The Pupillary Light Reflex as a Biomarker of Cognitive Age and Subjective Time Dilation

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Summary

Analysis of 41,053 pupillary light reflex (PLR) recordings demonstrates that specific pupillary dynamics, particularly maximum and average constriction speeds and maximum and minimum diameters, vary predictably with age. These effects are robust across individuals aged 10–80 years and show high explanatory power ($R^2 \approx 0.80$–0.89) for multiple parameters. We propose that the PLR constitutes a fundamental, involuntary measure of neural processing speed, awareness, and perceptual integration. As such, PLR metrics enable estimation of "cognitive age," a biologically grounded construct distinct from chronological age.

Introduction

The subjective cognitive experience is not constant across the human lifespan. Older adults consistently report that experience of time and information changes with age, a phenomenon documented across cultures and historical periods (Block et al., 1999; Wittmann & Lehnhoff, 2005). Traditional explanations emphasize psychological accounts such as proportional theory, which posits that each successive year represents a smaller fraction of total lived experience (James, 1890). While intuitively appealing, such explanations remain descriptive and lack a direct neurophysiological linkage.

Converging evidence from cognitive neuroscience indicates that aging is accompanied by a generalized slowing of neural processing speed, affecting perception, attention, working memory, and motor responses (Salthouse, 1996, 2010). Processing speed has been proposed as a core limiting factor underlying age-related cognitive decline, rather than deficits within specific cognitive domains (Birren & Fisher, 1995). However, most measures of processing speed rely on voluntary responses and are therefore confounded by motivation, strategy, and task familiarity.

The pupillary light reflex offers a unique solution to this limitation. The PLR is a rapid, involuntary neurophysiological response mediated by a well-characterized subcortical circuit that links retinal phototransduction to midbrain nuclei and autonomic output to the iris musculature (Loewenfeld, 1999). Because the PLR operates outside conscious control, it provides a direct assay of neural transmission speed, synaptic efficiency, and neuromuscular execution. Recent advances in app-based pupillometry allow reasonable resolution of pupil dynamics in a highly deployable form factor, enabling decomposition of the PLR into amplitude, speed, latency, among other parameters. Importantly, pupil dynamics are increasingly recognized as reflecting central nervous system function rather than merely peripheral autonomic tone (Joshi & Gold, 2020). Changes in PLR parameters have been linked to neurodegenerative disease, traumatic brain injury, and altered states of consciousness (Stergiou et al., 2009).

In this work, we analyze a large-scale dataset of 41,053 PLR measurements to test the hypothesis that age-related changes in PLR dynamics reflect fundamental slowing of neural processing. We further propose that these changes can be leveraged to estimate cognitive age as a novel neurophysiological biomarker.

Methods

Population

Data were aggregated and anonymized from 13,762 neurologically diverse individuals aged 10–80 years taken across 361 test administrators. Participants reported no history of neurological disease and were symptom free at the time of testing. The large sample size enabled stable estimation of age-related trajectories across the lifespan.

Apparatus

Pupillary responses were recorded using Reflex, a mobile app produced by Brightlamp Inc. that operates in the visual light spectrum, with a temporal resolution of 30 Hz. Light stimuli were delivered monocularly at approximately 30 lumens (50% device intensity), with a stimulus duration of 5 s in 88% of tests to capture full constriction. The remaining fraction of tests were a combination of other time durations, such as 7 s, but still had the required criteria of the stimulus being on for the duration of the test.

Parameters

Nine PLR parameters were extracted:

- Latency (seconds, s)
- Maximum diameter (millimeters, mm)
- Minimum diameter (millimeters, mm)

- Constriction amplitude (millimeters, mm)
- Maximum constriction speed (millimeters per second, mm/s)
- Average constriction speed (millimeters per second, mm/s)
- Constriction time (seconds, s)
- Average diameter (millimeters, mm)
- Release amplitude (millimeters, mm)

These parameters jointly capture mechanical, temporal, and speed-related aspects of the PLR. Common terminology associated with constriction speeds is to incorrectly label them as directionless velocities. Reflex reports values as speed with no direction.

Analysis

Mean values for each parameter were computed for each year of age from 10 to 80. Model fitting was conducted using least-squares optimization across linear, quadratic, exponential, logarithmic, and power functions. Model selection was based on R^2 values. In instances where models were approaching linearity, a linear model was forced even if it resulted in a slightly lower R^2. Ninety-five percent confidence intervals were calculated using standard errors of the fitted curves, adjusted for distance from the data centroid.

Results

Age-related effects were observed across all PLR parameters, with particularly strong and consistent trends in amplitude, diameters, and constriction speeds.

