significant ($p < 0.05$), and therefore, we conclude that there are significant differences among the ratios of the Cognitive Load between all event phases.

Adaptive Training

Over the course of the project we were able to use the Cognitive Load levels as trigger to create dynamic trainings which can be adapted in real-time. This approach allows for a subjective but comparative evaluation of Cognitive Load which in theory signifies a state of under-challenge. Whenever this lower threshold is breached, a stress event is triggered, subsequently raising CL again to keep students challenged for optimal learning.



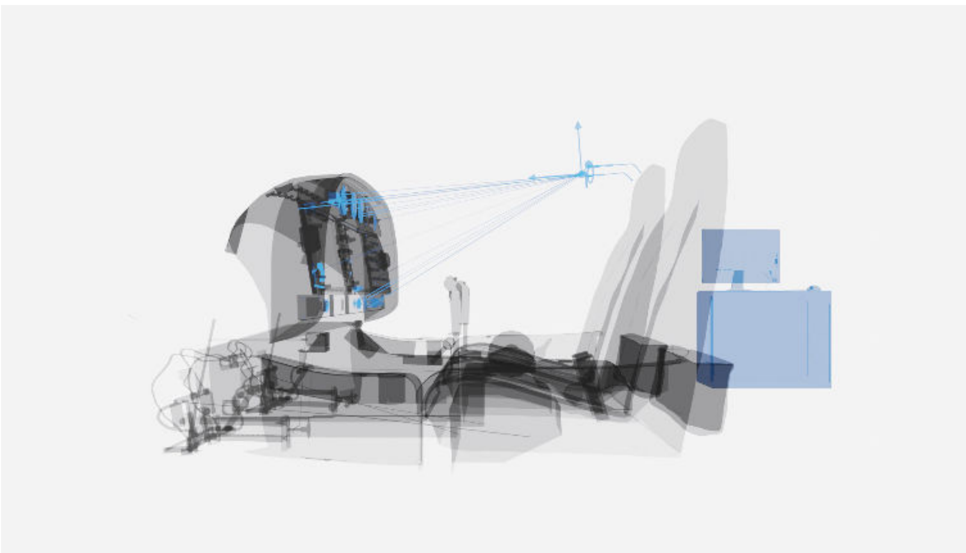


Visualization of individual experiment of phase 2: If the Cognitive Load levels fall below a certain threshold, they trigger an event to adapt the training to increase stress or complexity. The trigger estimations are computed with the proposed method with a 30 second window. Phases of lower Cognitive Load (with respect to the overall distribution) are plotted as black dots. These are phases when a stress event could be triggered.

Validation & Applications

Modeling Cognitive Load and Perception in Pilot Training

In a collaboration with Lufthansa Aviation Training Zürich, we have developed a pilot training assistance system, which allows the live monitoring of trainee's visual attention, interaction and associated Cognitive Load levels. This information is provided live and during run-time to the supervisor for individualization and optimization of the training and is recorded to support subsequent de-briefing activities.



Associating Visual Attention and Cognition

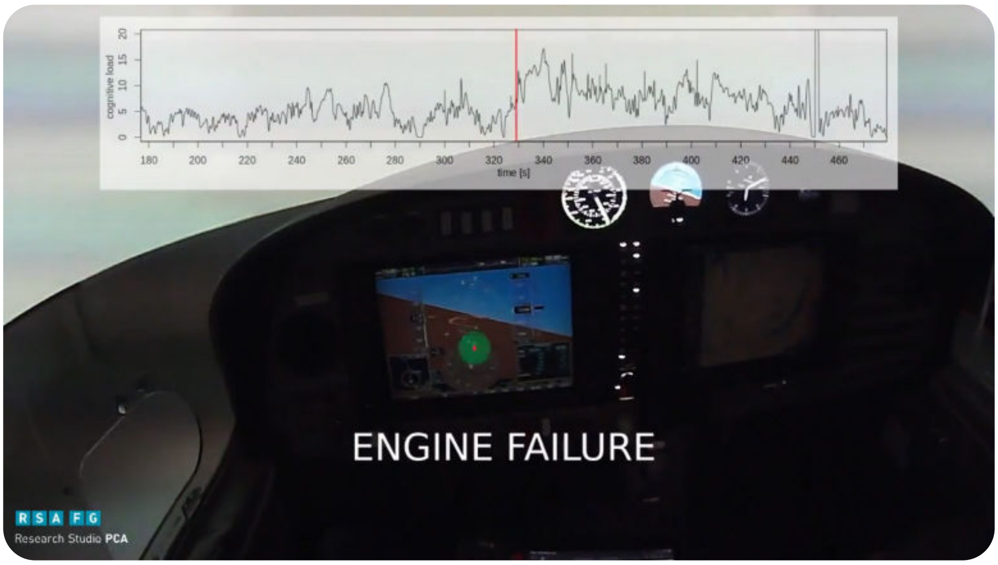
In this project, we realized the combination of accurate 3D gaze tracking and analysis of associated Cognitive Load levels to enable the analysis of efficiency and effectiveness of information intake, interaction with instruments in the cockpit, as well as workload management and resilience in task performance.

