PUPIL DILATION IN TIME PERCEPTION

A Master's Thesis

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I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Arts.

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ABSTRACT

PUPIL DILATION IN TIME PERCEPTION

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Time perception corresponds to how we perceive and understand the duration, sequence, and pacing of incidents in our surroundings and is the subjective experience of the course of time. The integration of data from various sensory inputs as well as higher-order cognitive processes like attention, recall, and decision-making are all part of this intricate and multidimensional process.

Pupil size is known to increase in response to all kinds of demands like attention, working memory, decision-making, difficult perception, memory recall, etc. In fact, studies show increased pupil size to any kind of task demands.

A recent study suggested a dichotomy of task demands based on their distinct neural responses (Farooqui and Manly, 2018). The commonly recognized type of task demand (i.e., type I demand) pertains to issues like increased attention, working memory, the complexity of decisions, etc. For what is being done at that moment. This kind of demand increases activity in the control-related fronto-parietal regions and is well-known to increase pupil size. Farooqui and Manly suggested a different kind of demand (or type II demand) that is related to the length and complexity of the episode of cognition being organized as one unit. They argued that this demand comes about because we execute long tasks as one entity. We, e.g., write emails, shop and not individually execute their very-many component acts. Longer tasks require a longer period of cognition to be organized and controlled as one unit. They evidenced that this demand leads to a deactivation of the control-related fronto-parietal regions and suggested that this demand may psychophysiologically be the opposite of type I demands. The current study investigates this thesis.

We used a time-interval replication task. Time-interval replication involves creating an extended cognitive episode. Longer intervals will require creating longer episodes and hence involve higher type II cognitive demands. If type II demands indeed generate the opposite psychophysiological response compared to type I demands, we can expect longer time-interval replications to lead to a decreased pupil size.

Participants were given various time intervals, e.g., 11 seconds, to replicate by pressing a button at the beginning and at the end of the interval. We used a set of short (8-12 seconds) intervals and a set of long (14-18 seconds) intervals. Long intervals were expectedly more demanding and led to a more erroneous performance. We tested 30 participants (22 females, ages 18-27).

If, as is popularly thought, pupil size increases during any kind of demand, then it should be larger when participants replicated longer durations. In contrast, if type II demands of creating longer cognitive episodes were psychophysiologically opposite, then pupil size may be smaller during longer durations. We found this was indeed the case. We show that task demands related to organizing longer cognitive episodes may indeed be distinct from the commonly recognized task demands related to increased attention and working memory.

Keywords: *Pupil dilation, Pupil size, Time perception, Time intervals, Internal task, Cognitive demand, Work load*.

ÖZET

ZAMAN ALGISINDA GÖZBEBEĞİ BÜYÜMESİ

Inan, Cansel

Yüksek Lisans, Psikoloji

Tez Danışmanı: Asst. Prof. Dr. Ausaf Farooqui

Temmuz 2023

Zaman algısı, çevremizdeki olayların süresini, sırasını ve hızını nasıl algıladığımıza ve anladığımıza karşılık gelir ve zamanın akışının öznel deneyimidir. Dikkat, hatırlama ve karar verme gibi üst düzey bilişsel süreçlerin yanı sıra çeşitli duyusal girdilerden gelen verilerin entegrasyonu, bu karmaşık ve çok boyutlu sürecin bir parçasıdır.

Gözbebeği boyutunun dikkat, işleyen bellek, karar verme, zor algılama, hatırlama hatırlama vb.

