



Age-Dependent Changes in Pupillometric Indicators of Cognitive Load During Hands-Off L2 Driving

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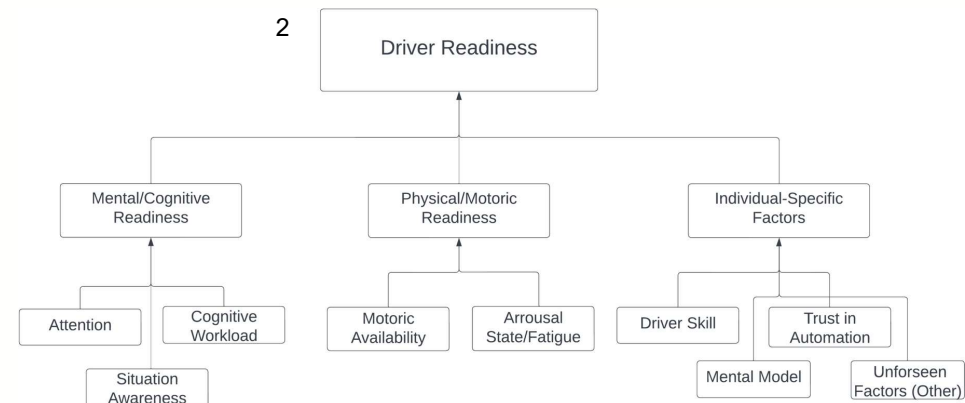
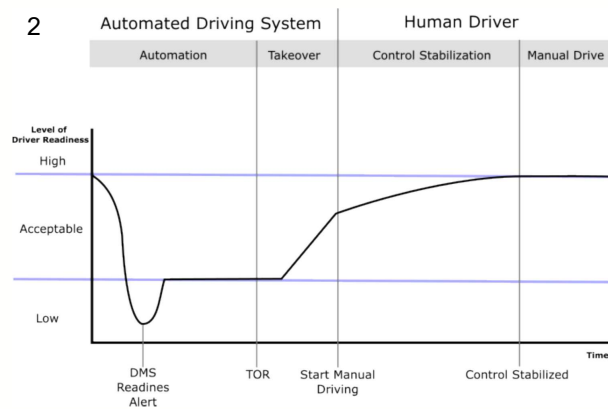
⁴ Seeing Machines, Canberra, Australia

Driver Readiness



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- Driver Readiness (DR) is defined as the probability of a successful transition of control¹.
- There have been many attempts to standardise DR².
- DR remains an amalgamation of varying constructs.



¹ International Organization for Standardization. (2025). *Road vehicles—Driver readiness and intervention management—Part 1: Partial automation (Level 2) (ISO/TS 5283-1:2025)*. <https://www.iso.org/standard/85035.html>

² Gonçalves, R. C., Goodridge, C. M., Kuo, J., Lenné, M. G., & Merat, N. (2024). Using driver monitoring to estimate readiness in automation: a conceptual model based on simulator experimental data. *Cognition, Technology & Work*, 26(4), 569-584.

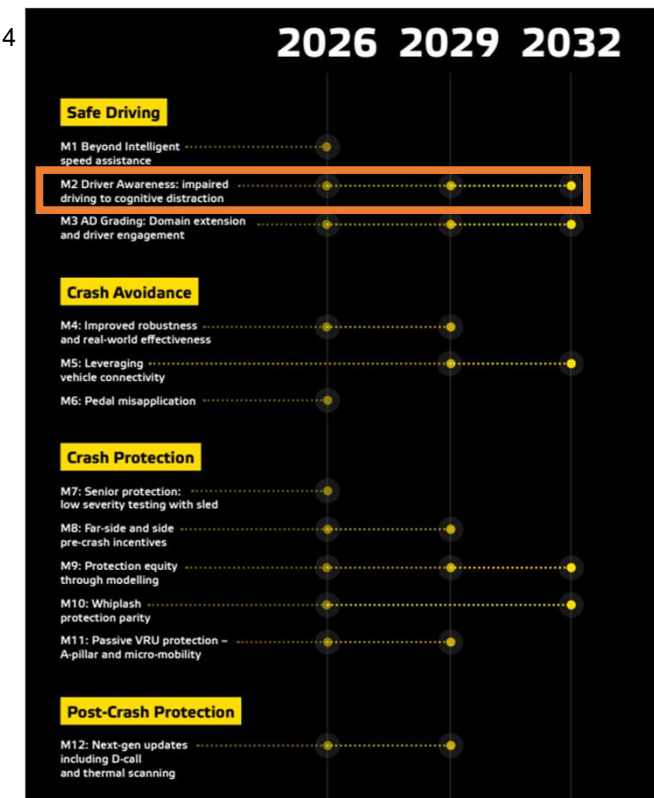
DMS and cognitive readiness



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- Driver Monitoring Systems (DMS) comprise of in-vehicle sensors and cameras that establish whether a driver is “ready”.
- DMS are increasingly expected in new vehicles^{1,2}.
- Identifying cognitive load and/or distraction is a big challenge for DMS.
- **Cognitive load** refers to the amount of information processing resources required for completing a task³.
- **Cognitive distraction** refers to diverting attention away from the driving task³.