Aviation & Pilot Training

Competency-based Training & Assessment

Aviation is among the first industries to move towards Competency-based Training, replacing traditional measures of experience (hours on a job) with objective measurements of observed performance (Evidence-based Training), thus improving objectivity and introducing data-driven individualization and hence optimization of training content, schedules and equipment usage. This shift towards training underlying problem-solving competencies is expected to improve training and education quality (hence safety), while optimizing training resource usage (saving costs).

The developed solution towards Cognitive Load analysis in pilot training provides the optimal, scalable tool for data-driven evaluation of pilot trainees, that (i) allows the detailed analysis of individual strengths and shortcomings, (ii) provides objective, high quality, and live data to supervisors to evaluate their students, (iii) provides fundamental materials for sustainable learning in debriefing



Example of Cognitive Load levels of professional pilot on a DA42 flight simulator. Simulating an engine failure, the machine is tilting to one side, requiring the pilot to take corrective actions. This results in a massive increase in Cognitive Load which slowly decays over the next minutes.

Lufthansa
Aviation Training
Train smart. Fly safe.

Validation & Applications

Mountainbiking

Together with the Austrian National Team in Mountainbiking, we have used mobile eye trackers and our Cognitive Load analysis to model the processing of visual information of professional riders, modeling gaze behavior and its correlation to expertise and performace, decision-making and associated Cognitive Load levels.