Yakın zamanda yapılan bir çalışma, görev taleplerinin farklı sinirsel tepkilerine dayalı bir ikilemi önermiştir (Farooqui ve Manly, 2018). Yaygın olarak kabul edilen görev talebi türü (yani, talep türü), artan dikkat, işleyen bellek, kararların karmaşıklığı vb. konularla ilgilidir. O anda yapılan şey için. Bu tür bir talep, kontrolle ilgili fronto-parietal bölgelerdeki aktiviteyi arttırır ve gözbebeği boyutunu arttırdıgı iyi bilinir. Farooqui ve Manly, tek bir birim olarak organize edilen biliş bölümünün uzunluğu ve karmaşıklığı ile ilgili farklı türde bir talep (veya tip II talep) önerdiler. Bu talebin, uzun görevleri tek bir varlık olarak yürütmemizden kaynaklandığını savundular. Örneğin, e-posta yazıyoruz, alışveriş yapıyoruz ve bunların pek çok bileşen eylemini bireysel olarak gercekleştirmiyoruz. Daha uzun görevler, tek bir birim olarak organize edilmek ve kontrol edilmek için daha uzun bir biliş süresi gerektirir. Bu talebin kontrolle ilgili fronto-parietal bölgelerin devre dışı kalmasına yol açtığını kanıtladılar ve bu talebin psikofizyolojik olarak tip I taleplerin tersi olabileceğini öne sürdüler. Mevcut çalışma bu tezi araştırmaktadır.

Bir zaman aralığı çoğaltma görevi kullandık. Zaman aralığı replikasyonu, genişletilmiş bir bilişsel bölüm oluşturmayı içerir. Daha uzun aralıklar, daha uzun bölümler oluşturmayı gerektirecek ve dolayısıyla daha yüksek tip II bilişsel talepleri içerecektir. Tip II talepler gerçekten de tip I taleplere kıyasla zıt psikofizyolojik tepkiler üretiyorsa, daha uzun zaman aralığı replikasyonlarının gözbebeği boyutunun azalmasına yol açmasını bekleyebiliriz.

Katılımcılara, aralığın başında ve sonunda bir düğmeye basarak tekrarlamaları için çeşitli zaman aralıkları, örneğin 11 saniye verildi. Bir dizi kısa (8-12 saniye) aralık ve bir dizi uzun (14-18 saniye) aralık kullandık. Uzun aralıklar, beklendiği gibi daha zorluydu ve daha hatalı bir performansa yol actı. 30 katılımcıyı test ettik (22 kadın, 18-27 yaş).

Popüler olarak düşünüldüğü gibi, herhangi bir talep sırasında gözbebeği boyutu artıyorsa, katılımcılar daha uzun süreleri tekrarladıklarında daha büyük olmalıdır. Aksine, daha uzun bilişsel epizodlar yaratmaya yönelik tip II talepleri psikofizyolojik olarak zıtsa, o zaman gözbebeği boyutu daha uzun süreler boyunca daha küçük olabilir. Durumun gerçekten böyle olduğunu gördük. Daha uzun bilişsel bölümlerin düzenlenmesiyle ilgili görev taleplerinin, artan dikkat ve çalışma belleği ile ilgili yaygın olarak kabul edilen görev taleplerinden gercekten farklı olabileceğini gösteriyoruz.

Anahtar sözcükler: *Gözbebeği genişlemesi, Gözbebeği boyutu, Zaman algısı, Zaman aralıkları, İç görev, Bilişsel talep, İş yükü*.

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CHAPTER 1

INTRODUCTION

1.1. Estimation of Time

Duration is determined by the particular events that individuals choose to focus on within the course of their lives. This could be, for instance, the period of a kiss, a dinner, or a journey and is measured with common units such as the second, the day, and the year. A particular interval may always be split into a chain of events dividing shorter durations.

Certainly, human experience consists of several overlapping changes rather than just one single set of occasions. To exemplify, the length of a TV series and breakfast can be combined when both are integrated into the greater span of an ocean voyage (Fraisse, 1984).

Time perception, or chronoception, is a multidisciplinary field encompassing psychology, cognitive linguistics, and neuroscience. It investigates how individuals subjectively experience and perceive time, including their sense of duration and the unfolding of events. Hence, duration and sequence are fundamental aspects of what is perceived in change. This field involves measuring individuals' own perceptions of time as they navigate through the indefinite passage of moments.

The sense of time is a complicated phenomenon involving brain systems that are impacted by cognitive processes and environmental stimuli. How people experience time may be influenced by factors including one's emotional state, degree of concentration, memory, and illnesses. Regardless of this knowledge, the brain processes underpinning time perception are still poorly understood. The objective is to investigate the diseases, theories, executive processes, and neurofunctional features that help us understand how time is experienced.