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¹ Euro NCAP. (2023). *Assessment Protocol – Safety Assist, Safe Driving: Implementation 2023. Version 10.3*.

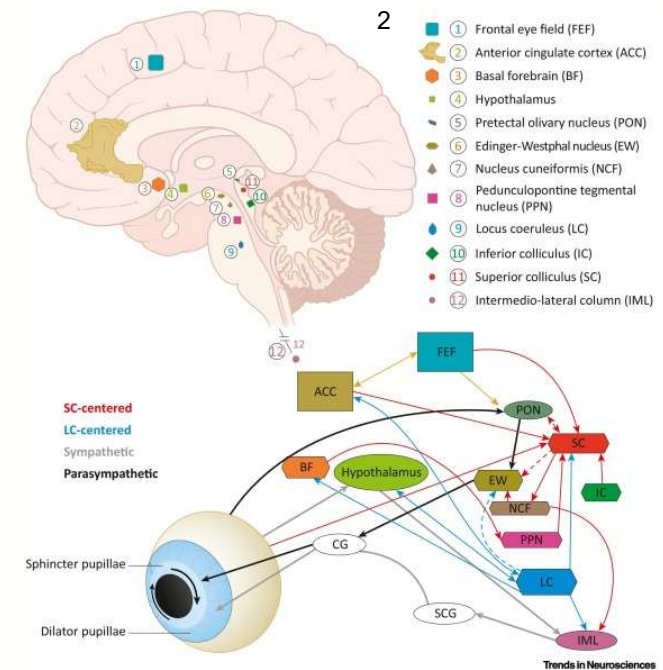
² European Commission. (2022). *Road safety thematic report – Driver distraction*. European Road Safety Observatory. Brussels, European Commission, Directorate General for Transport.

³ Engström, J., Markkula, G., Victor, T., & Merat, N. (2017). Effects of cognitive load on driving performance: The cognitive control hypothesis. *Human factors*, 59(5), 734-764.

⁴ Euro NCAP. (2022). *Euro NCAP Vision 2030: A safer future for mobility*. https://cdn.euroncap.com/cars/assets/euro_ncap_roadmap_vision_2030_3830ee68ad.pdf

Neural dynamics and pupillometry

- Pupillometry is the non-invasive measurement of pupil size and reactivity.
- Pupil size offers a peripheral method for estimating neural activity associated with cognitive effort¹.
- The Locus Coeruleus Norepinephrine (LC-NE) system has been linked to cognitive modulations in pupil size³.



¹ Vilotijević, A., & Mathôt, S. (2024). Functional benefits of cognitively driven pupil-size changes. *Wiley Interdisciplinary Reviews: Cognitive Science*, 15(3), e1672.

² Strauch, C., Wang, C. A., Einhäuser, W., Van der Stigchel, S., & Naber, M. (2022). Pupillometry as an integrated readout of distinct attentional networks. *Trends in Neurosciences*, 45(8), 635-647.

