Advanced Review

Pupillometry

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Pupillometry is the study of changes in the diameter of the pupil as a function of cognitive processing. This review paper provides a brief historical overview of the study of pupillometry in cognitive science. The physiology of pupillary responses is introduced, leading to an outline of early pupillometry work, which began with the seminal work of Hess and Polt in the 1960s. The paper then presents a broad review of contemporary research in cognitive sciences that relies on pupillometry. This review is organized around five general domains, namely perception, language processing, memory and decision making, emotion and cognition, and cognitive development. In order to illustrate the nature of the method, and the challenges of analysis, the next section of the review details the process of compiling, processing, and analyzing data from a simple, typical pupillometry study.

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INTRODUCTION

The pupil is the opening of the iris that permits light to enter the eye and reach the retina, thus allowing vision. In humans and many animals (but not all, e.g., domestic cats), the pupil is circular in shape. The diameter of the pupil is controlled by two sets of smooth muscles in the iris. Sphincter or constrictor muscles decrease its diameter, while dilator muscles increase it. The function of such changes in diameter is to modulate the amount of light that reaches the retina, thus optimizing vision. In relatively darker conditions, the pupil dilates, whereas it constricts in relatively brighter conditions. This is known as the pupillary light reflex, and has clinical use as alterations in pupil function can indicate neurological or drug intoxication problems. The use of a penlight by medical staff assessing a patient reflects such clinical utility.

For over 50 years now, researchers have been interested in the fact that changes in pupil diameter can index cognitive functioning.[1] Coarsely put, the pupil dilates when participants are in conditions of increased attention or cognitive load, or of emotional or cognitive arousal. Pupillometry is the study of such changes in pupil diameter as a function of cognitive activity. In this paper, we provide a brief historical background to the rationale behind pupillometry. We then discuss the physiology and psychology of task-evoked changes in pupil diameter. A review of recent work using pupillometry, across a range of domains within the cognitive sciences, highlights the scope and utility of the method. Finally, we discuss methods of data collection and analysis involved in pupillometry. Sample data are used to highlight different approaches to analysis.

A BRIEF HISTORY BEFORE PSYCHOLOGY

Interest in the eye and the pupil goes back to antiquity. Eyes have been described as the 'window to the soul'; this citation is frequently attributed to Cicero (106–47 BCE), a roman politician. The word pupil comes from the Latin 'pupilla', which means 'little doll' because of the small reflected images one can see when looking in the eyes of another person.[2] The size variation of the pupil was also well known, as well as its relevance in various domains. Galen, a roman physician (129–216 CE), used plants to dilate pupils during cataract surgery. Courtesans in Italian medieval

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times also used a substance, atropine (extracted from the plant atropa belladonna), in order to dilate their pupils and appear more attractive when they were courting.

Several physicists such as Archimedes (287–212 BCE) and Galileo (1564–1642) developed specific methods to determine pupil size using cylinders or rectangular pieces of paper, respectively.[2,3] Over time, different tools were used to improve direct observation such as compass, reticles, crosshairs, and other optical devices, or even black circle templates to find the best match with the actual size of the pupil.[2,4] Some of these tools were connected to recording devices such as kymographs.

The advent of image capture on a light sensitive support allowed researchers to work offline on still images of the pupil.[4–8] To improve measurement accuracy across lighting conditions, ultraviolet radiations then infrared sensitive photography were used.[2] Improvements such as increased number of pictures per second through cinematographic methods[9] allowed timeline representations of pupil size variations that were called 'pupillograms'.[2] These graphics were the result of a tedious and time consuming process. Researchers had to develop every picture, project each frame on a screen, and then measure the pupil size with a compass or a ruler. Considerable efforts were made in order to automate acquisition of pupil diameter data (see Ref 10 for a detailed explanation; see also Ref 4). Pupillometry methods expanded with the arrival of eye tracking devices. Eye trackers are quite accurate and allow monocular or binocular online automatic recording. They do not require observer coding before analyzing data, which is more objective and also saves time.

PHYSIOLOGY OF PUPIL DILATION AND CONSTRICTION

In dark ambient conditions, the pupil tends to dilate whereas in bright conditions, it tends to constrict. This is called the pupillary light reflex, and was first reported by Rhazes (850–923 CE), the Persian polymath.[2] The light reflex is the main potential confound in cognitive pupillometry. The luminance of every aspect of the experimental conditions has to be controlled before collecting data (experimental cubicle, stimuli, inter-stimuli luminance), because light emitted or reflected by a particular area will affect pupil diameter. Luminance is typically measured in candela per square meter (cd/m^2) units.