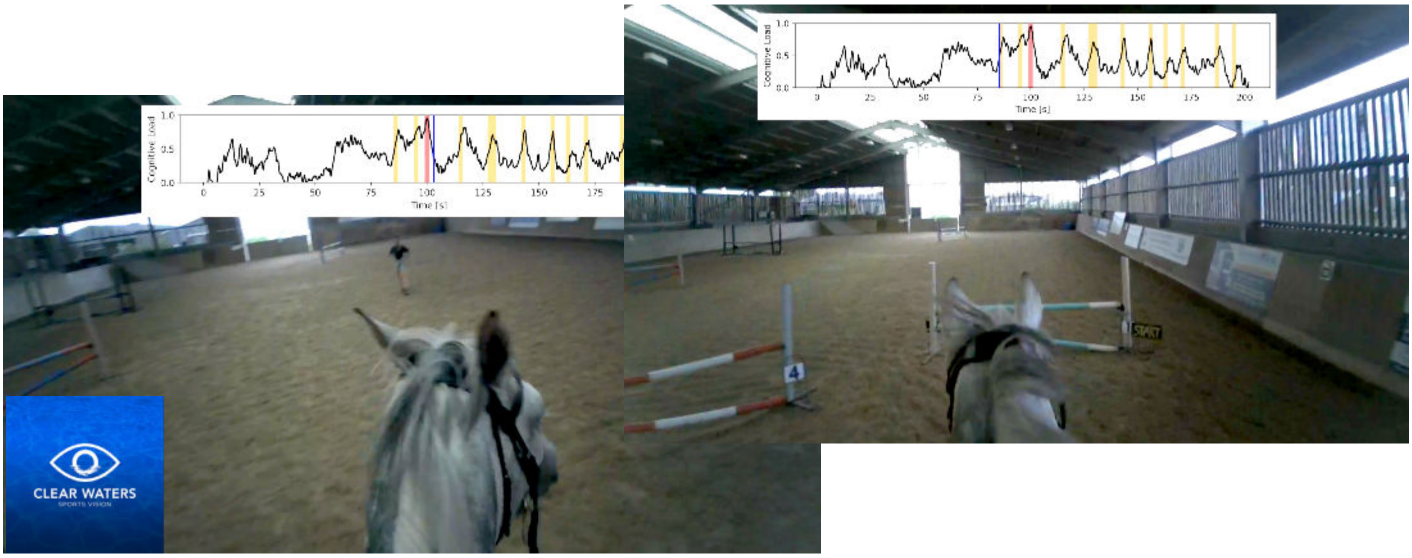
Cognitive Load in Ice Hockey

In our collaboration with Lee Waters, SOMAREALITY is applying the Cognitive Load analytics in professional ice hockey, analyzing the cognitive processes and cognitive load to identify potentials for optimization of communication as well as overall performance.

Professional Sports

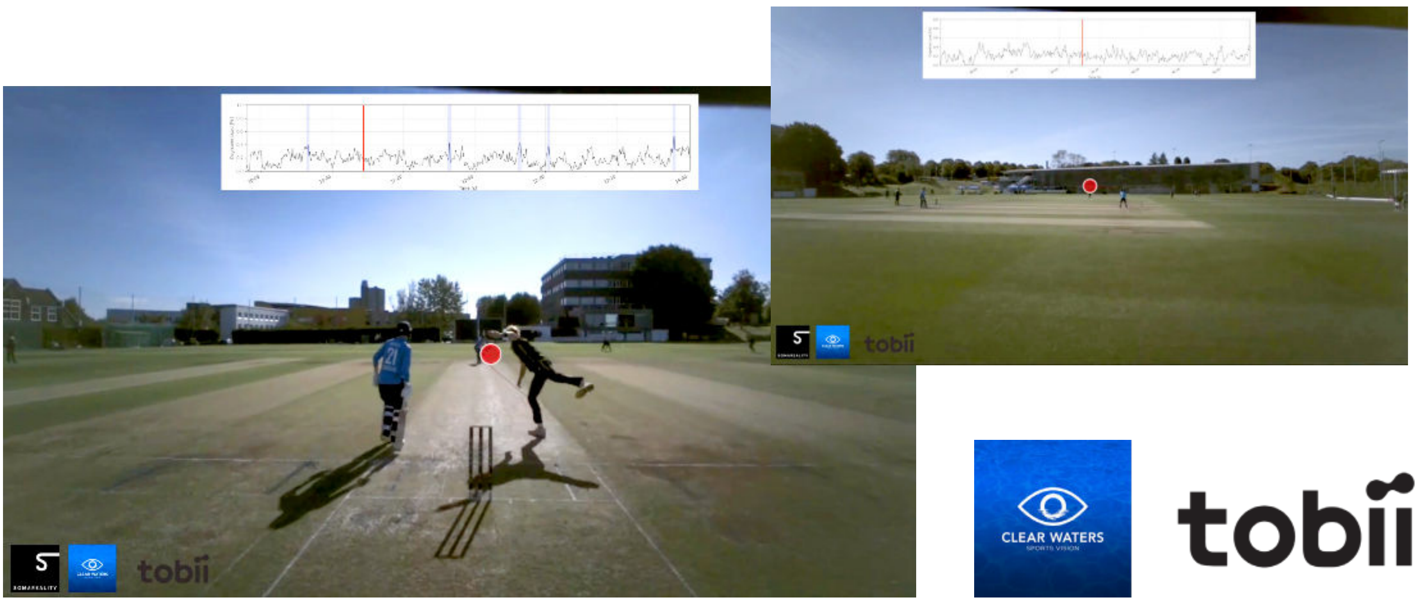
Cognitive Load in Show Jumping

In show jumping, our Cognitive Load analytics are being successfully used to monitor mental workload in jumping training. In this context, being too cognitively overloaded negatively affects learning, memory, performing skills, gaze behaviour, and decision making. Measuring both gaze behaviour and Cognitive Load will prove a vitally important tool for consistent and effective training and development.