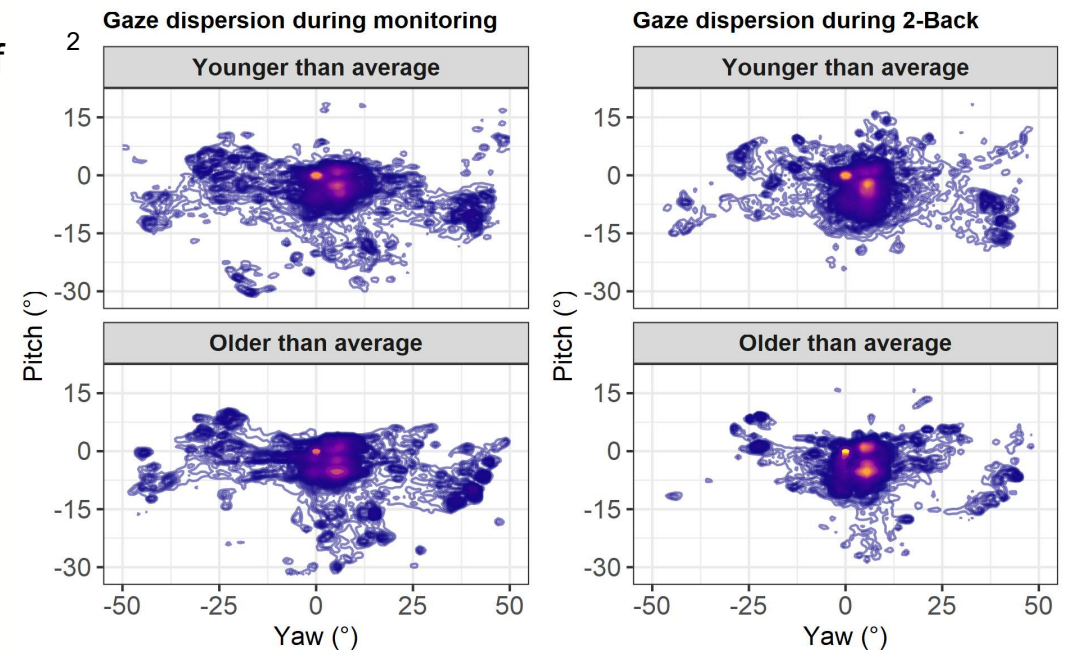
³ Joshi, S., & Gold, J. I. (2020). Pupil size as a window on neural substrates of cognition. *Trends in cognitive sciences*, 24(6), 466-480.

Demographic factors are important for predicting driver state



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- Driver age has been a consistently important feature when modelling the takeover performance of drivers¹.
- Indicators of cognitive load (e.g., gaze entropy) have been found to differ dependent on driver age².
- Age-related impairments in the LC-NE system are linked with natural cognitive decline³.
- Research question: is pupil size also prone to age-dependent changes?



¹ Qin, H., Gonçalves, R., Goodridge, C. M., & Merat, N. Eye-Tracking Indices of Cognitive Load Predict Reaction Time to Urban Traffic Hazards: Machine Learning Classification and Regression Across Manual and Level 2 Assisted Driving. *Available at SSRN 7240439*.

² Goodridge, C. M., Gonçalves, R. C., Arabian, A., Horrobin, A., Solernou, A., Lee, Y. T., ... & Merat, N. (2024). Gaze entropy metrics for mental workload estimation are heterogenous during hands-off level 2 automation. *Accident Analysis & Prevention*, 202, 107560.

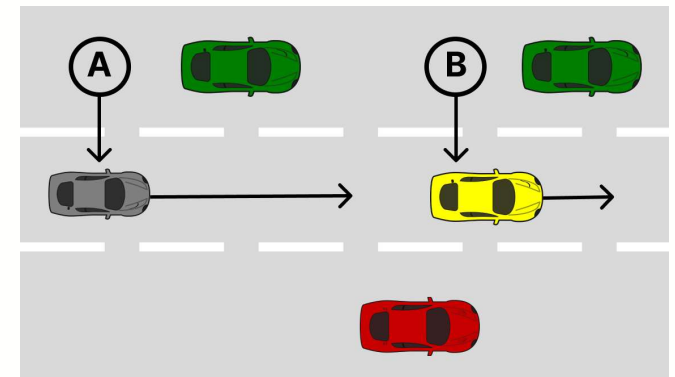
³ Kremen, W. S., Panizzon, M. S., Elman, J. A., Granholm, E. L., Andreassen, O. A., Dale, A. M., ... & Franz, C. E. (2019). Pupillary dilation responses as a midlife indicator of risk for Alzheimer's disease: association with Alzheimer's disease polygenic risk. *Neurobiology of aging*, 83, 114-121.

Method



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- Driving simulator experiment¹ comprised of two experimental blocks:
 - One with auditory N-back (2-back) during hands-off L2 driving;
 - Another just monitoring during hands-off L2 driving.
- Each block consisted of 10 discrete trials: 30 s of manual driving, ~2 minutes of hands-off L2 driving.
 - **4/10** trials were critical (**2** with a TTC of 3 s, **2** with a TTC of 5 s).
 - **6/10** were non-critical trials (**2** involving no lead vehicle, **4** involving a lead vehicle that did not decelerate).
- **38** participants, average age = **38.81** years, age range = **22-65** years, SD = **12.50** years.
- Analysis focused on mean and standard deviation (SD) of pupil diameter.