It was found that, in accordance with how long the time period is interpreted, multiple cognitive operations which are not strictly components of an essential time-keeping mechanism but still affect the perception of duration may be included. Such procedures might additionally include different brain areas and functions (Wittmann, 2009). Heavey et al. (2008) also explained the inner experience by conducting Descriptive Experience Sampling (DES) on college students. He stated that inner speech, feelings, inner seeing, and unsymbolised thinking vary greatly among individuals (Heavey & Hurlburt, 2008). According to Evans et al. (2004), people utilize language constructs to define motor events, places, and spatial measurements when it comes to referring to the passage of time. To exemplify, these can be statements such as ”time just flew by” or ”a situation endured long” and show that time is not an empirical fact. According to current psychological studies, personality traits such as emotions, mood, drive states, and cognitive abilities such as working memory, attention, and long-term memory also have an influence on endurance estimations.(Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007; Rammsayer, 1997).

By combining research on time perception and the neurological bases of that perception, the frontal cortex, parietal, basal ganglia, cerebellum, and hippocampus have improved our understanding of the regions pertinent to time perception. These brain processes can only be fully understood when memory, attention, and other emotional states are involved.

1.1.1. Relativeness of the Time

Time can, frequently be over or underestimated. It feels like go more slowly when we are looking forward to something important, such as waiting until the day we go on vacation than it does when the vacation is getting over and we are preparing to return to work. Furthermore, a specific neural timing mechanism can have a role in people's ability to clearly interpret temporal occurrences. People can appropriately coordinate their motions to regular rhythms, distinguish between tones with differing durations, or repeat given intervals, particularly during shorter periods of within a few seconds (Eisler & Eisler, 1994). Yet, there is no solid knowledge of exactly which temporal systems are responsible for these time-processing abilities.

Coming to the point, time is ever-present. Whether it's waiting in line at a grocery store or planning a vacation a year in advance. Despite the absence of a specific internal organ dedicated to sensing time, there have been numerous theories proposed to explain how humans perceive time. These anticipations generally share common points and follow a general theme. They may vary in their specific explanations. For example, some theories propose that our sense of time is impacted by external cues such as changes in the environment or consistent patterns of events, whereas others advocate that it is shaped by our internal biological processes, like circadian rhythms or memory mechanisms.

1.1.2. Explaining the Time

Considering internal biological processes, in the previous research time perception has taken by in the concept of state-dependent, spectral time, linear and non-linear network models in terms of *neurobiological internal clocks*. A pacemaker-switch-accumulator system is frequently used in studies of the *scalar expectancy theory* (SET). Once attention is directed toward a stimulus that needs to be timed, the switch shuts, enabling the pacemaker's signals to move into the accumulator. This activates the pacemaker, which is regulated by attention. The switch opens again and stops the transmission of pulses upon stimulus displacement. As a consequence, time is measured using the total number of impulses that have been accumulated during a period of time.(Moskowitz, Olcaysoy Okten, & Gooch, 2017).

In order to comprehend how time frame judgements, internal clock acceleration, internal attention, and memory impairments are related to one another, researchers have looked at the *information processing model* in connection to the time scalar theory. In such studies, many participant groups have taken part in various activities that have to do with the reproduction and production of time, time reaction, recall, and attention. Numerous research has shown a connection across time estimates, cognitive processes (memory speed and processing), task duration, and aging. As reported by Tse et al.(Tse, Intriligator, Rivest, & Cavanagh, 2004), the brain can only utilize a proportion of the information that has been processed, and this is skewed as a result of the subjectively perceived extension of time. *The state-dependent model* in contrast, proposes that the association between the stimuli may be modeled as a complicated nonlinear function and that this function can be utilized to clarify how neural networks encode temporal processing. Both continuous activity (in motion state) and dependent features of neural time (hidden state) are possible in neuronal networks. (Laje & Buonomano, 2013).