Pupil diameter can vary from 1.5 to 9 mm, and reacts to stimulation in about 200 ms.[11] In standard light conditions, pupil size is about 3 mm.[12] Variations of pupil size are caused by two smooth muscles in the iris: the sphincter (or constrictor) and dilator pupillae. The dilator muscle is under adrenergic control (sympathetic system) from the superior sympathetic ganglion. The sphincter pupillae is innervated by cholinergic fibers of the parasympathetic system from the Edinger–Westphal nucleus.[13,14] Therefore, dilation can be attributed to the activation of the sympathetic system, leading to the stimulation of the dilator muscle, and a parallel inhibitory parasympathetic mechanism.

Pupillary response induced by cognitive load is tightly linked to locus coeruleus (LC) neuron activation.[1,15,16] The LC is a subcortical structure, and is the conductor of the noradrenergic system in the whole brain.[1,17,18] The LC and norepinephric system (LC–NE) are involved in different processes including stress variations, memory retrieval,[19] or selective attention,[20] on top of general functions such as arousal and the sleep-wake cycle.[21,22]

This close connection has been shown by use of single-cell recording technique in monkeys, highlighting the correspondence between the baseline firing rate of a LC neuron and pupil size.[23,24] Therefore, researchers use task-evoked pupil dilation as an index of activity in the LC–NE system.[1] In fact, recent work uniquely highlights the close relationship between the LC–NE system and pupil diameter changes, relating pupil dilation to fMRI recording of the LC.[25]

Researchers have shown that the LC displays two main activation profiles: tonic and phasic modes.[17,26] Gilzenrat et al.[27] suggested those two modes are two ends of a continuum. The phasic mode has neurons firing rapidly to optimize performance during a specific task, to focus attention on an 'exploitation' mode. This LC activation leads to rapid pupil dilation. The tonic mode, conversely, is more efficient in sustained processing. This mode is associated with an elevated baseline firing rate in the LC. It promotes disengagement from the task and diffuse 'exploration'.[1,27,28]

PSYCHOLOGY AND PUPILLOMETRY (A BRIEF HISTORY)

Researchers in ophthalmology and optometry have been aware of pupil behavior for a long time. As far as psychology is concerned, interest in pupillometry is more recent. Even though tasked-evoked pupil responses from psychological effects were noticed in the 1760s, understanding of this phenomenon was lacking.[13] Many early studies were single case studies on clinical patients.[9] Berrien and Huntington[29] used a short-focused telescope moved by an observer with an infrared lamp and head rest device to assess the emotional effect of lying. They showed a specific pattern of slow dilation—quick constriction associated with deception. Other significant early works in psychology were Hess and Polt's studies[30,31] showing, respectively, the relevance of the pupil as an index of specific interest or mental load.

Ensuing studies showed that pupil size variations could be considered an index of arousal and implicit processing. Women display relatively larger pupil dilation when they look at pictures of babies, mothers with a baby, or nude males than to other pictures of people, whereas heterosexual men's pupils were larger when they looked at pictures of naked women.[30] Interest in pictures of the opposite sex was replicated.[32] In a similar study, Hess et al.[33] showed that homosexual men selectively displayed pupil dilation when they looked at nude male pictures. Pupil dilation as a function of participants' idiosyncratic interests was also found with food and taste,[34,35] and music.[34] Researchers discussed the impact of negative stimuli on pupil size with contradictory results (see Ref 13 for details). Although some researchers suggested that negatively valenced stimuli could constrict the pupil,[34] these results were likely due to luminance confounds, as psychological effects on pupil diameter are exclusively linked to dilation,[36] owing to the physiology of the LC–NE system.[1]

On a sensory level, however, pupil dilation in reaction to painful stimuli has been known for a long time.[37] Indeed, pupil dilation appears a sensitive, analog index of pain perception, reflecting intensity of noxious stimulation, and also sensitive to gender differences identified in typical verbal reports from pain studies.[38] Chapman et al.[39] related similar pupil dilation effects to noxious stimuli to peak latency and brain evoked potentials. This effect appears robust to a degree of variation in ambient luminance.[40]

In parallel to these studies using pupil variation to assess arousal and emotional responses, researchers also noticed the relevance of pupillometry to index mental load. In one of their first studies, Hess and Polt[31] asked participants to solve multiplications. The more difficult the problems, the more pupil diameter increased. The impact of cognitive load in mental arithmetic tasks was replicated in several studies.[41–44] It was also found in other areas such as sustained attention processing,[45,46] working memory,[47–49] and decision making.[50]

Some general and methodological concerns must be taken into account when designing pupillometry tasks. First, while pupil size can double due to luminance variations, changes due to cognitive load or arousal are rarely larger than 0.5 mm.[51] Second, although pupillary responses are generally involuntarily, people can learn to induce pupil dilation by mentally manipulating their thoughts (e.g., thinking about sexual images or doing mental arithmetic, see Refs 1 and 52). However, people cannot inhibit pupil reaction to stimuli.[36] Third, when fatigue develops, the average size of the pupil decreases and begins to fluctuate remarkably.[27,53] Thus, conceiving a pupillometry task requires that researchers pay attention to many details that can cause pupil diameter fluctuations independently of the study purpose,[13] on the top of luminance and drug effects.