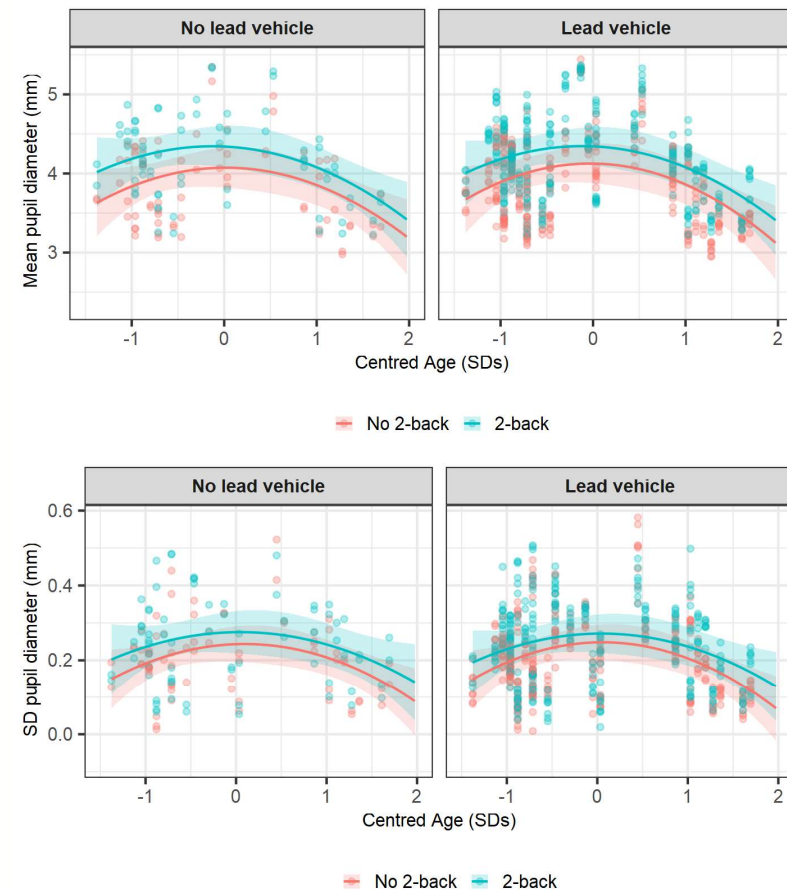
¹ Goodridge, C. M., Gonçalves, R. C., Arabian, A., Horrobin, A., Solemou, A., Lee, Y. T., ... & Merat, N. (2026). Pupillary dynamics during hands-off L2 driving and transitions of control under high cognitive load. *PLoS One*, 21(8), e0355165.

Results: pupil diameter during hands-off L2 driving



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- Drivers' pupils were larger during 2-back (**4.345 mm**) relative to no 2-back trials (**4.080 mm**) ($\beta = 0.284$, [0.201, 0.368]).
- Drivers' pupils were more variable during 2-back (**0.277 mm**) relative to no 2-back trials (**0.242 mm**) ($\beta = 0.041$, [0.022, 0.061]).
- Age demonstrated a negative quadratic relationship with mean ($\beta = -5.008$, [-9.182, -0.833]) and SD of pupil diameter ($\beta = -0.959$, [-1.756, -0.163]).
- Pupil reactivity decreases significantly from 38.53 years of age.