Cognitive Load in Cricket

Using Cognitive Load in cricket provides a unique and powerful perspective to influence the understanding, training and reflective practice of officials. In collaboration with Lee Waters and Clear Waters Sports Vision Research, we apply our Cognitive Load analytics in professional cricket to you optimize referee performance and training.

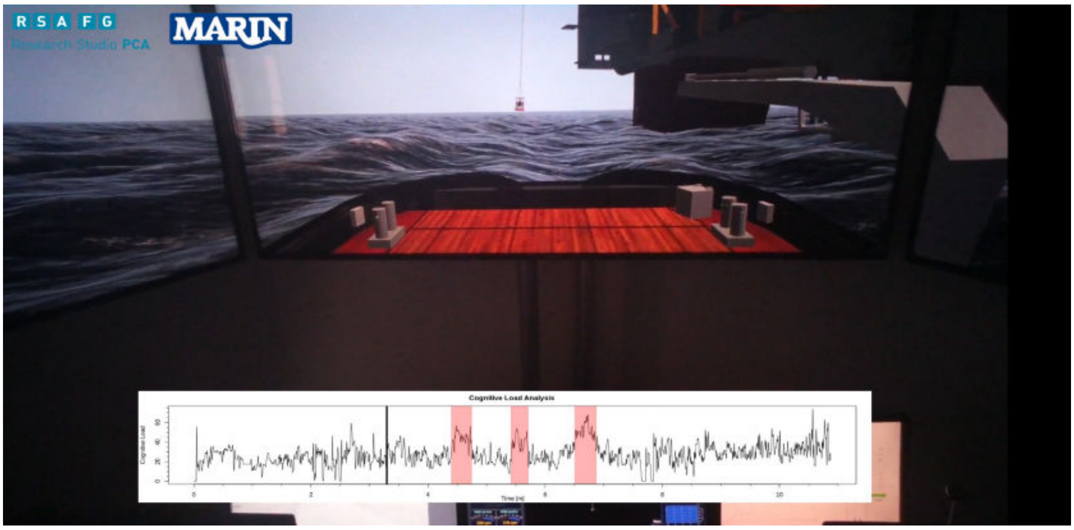


Validation & Applications

Ship Simulation Training

Cognitive Load analysis enables the individualized analysis of ship captains in advanced, large-scale ship training simulators as by MARIN. In collaboration with Noldus Information Technology, we have conducted studies, demonstrating the real-time functionality of our Cognitive Load Analysis for live monitoring as well as detailed analytics in adjacent debriefing sessions.

Noldus
Information Technology



Real-world Driving and Driver Simulation

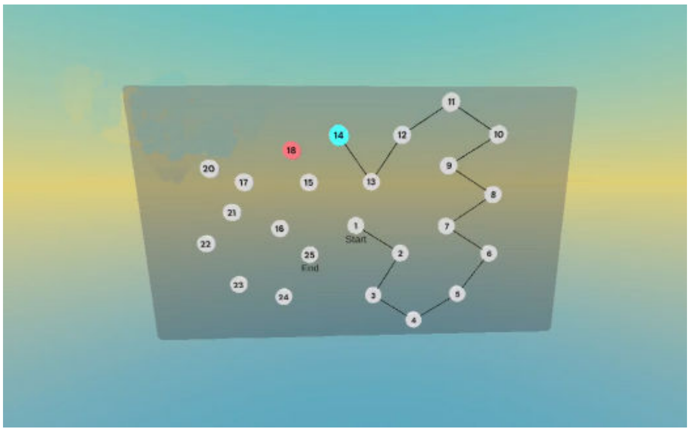
In collaboration with Noldus Information Technology, we have demonstrated and validated the Cognitive Load Analysis in both real and simulated driving applications, employing both wearable and remote Tobii eye trackers.