It must finally be noted that some eye trackers introduce errors in pupil size estimation as a function of gaze position.[54] Indeed, pupil size is estimated from 2D video images, and as the point of gaze moves away from the camera, the viewed pupil will shift from circular to elliptical, and thus compensation must be made in the estimation of its diameter. Fortunately, such errors are systematic, and relatively easy to assess and correct.[55]

CURRENT USES OF PUPILLOMETRY

Use of pupillometry in current research is broad in scope. Given the size of the literature, as well as space constraints, we favored breadth over depth, and have organized our review around the general themes of perception, language processing, memory and decision making, emotions, and cognitive development. We ignore the substantial literatures outside the cognitive sciences, especially those associated with human factors (e.g., driving) and clinical/medical assessment.

Perception

Top-down effects of perception can be revealed through pupillometry. The pupillary light reflex can be artificially created by showing pictures containing the sun, even if the luminance of the picture is manipulated in such a way that it should otherwise produce dilation.[56] Generally, the illusion or suggestion of brightness decreases the diameter of the pupil.[57] In one particular study, the constriction of the pupil to natural images containing the sun was largest when images were presented upright, compared to upside down, despite constant luminance between otherwise identical images.[58] In a second study, the authors replicate the effect with sun and moon, but report greater constriction to the sun despite controlling for luminance. Interestingly, the pupil does not only adjust as a function of the luminance and complexity of visual fields, but also to instructed imaginary levels of luminance and complexity while participant look at an empty background.[59] In fact, changes in pupil diameter do not appear to reflect low-level attentional processes such as the orienting reflex.[60] However, an unpredictable context (such as sound cues) can modulate pupil diameter during visual processing.[61]

The subliminal mere exposure effect (SMEE), where participants are familiarized to stimuli they cannot consciously perceive (and subsequently prefer those arbitrarily familiar stimuli), can also be assessed through pupillometry. Participants' pupils dilated significantly more to stimuli when those had been SMEE-induced than not.[62] Pupillometry is also a useful index of visual processing in the attentional blink task, which assesses whether participants notice the second of two stimuli presented in rapid succession. So called blinks, as well as correct performance. is indexed by both the latency and amplitude of the pupil response.[63] As well, pupil diameter has been shown to vary as a function of the size of the action-perception congruency effect in visual attention in an action-planning task.[64] Action-congruency effects are those where perceptual performance is enhanced by responses that are congruent with the stimuli (e.g., grasping rather than pointing at targets). Current research also examines the relation of pupil diameter to working memory load during visual search tasks, using the former to predict the latter.[65] In the case of inattentional blindness (IB), where participants fail to notice a salient stimulus that is not relevant to the primary task they perform, pupil dilation proved a useful measure of cognitive load associated with the primary task, but unrelated to IB per se.[66] Relatedly, pupillometry data supports the hypothesis that processing speed training increases the efficiency of attentional resource allocation.[67] Generally, pupillometry is considered discriminately sensitive to different components of attention, based on the onset, acceleration, or duration of dilation events.[68] In other words, the delay, speed, and length of a change in pupil diameter index various aspects of attention. A similar usefulness of pupil dilation to the study of attention has been observed before stimulus onset (thus, anticipation) by manipulating asynchrony between target and distractor stimuli in a flanker task,[69] a procedure that measures response inhibition.

Language Processing

Pupil dilation as a marker of cognitive load is further revealed in studies of language, especially as a dynamic marker of processing.[70] For instance, pupil diameter appears to be a quadratic function of speech intelligibility, reaching peak values at medium levels of interference, and tapering off thereafter as intelligibility decreases.[71] Generally, pupil diameter proves a reliable index to various alterations to verbal language,[72] including alterations due to hearing loss.[73] Similarly, pupil dilation indexes the difficulty of word retrieval in bilingual participants, correlating with both word frequency and neighborhood density,[74] with a similar effect observed in toddlers.[75] Interestingly, increased pupil diameter appears to predict the wandering of attention during reading tasks.[76] In an interesting study on poetry, researchers found increased pupil dilation to rhythm violations but not to other violations such as semantic, syntactic, or metric.[77]

Memory and Decision Making

Pupillometry has been shown to exhibit unique and distinct properties from eye gaze data in decision making tasks. In difficult decision making circumstances, pupil dilation predicts decision thresholds, when a choice is made, whereas eye gaze is a better predictor of decision drift, or the unfolding in time of the decision process.[78] Importantly, pupil dilation appears to index the processes involved in decision making, rather than the outcome,[79] including conflict resolution.[80] Specifically, it appears particularly sensitive to reward cues.[81] Indeed, learners in a gambling task showed enhanced pupil dilation to uncertainty, relative to feedback magnitude,[82] and similarly to changes in reward contingencies.[83] It also distinguishes the processing load involved in planning relative to online information processing.[84] Furthermore, pupil dilation can reflect the interaction between emotion and cognition, as was shown in analogical reasoning.[85] This effect appears to be independent of the impact of processing load per se on pupil diameter.[86]