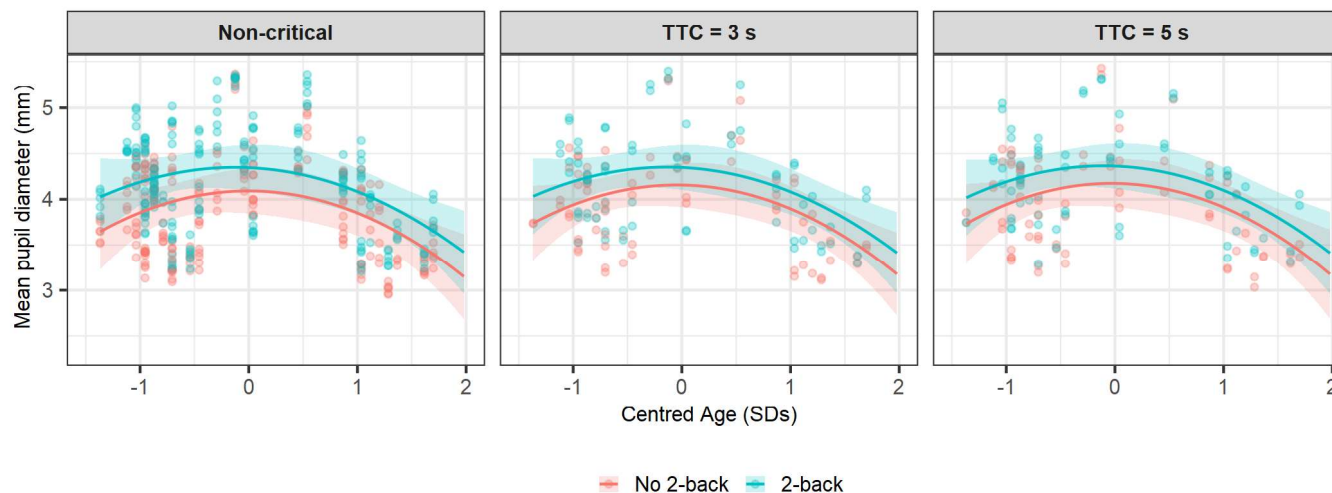


Results: pupil diameter during transitions of control



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- Drivers' pupils were larger during critical transitions relative to non-critical transitions.
- This effect was more pronounced following no 2-back trials (**non-critical = 4.091 mm; TTC 3 s = 4.155 mm; TTC 5 s = 4.173 mm**) relative to 2-back trials (**non-critical = 4.345 mm; TTC 3 s = 4.348 mm; TTC 5 s = 4.363 mm**) ($\beta = 0.063$, [0.024, 0.105]).
- Age demonstrated a negative quadratic relationship with mean pupil diameter ($\beta = -5.269$, [-9.416, -1.123]).



Conclusions



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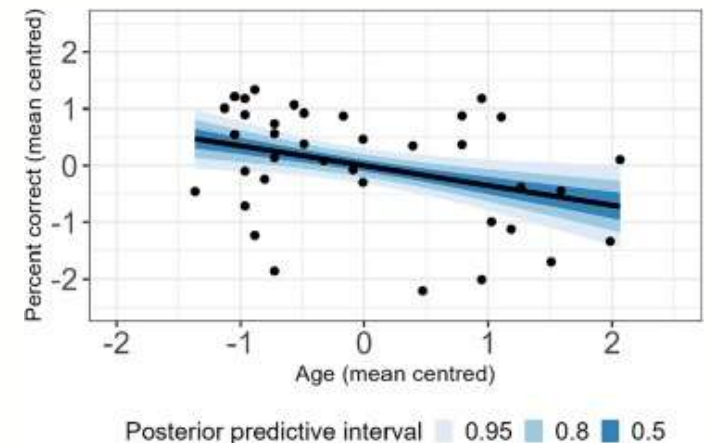
- Evidence that the reactivity of the pupil declines with age.
- Middle aged drivers (38.53 years of age) showed the highest pupillary activity, indicating stronger cognitive resource mobilisation.
- Older-than-average drivers demonstrated diminished pupillary reactivity during the 2-back task and transitions of control.

Why do older drivers have less reactive pupils?



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- Physiological? Age-related changes in pupillary muscles and LC-noradrenergic neurons¹.
- Cognitive? The Inhibitory Deficit Hypothesis² proposes that people exhibit reduced ability to suppress irrelevant information as they age.
- Reduced inhibitory control compromises mobilisation of cognitive resources.
- Older drivers perform worse on the 2-back task in driving studies³.



¹ Granholm, E., Morris, S., Asarnow, R. F., Chock, D., & Jeste, D. V. (2000). Accelerated age-related decline in processing resources in schizophrenia: evidence from pupillary responses recorded during the span of apprehension task. *Journal of the International Neuropsychological Society*, 6(1), 30-43.

² Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *Psychology of learning and motivation*, 22, 193-225.

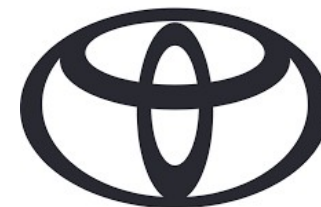
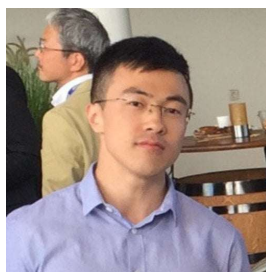
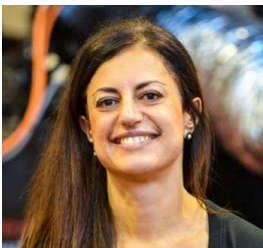
³ Goodridge, C. M., Goncalves, R. C., Arabian, A., Horrobin, A., Solemnou, A., Lee, Y. T., ... & Merat, N. (2024). Gaze entropy metrics for mental workload estimation are heterogeneous during hands-off level 2 automation. *Accident Analysis & Prevention*, 202, 107560.

Take home messages



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- A one size fits all approach to DMS is unlikely to provide valid and reliable results.
- Demographic information that is simple to collect can improve model performance.
- The requirement for providing additional information to improve DMS should be framed as a positive.



Thank you!