Latency

Response latency is defined as the time it takes for the pupil to start responding to a stimulus. Latency was shown to not have any significant relationship with age (R^2=0.01) as seen in Figure 1. This has a few possible explanations - one of which is that pupillary response latency does not significantly vary with age. Alternatively, since the measuring device samples at 30 Hz, it is possible that the variation is not reliably measurable at this sample frequency.

Amplitudes

Constriction amplitude is defined as the difference between the initial and minimum diameter. Constriction amplitude demonstrated a strong exponential relationship with age (R^2 = 0.81). As shown in Figure 2, amplitude decreases rapidly during early adulthood and asymptotically stabilizes in later decades.

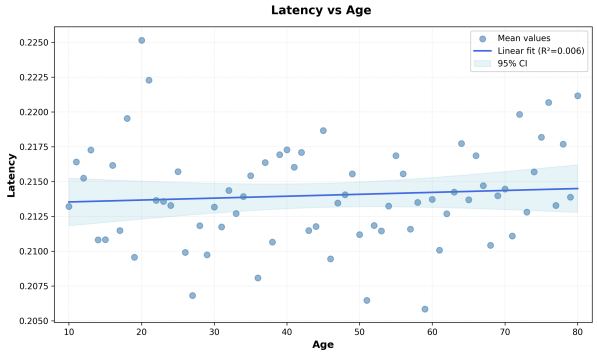

Figure 1: Latency shows no substantial correlation with age.

Release amplitude is defined as the the difference between the final diameter and the minimum diameter. Release amplitude exhibited an exponential relationship with age (R^2 = 0.75) as shown in Figure 3. Release amplitude is typically associated with increased sympathetic activity which is expected to be more prominent at a younger age.

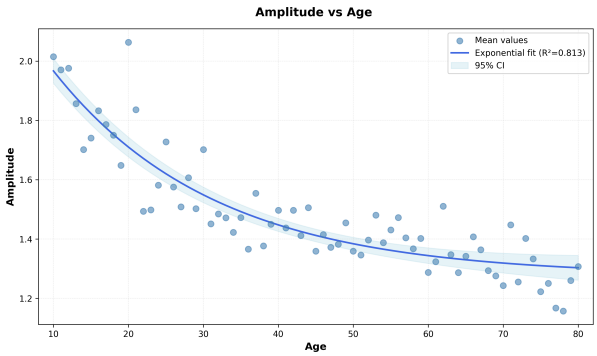

Figure 2: Pupillary constriction amplitude increases exponentially with age (R^2=0.81).

Constriction Time

Constriction time is defined as the elapsed time from the stimulus occurring to the minimum diameter being reached. Time required for complete constriction exhibited a weak quadratic fit (R^2=0.38), showing accelerating prolongation in older decades, shown in Figure 4, after a deceleration that occurred until approximately 50 years of age.

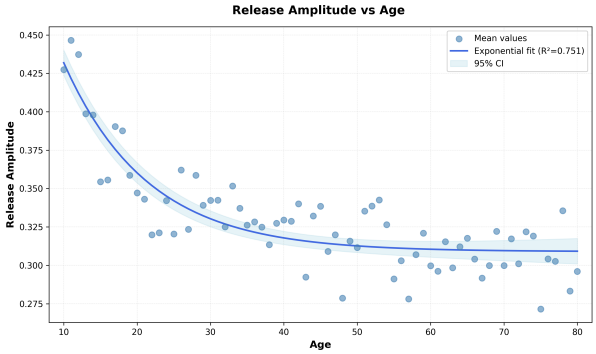

Figure 3: Release amplitude demonstrates similar exponential increase (R^2=0.75).

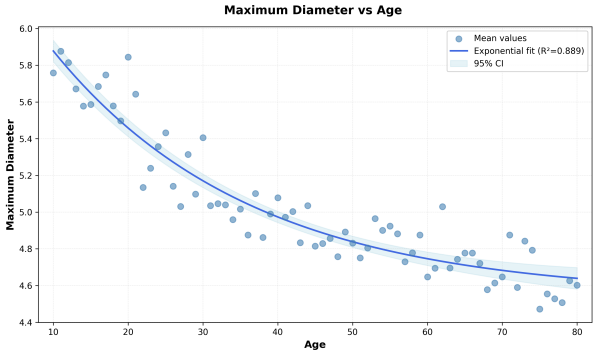

Figure 5: Maximum pupil diameter demonstrates strong exponential fit (R^2=0.89).