The usefulness of pupillometry for memory research is increasingly highlighted.[87] For example, pupil diameter reflects the relative value of items studied in a word recall task, independent of gaze fixation to the items.[88] Some work suggests that pupillary effects reflect retrieval rather than encoding,[89,90] but other research has shown a link between pupil dilation and item encoding.[91,92] Generally, however, pupil dilation is thought to index the strength of the memory.[93–95] The relationship with pupil diameter can also reflect stress levels during encoding.[96]

Emotion and Cognition

Pupillometry is a useful and reliable measure of participants' responses to emotional stimuli. Pupil dilation can be observed when participants view arousing (positive or negative) relative to neutral images.[97] Changes in pupil diameter discriminate whether participants were touched by a human hand relative to similar mechanical pressure, an effect enhanced by smiling from the human performing the touching.[98] Similarly, pupil dilation is enhanced in face to face interactions when participants are aware that others gaze at their own eyes.[99] Face processing reveals a correlation between pupil diameter and pleasantness ratings,[100] and has been further shown to be modulated by experimental exposure to the hormone oxytocin.[101] Pupil dilation can also be modulated by sexual orientation when viewing erotic images.[102]

Pupillometry further reveals sustained processing of emotional faces in depressed relative to non-depressed participants,[103] as well as the general ability to discriminate emotional states from faces[104] and bodily expressions of emotion.[105,106] Furthermore, pupil dilation can index illusory correlations following aversive learning.[107] Participants showed largest dilation to cues that predicted the larger levels of aversiveness rather than the likelihood of aversive stimulation. Pupil dilation can also be used to index abnormal light sensitivity in participants with seasonal affective disorder (SAD), which further varies as a function of two distinct genotypes related to the melanopsin gene.[108]

Cognitive Development

The use of pupillometry in infancy research experienced resurgence in the late 2000s, some 40 years after Fitzgerald and colleagues' pioneering work.[109,110] Sirois and Jackson showed how pupil dilation is sensitive to perceptual dynamics in typical Violation of Expectation (VoE) studies with infants,[111,112] providing an alternative to looking time measures, which are coarser. Pupillometry has also been used to examine the development of intentional actions in 7- and 12-month-olds.[113] The utility of pupillometry for infant studies has also been shown in the area of social cognition, where infants show increased pupil diameters when shown irrational social actions, relative to rational ones,[114] with sensitivity to contextual constraints.[115] Similarly, infants' processing of emotional faces reflects the type of parental exposure, whereby larger pupil diameter was associated with neutral images of the parent who is not the primary caregiver.[116] Generally, pupil dilation reflects emotional processing in infants,[117] and can be used to track its development.[118] For example, pupillometry has been used to study (and reveal) empathy in 2-year-olds.[119] In adolescents, it has been shown to reflect the physiological response to peer rejection.[120]

Pupillometry has recently been used to study atypical development as well. For example, 2-year-olds with Autistic Spectrum Disorder (ASD) have been shown to have greater tonic and phasic pupil dilation on visual search tasks than typically developing (TD) controls, suggesting enhanced attentional focus.[121] Similarly, pupil dilation effects have been shown for social relative to non-social stimuli, whereby TD children aged 4 exhibit significantly larger pupils than ASD children.[122] The ability to discriminate children with ASD from TD controls with pupillometry has been shown as late as aged 10 years.[123]

DATA PROCESSING AND ANALYSIS

Pupil diameter is a continuous variable expressed over time. In cognitive science research, the aim is to evaluate fluctuations of this variable as a function of time-locked events (e.g., picture or sound onset, or specific events at precise times in video or real-world sequences). This can lead to experiments where substantial data is collected on individual trials, especially when using eye tracking equipment at a high sampling rate. In the vast majority of cases, various steps in data processing are required before analyses are conducted. In this section, we discuss data from a simple yet typical experiment that should induce task-evoked pupillary responses. The aim is to illustrate processing and analyses of pupil data, in the form of a step-by-step example.

One of the authors provides online access to sample data and analysis software for instructional purposes (http://www.uqtr.ca/~siroiss/pupillometry). The data is from eight adults (5 female, 3 male, aged between 21 and 42) who took part in the pseudo-experiment shown in Figure 1. They were asked to carry out mental arithmetic on the six addition problems illustrated, with 10 seconds allowed on each trial. All problems required that participants add three-digit numbers and report the sum out loud. Easy problems were designed so that no carry operation was required for any column (units, tens, or hundreds). The answer can be easily verbalized by performing the sum left to right. Conversely, hard problems introduced a carry operation on all three columns. Thus, participants had to carry sums right to left, with three instances of carry, and remember all three sums in order to produce the verbal answer, which required assembling these sums left to right. It is expected that the cognitive load on such problems, relative to the easy ones, would yield differences in pupil diameter. All participants saw the same sequence of problems, alternating easy and hard ones.