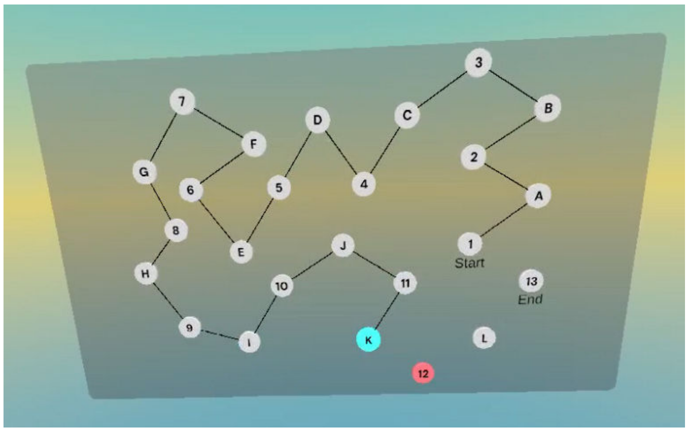
Noldus
Information Technology

Training & Assessment

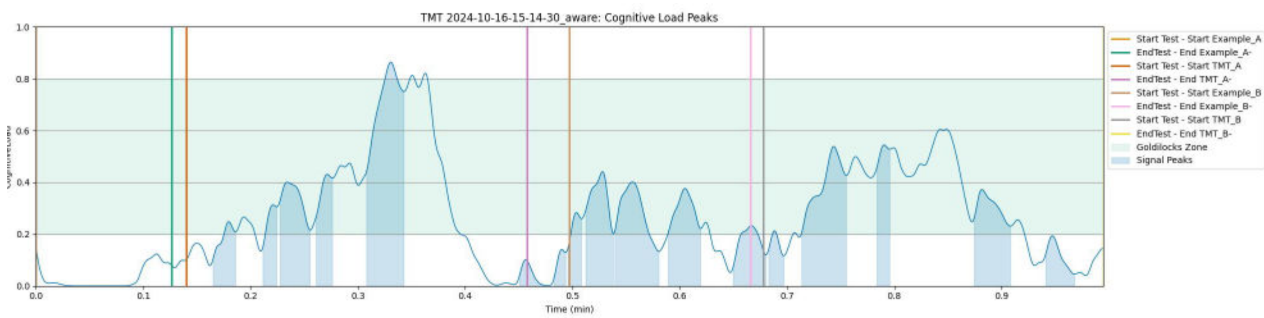
Cognitive Assessments in VR

The Trail Making Test (TMT) is a widely used neuropsychological assessment tool designed to measure various aspects of cognitive flexibility, visual attention, and processing speed. The test typically consists of two parts: TMT Part A, where the participant connects numbered circles in ascending order, and TMT Part B, which requires connecting circles that alternate between numbers and letters. The differences in difficulty between Part A and Part B are used to assess mental flexibility, as switching between numbers and letters demands increased cognitive control. The TMT is commonly used to detect deficits in executive function, often affected by conditions such as brain injuries, dementia, and other cognitive disorders.





SOMAREALITY has implemented the Trail Making Test in Virtual Reality (VR) with embedded eye tracking to provide a dynamic environment that can enrich assessment quality. The VR enables a more detailed analysis of performance, such as the time taken, path deviations, and decision-making patterns. In combination with eye-tracking technology, a VR-based TMT can capture detailed gaze data, including fixation points, saccades, and areas of visual attention. This data reveals additional insights into cognitive strategies and visual processing, such as whether participants are focusing on certain areas, how quickly they shift their gaze, and if they struggle to locate the next target in the sequence. These details are particularly useful for understanding attentional control and visual search behavior, which are harder to capture in the traditional pen-and-paper format.



Furthermore, adding cognitive load analysis to this VR-based setup enhances its diagnostic power. By evaluating cognitive load, clinicians and researchers can better understand the cognitive demands experienced by each participant during different sections of the test. For instance, an increase in cognitive load during Part B relative to Part A would be expected, but unusually high levels might indicate difficulties with task-switching or processing speed deficits.

What you need...

Eye Tracker

Provides pupil dilation levels in real-time with no restrictions to movement and minimal intrusiveness.