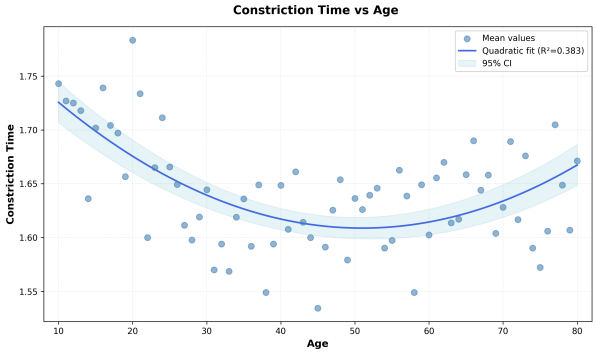

Figure 4: Constriction time increases quadratically, accelerating in later decades (R^2=0.38).

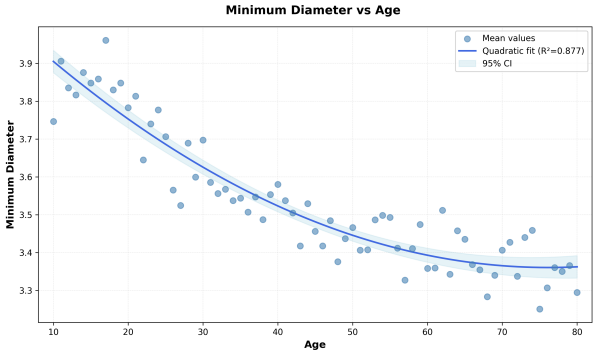

Figure 6: Minimum diameter decreases with a quadratic trajectory (R^2=0.88).

Pupil Diameters

Maximum diameter is defined as the maximum diameter observed during a pupillometry test. In almost all tests the maximum diameter is seen within the first few test frames taken from the sampled video. Minimum diameter is defined as the smallest observed diameter during a pupillometry test. Average diameter is defined as the sum of diameters observed across a pupillogram divided by the total number of sample frames taken. Maximum diameter (R^2=0.89), minimum diameter (R^2=0.88), and average diameter (R^2=0.89) all showed strong decreases with age (Figures 5-7). This reflects well-documented age-related decrease in pupillary size.

Constriction Speeds

The constriction phase of the pupillary light reflex follows a decreasing gradient where the pupillary motion is slowing over time. Average constriction speed is defined as the sum of diameters from the start of pupillary constriction to the minimum diameter divided by the time time it took to achieve complete constriction (Constriction time - Latency). Maximum constriction speed is defined as the maximum observed rate of constriction during the constriction phase - typically occurring at the onset of constriction. Average constriction speed declined linearly with age (R^2 = 0.85), while maximum constriction speed followed an exponential decay (R^2 = 0.80). These speed measures exhibited some of the strongest age associations, along with maximum and minimum diameters, in the dataset.

Discussion

Neural Pathways of the Pupillary Light Reflex

The PLR is mediated by a remarkably compact and evolutionarily conserved circuit. Photoreceptors in the retina transmit signals via intrinsically photosensitive retinal ganglion cells to the pretectal olivary nucleus in the midbrain. From there, bilateral projections reach the Edinger–Westphal nuclei, which send parasympathetic efferents through the oculomotor nerve to the ciliary ganglion and ultimately the sphincter pupillae muscle (Loewenfeld, 1999;

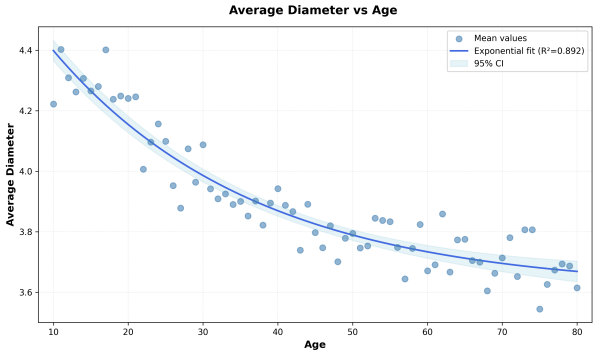

Figure 7: Average diameter demonstrates strong exponential fit (R^2=0.89).

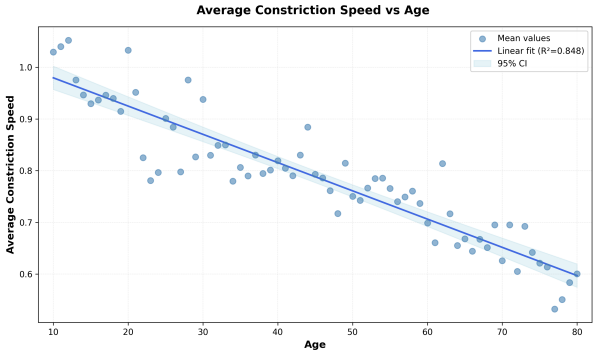

Figure 9: Average constriction speed shows strong linear decline (R^2=0.85).