Easy problems

267	528	354
+122	+211	+625
=	=	=

Hard problems

549	497	721
+793	+856	+489
=	=	=

FIGURE 1 | The six arithmetic problems shown in the pseudo-experiment.

Data were collected using a Tobii T120 eye tracker (Tobii Technology, Stockholm, Sweden), running at 60Hz, with a built-in 34×28 cm screen (resolution set at 1280×1024 pixels, 60 Hz refresh rate), located in a dimly lit, soundproofed cubicle. On each trial, a fixation cross was presented at the center of the screen, and remained there until the participant had fixated on it for at least 100 consecutive milliseconds. It was followed by an addition problem, which remained on screen for 10 seconds, and then a 2 second blank screen until the next trial. There were thus 600 samples collected on each trial, plus a variable number of samples associated with the fixation cross (depending how long participants took to fixate for the minimum duration).

Raw data from the six trials, limited to the 10 seconds when the problems were displayed, are shown in Figure 2. This figure highlights three difficulties in the use of pupillometry data. First, the scatterplots highlight the large quantity of data to be summarized even in such a short, simple task, with few participants. Second, there are gaps in the data when participants blink, or briefly move their heads in such a way that the eye tracker fails to find the eye and estimate, among other things, pupil diameter. Finally, participants differ in their baseline pupil diameters. In this dataset, there appear to be two subsets of participants, clustered around 3 and 4 mm diameter.

For missing data samples, we have favored a method of regressing each eye onto the other, applying a low-pass filter (4 Hz) to remove jittering, and using linear interpolation for samples where data are missing from both eyes[111] (see also Refs 51, 85, 124). The issue of variable baseline diameter between participants is addressed by subtracting a pre-trial baseline value, such that data is transformed into relative changes in pupil diameter, which standardizes participants at (or near) zero at the onset of trials.[97,99,125] This reduces variability from absolute values, which is both statistically useful and practically relevant for assessing *changes* in pupil size as a function of independent variables. For these data, we took the unweighted mean diameter from the last six samples (100 ms) before the onset of each trial, while participants looked at the fixation cross. Figure 3 plots the mean change in pupil diameter for easy and hard problems, following these procedures of linear interpolation of missing samples and baseline correction.

Eyeballing the descriptive data in Figure 3 suggests that, as expected, hard problems involve a more important and sustained cognitive load than easy problems. While the latter show a slow, steady decline in arousal, the former exhibit relatively increased, sustained arousal for the duration of the trial. An outstanding question is how to analyze the data. A common approach is to average pupil diameter values within arbitrary time windows at specific times following an event.[99,117,118,126] With this example data, we could use a repeated-measures ANOVA with problem type (easy or hard) and, for example, time since the problem onset (0, 2, 4, 6, or 8 seconds) as independent variables, in order to look at the effect of problem type over the course of a trial. As a dependent variable, we could arbitrarily take the median pupil diameter within 100 ms after each of those five time points. The results of this data reduction are shown in Figure 4.

The analysis identifies a significant interaction between time and problem type ($F_{(4,4)} = 4.418$, $p = 0.007$), as well as significant main effects for both time ($F_{(4,4)} = 15.715$, $p = 0.0$) and problem type ($F_{(4,4)} = 9.768$, $p = 0.017$). Polynomial decomposition of the interaction suggests significant linear, cubic, and quartic relationships, whereas the effect of time is both linear and quadratic. These results are consistent with the general impression derived from looking at the data in Figure 3. They are particularly impressive given the small sample size, which suggests both a robust effect and the relative advantage of repeated-measures over independent groups. Alternatively, in many cases, researchers carry out pairwise comparisons on critical intervals.[94,114] If we replace the ANOVA with pairwise comparisons of type at each time interval, we find a significant difference only at 6 and 8 seconds post-stimulus onset ($ts > 3.57$, $ps < 0.01$), and in the case of the difference at 6 seconds (the most 'convincing' in Figure 4), it barely remains significant after Bonferroni correction, meaning that in experiments where effects may be subtle, many false negatives may be reported. The common approach of reducing rich data to discreet values at arbitrary intervals, illustrated here, and the added problem of multiple statistical tests, is in our view a weak use of pupillometry data.