AR/VR Headsets with integrated Eye Tracking

Wearable Eye Tracker

Remote Eye Tracker

Requiremen
Eye Tracke

open access to relevant data streams

- pupil dilation
- pupil dilation confidence
- world camera image (or screen image capture)

Soma Aware S

Free Hardware Choice

Compatibility with most available Eye Trackers

Brightness Compensation

From the lab into real-world applications via compensation of environmental brightness

Real-time Insights

Obtaining expressive, continuous Cognitive Load measures in real-time

Soma Aware SDK for Data Processing & Analytics

Enables the analysis of raw eye tracking data and provides insights on Cognitive Load levels in real-time and via extensive offline reports

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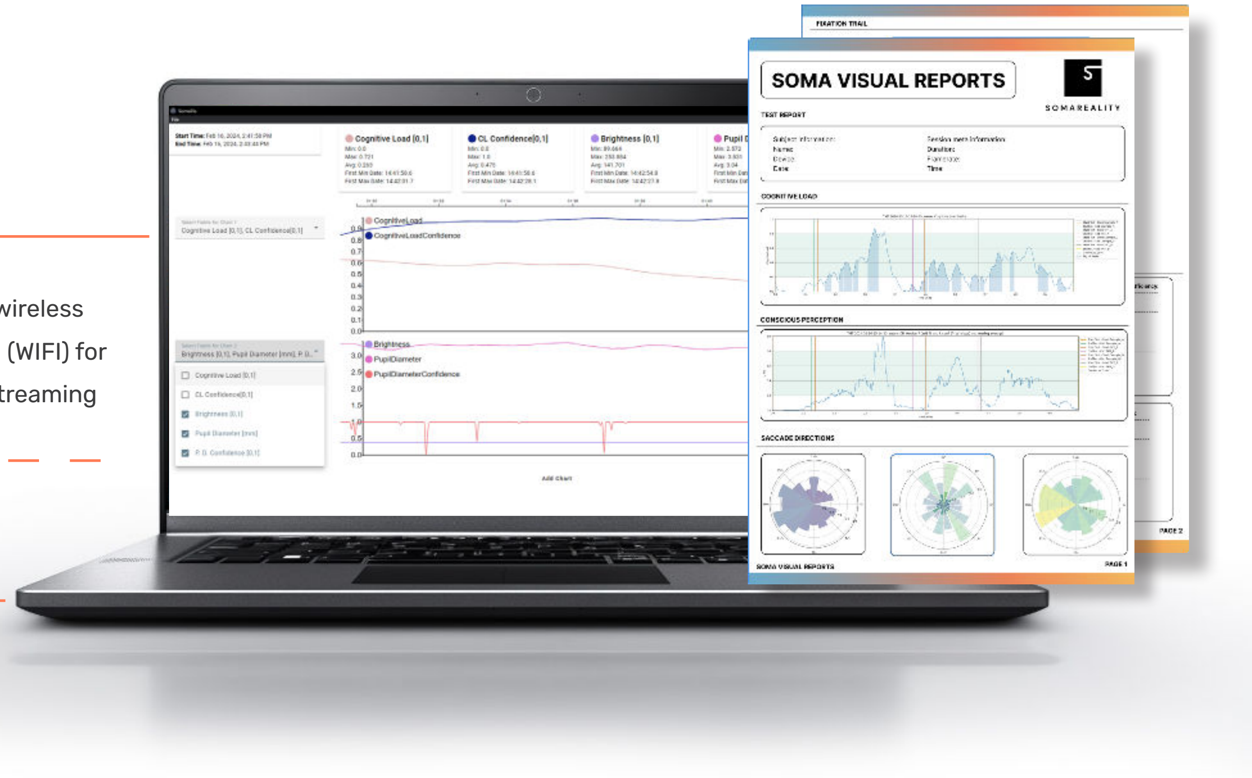
er and API

Wired or wireless connection (WIFI) for live data streaming



DK provides

In-Task Analytics

Integration in processing and analytics processes

Green Field Capability

Complete freedom of motion for your Cognitive Load Studies

Contextualization

Combination with further SOMA biomarkers (Visual Attention, Perception, Consciousness)

Team

At SOMAREALITY, we believe in a world where everyone can unlock their full cognitive potential. Therefore, we develop scientifically validated digital biomarkers to enable technologies in industry, health care, society and beyond.

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