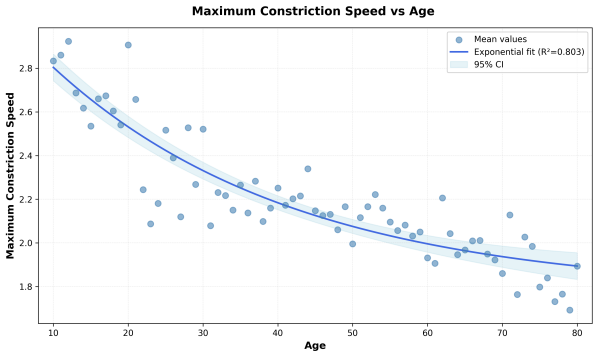

Figure 8: Maximum constriction speed declines exponentially (R^2=0.80).

McDougal & Gamlin, 2015).

Because this pathway involves relatively few synapses and minimal cortical involvement, its temporal properties provide a sensitive index of conduction speed, synaptic efficiency, and neuromuscular transmission. Age-related myelin degradation, synaptic loss, and neurotransmitter changes are therefore expected to manifest clearly in PLR dynamics (Peters, 2002).

PLR as a Measure of Cognitive Processing Speed

Processing speed is widely regarded as a foundational constraint on higher cognition (Salthouse, 1996; Finkel et al., 2009). The strong age-related decline observed in PLR constriction speed suggests that pupillary dynamics capture this constraint at a fundamental physiological level. Unlike reaction-time tasks, PLR measures are involuntary and free from strategic compensation, making them especially well suited for biomarker development.

Temporal Perception and Time Dilation

We speculate that age-related slowing of PLR dynamics reflects a broader slowing of neural "clock speed." If perceptual and cognitive events are sampled more slowly, subjective experience remains internally coherent while objective time advances further between sampled events. This provides a mechanistic account of why time appears to accelerate with age, consistent with neurocomputational models of temporal perception (Wittmann, 2013).

Consider: if a neural event that required 100ms at age 20 requires 150ms at age 70, the subjective experience of that event remains constant while objective time has progressed 50% further. Accumulated across millions of neural events, this produces the sensation that time is "speeding up" when in fact one's internal processing has slowed down. The pupillary system, with its rapid time course and precise measurement, may offer an objective correlate of this subjective phenomenon.

Cognitive Age Estimation

The high R^2 values observed for multiple parameters (particularly diameter and speed measures, $R^2 > 0.80$) suggest that PLR metrics could serve as biomarkers for "cognitive age." Unlike chronological age, cognitive age reflects actual neurophysiological function and may better predict cognitive performance, disease risk, and functional capacity.

We envision a composite PLR-derived metric combining speed, diameter, and temporal parameters to estimate cognitive age. Individuals whose PLR profile resembles younger cohorts may possess "younger" neural function regardless of birth date. Conversely, accelerated PLR aging could identify individuals at risk for cognitive decline before clinical symptoms emerge.

Cognitive Age as a Biomarker

The high explanatory power of PLR parameters supports their use as biomarkers for cognitive age. A composite index incorporating constriction speed, temporal duration, and diameter measures could estimate an individual's neurophysiological age independently of chronological age. Such a metric has potential applications in early detection of cognitive decline, longitudinal monitoring, and evaluation of interventions aimed at preserving neural processing speed.

Mechanistic Considerations

The observed changes likely reflect multiple mechanisms: (1) reduced myelination and axonal conduction velocity, (2) synaptic loss and reduced neurotransmitter function, (3) structural iris changes affecting mechanical properties, and (4) autonomic system dysfunction. The fact that amplitude, pupil diameters, and speeds decrease suggests a universal process of age related PLR throttling.

Clinical and Translational Implications

Because pupillometry is non-invasive, rapid, and inexpensive, PLR-based cognitive age estimation is well suited for large-scale screening and clinical deployment. Importantly, deviations between chronological and cognitive age may identify individuals at elevated risk for neurodegenerative and other neurological diseases before overt symptoms emerge.

Limitations.

This study is cross-sectional, and longitudinal validation is an area of exploration worth pursuing. While PLR dynamics reflect fundamental neural properties, their relationship to specific cognitive domains warrants further investigation.

Conclusion

Age-related changes in pupillary light reflex demonstrate measurable neurophysiological slowing that parallels cognitive decline across the lifespan. Furthermore, we speculate that highly correlated decreases in pupillary parameters provides an explanation for the neural basis of altered time perception in aging. We propose that PLR-derived metrics can estimate "cognitive age," potentially distinguishing chronological age from neurophysiological function. This approach offers a rapid, non-invasive biomarker for cognitive aging that may enable early detection of decline and monitoring of interventions aimed at preserving cognitive function. Future research should examine the relationship between PLR parameters and subjective experience as a means of quantifying subjective time distortion. Environmental, genetic, and circadian influences on PLR aging should also be examined.

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