We favor an approach based on functional data analysis,[127] where temporal pupillometry data is

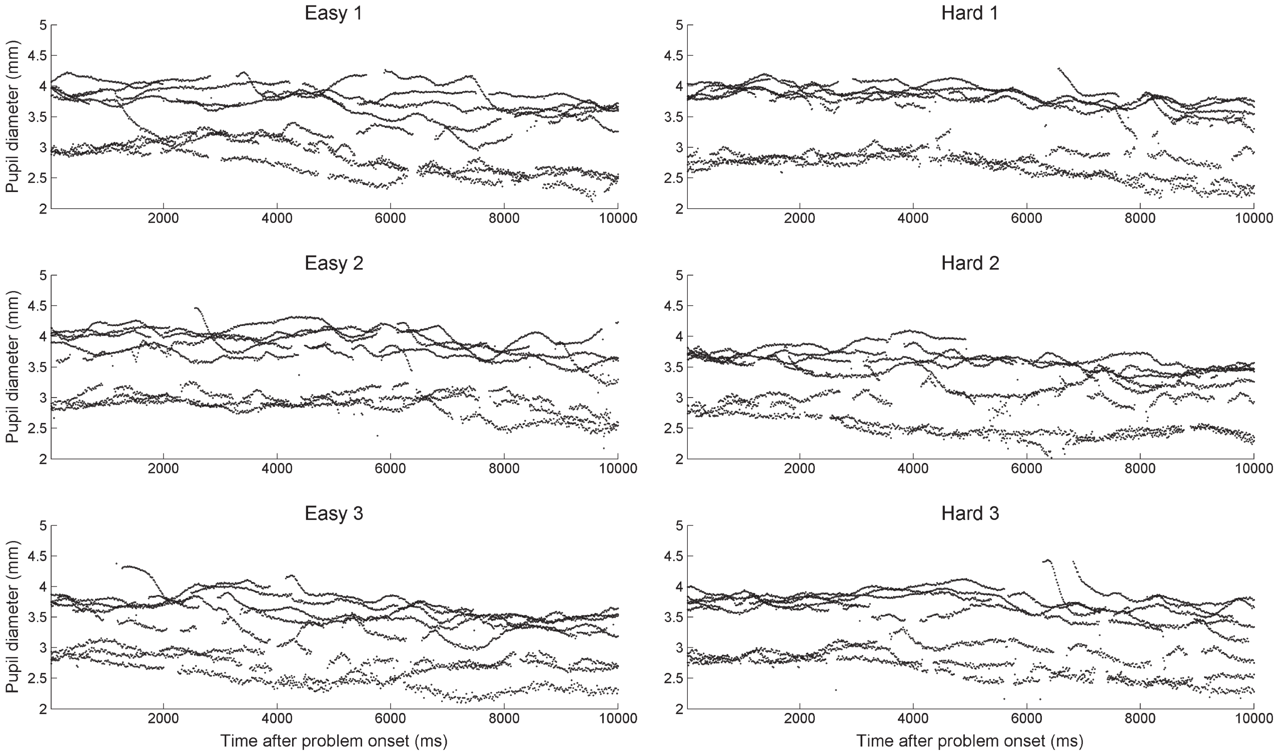

FIGURE 2 | Raw pupil data from participants for each of the problems shown.

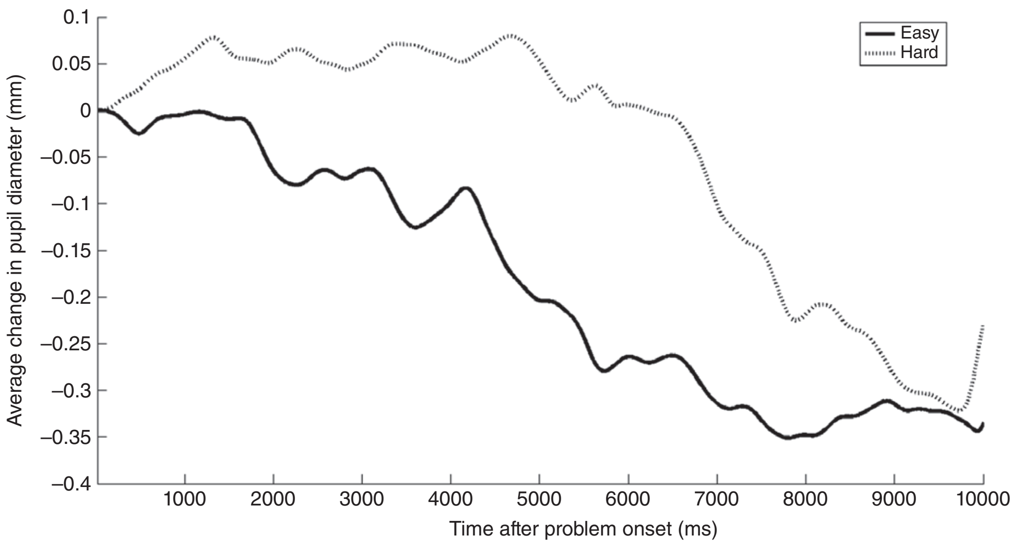

FIGURE 3 | Average change from baseline in pupil diameter, as a function of problem type.

transformed into curve functions (typically b-splines), and where statistical analyses are performed on those very functions.[55,111,112] One main advantage of this approach is that all of the data are used, rather than an arbitrary subset summarized to discreet values. Another, significant advantage is that while the original data is a function of time, so are the outcomes of statistical tests. For example, a *t*-test is not a single value but a curve function, which can be expressed over time, allowing us to examine if and when it exceeds the significance threshold. Such properties remove the unfortunate arbitrariness found in common approaches.

For example, we computed the difference between hard and easy problems from baseline corrected data for each participant (which would

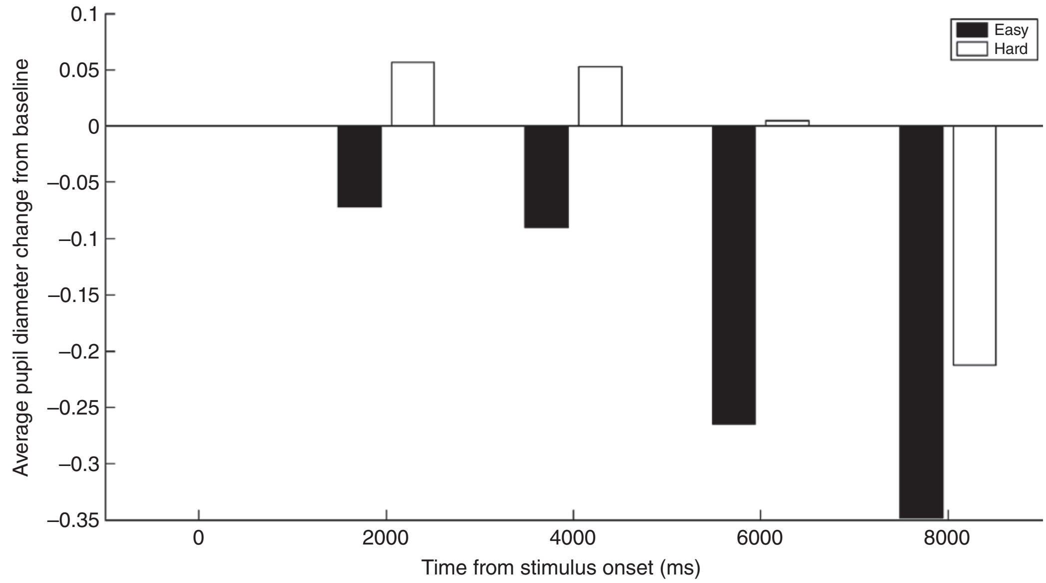

FIGURE 4 | Median pupil diameter change from baseline at various time points, as a function of problem type.

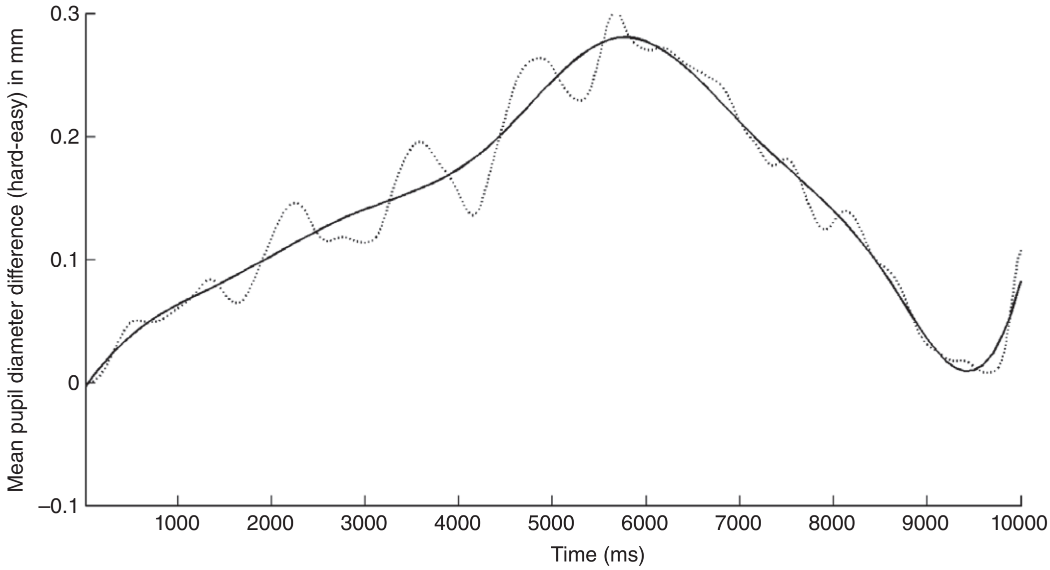

FIGURE 5 | Mean baseline-correct pupil diameter change subtracting easy from hard, transformed into functional (b-spline) object. The overlaid dashed curve is the raw mean difference between easy and hard.

illustrate how relatively more difficult hard problems were), and transformed these differences into b-splines following the procedures outlined in Jackson and Sirois.[111] The average spline is shown in Figure 5, along with the average difference from raw data. The splines introduce a degree of smoothing, but capture the shape of the original data.

A single-sample *t*-test can be performed on these functions, comparing the differences to the null hypothesis of 0. The result of this test is also a function, and is depicted in Figure 6. A narrative interpretation of this figure would be that after an initial peak of arousal favoring hard problems at about 200 ms, participants were similarly aroused as they processed the problems, but from about 4200 ms until 8750 ms following stimulus onset, arousal to hard problems was significantly greater than to easy problems. This simple interpretation was achieved without discarding any data, nor with any arbitrary decision about when to look for differences. We feel that the functional analysis route should be preferred over the common approaches found in the literature. Of course, this is not the only approach in the literature, and while we favor and thus use it,

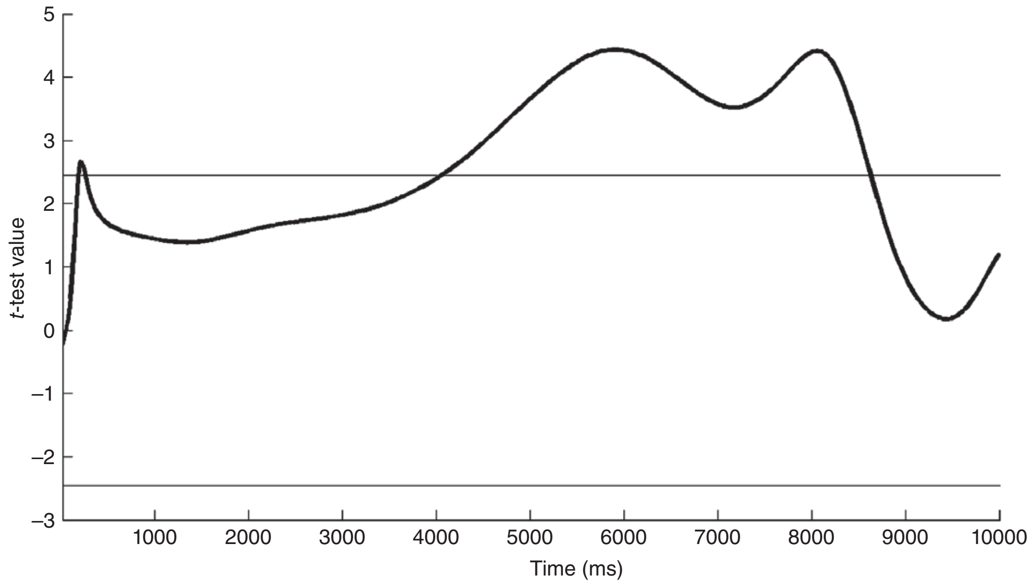

FIGURE 6 | Functional *t*-test of the difference between hard and easy problems. Solid horizontal lines represent the two-tailed critical value for *t*.

interested readers can also look at alternatives such as a recent one based on deconvolution.[128]

CONCLUSIONS

Pupillometry as a formal research tool and object of study within psychology and cognitive sciences has been around for barely 50 years, since the seminal work of Hess and Polt in the 1960s.[1] In those five decades, many technological and methodological advancements (including fast, consumer-level computers) have turned a tedious, expensive process into one that is relatively easy to carry out and non-invasive. Low cost and Do-It-Yourself eye tracking solutions, as well as open-source software, means that the tools are not only available to well-endowed laboratories, but researchers with modest means can also make use of the method. This bodes well for the future.

As our review has shown, pupillometry is widely used across the disciplines that comprise cognitive science. It is particularly well suited to particular research questions, such as implicit processing, and other processes not easily amenable to verbal report or simpler behavioral responses, or those liable to be affected by social desirability, for example. It is also useful with special populations who may not be able or willing to provide typical behavioral answers (complex motor or verbal responses) to certain research questions, such as pre-verbal infants, nonverbal adults, or children with ASD, to name a few.

An ongoing issue is how best to summarize and analyze pupillometry data, especially with the growth in sampling rates from new commercial hardware. As the analysis section illustrated, common approaches discard the majority of the data collected, along with important temporal features. Yet the usefulness of alternative approaches remains to be determined. Of course, such problems are not unique to pupillometry and have analogs in other domains, for example event-related potentials.[129,130]

In conclusion, pupillometry is an increasingly established method, with broad applicability and, at times, unique advantages over other research methods. Current breadth of work using the method suggests that much more is to come, and challenges relating to analyses are a subject of research in their own right.

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