Humans have an innate ability to manipulate and foresee a time independent of any particular timing mechanisms. This capability is inherent to our perception of time and is not restricted to any particular models or frameworks. As a consequence, the concept of time relies upon external context (sensitive information) and internal (emotional state) (Wittmann, 2009). The link between time and emotion alters how the internal clock adjusts to circumstances rather than how it functions (Fontes et al., 2016).

Based on clock models, an internal clock produces pulses that are tracked by an accumulator and saved in memory for comparison with a reference period later. Higher levels of arousal cause the internal clock to produce more pulses, which gives the impression that time is passing more slowly. Thereby, higher attentional demands may result in less effort put forth in making time judgments, which can have an impact on the output of the accumulator. Studies by Block et al. (2010); Brown (1997), Wöllner and Hammerschmidt (2021); and Zakay (2005) provide credence to this hypothesis.

1.1.3. Cognitive Processes' Effect on Time Perception

Furthermore, time perception and its distortions are significantly influenced by emotions (Droit-Volet, Ramos, Bueno, & Bigand, 2013; Mella, Conty, & Pouthas, 2011; Noulhiane, Mella, et al., 2007). Within the framework of Russell et al.'s (1980) emotional circumplex paradigm, the impact of emotions may be explored. This model suggests that there are two main categories for categorizing emotions: valence, which ranges from positive to negative or pleasant to unpleasant, and arousal, which ranges from low or calm to high or aroused. Moreover, researchers have examined how arousal affects perception of time through a variety of stimuli, including facial expressions (Gil & Droit-Volet, 2012), symbolic characters (Schwarz, Winkler, & Sedlmeier, 2013), dance motions (Allingham, Hammerschmidt, & Wöllner, 2021), and nonmusical noises including clicks (Mella et al., 2011; Noulhiane, Mella, et al., 2007; Treisman, Faulkner, Naish, & Brogan, 1990), laughing, and sobbing and also music and instrumental motives (Droit-Volet et al., 2013; Schwarz et al., 2013).

According to some studies, increased subjective arousal and longer duration comprehension are positively associated (Mella et al., 2011; Schwarz et al., 2013; Droit-Volet et al., 2013). Nonetheless, other research (Noulhiane, Mella, et al., 2007) has provided conflicting findings, suggesting that either heightened subjective arousal may be correlated to shorter duration comprehension or may not significantly affect time perception (Wöllner & Hammerschmidt, 2021).

Considering the valence of the stimulus, it also affects how time is perceived. According to Noulhiane's emotional research from 2007, people rated the length of emotional tones to be greater than neutral ones, with unfavorable sounds being regarded to be longer than good ones. Similar findings were made by Mella et al. (2011), who found that negative noises appear to stay longer than neutral sounds. These findings were verified by arousal measurements made using skin conductance. In Droit-Volet et al.'s (2013) research, tonal and atonal versions of the same musical compositions were created in order to alter the pleasantness of the music. Participants perceived shorter lengths of music to be more pleasant than less pleasant. The authors acknowledged the impact but proposed that this effect may be ascribed to a divergence of focus away from the time estimate.

1.1.4. Neuro-Cognitive Processes' Effect on Time Perception

In neurocognitive models, there are two main ways of looking at timing estimation which are prospectively and retroactively In the first scenario, a judge determines the length of a time period which is currently being experienced (Wittmann, 2009). Conversely, a person who is estimating time retrospectively is doing so for a or a passed period of time and after which awareness arises afterward. The assumption in models for estimating future time is that there is an "internal clock" linked to a pacemaker that generates a series of time units that are inputted into an accumulator. The time units created in an adaptation of these pacemaker-accumulator models known as the attentional-gate model are solely recognized when attention is focused on time.

An observer must split their attention between temporal and non-temporal activities, thus, prospective timing constantly represents a dual effort (Zakay & Block, 1997). Retrospective time estimate requires estimating the length of an already-passed time period. Then, based on the number of memory contents that have been interpreted and retained, an observer must determine a particular time in the past; in other words, the duration must be recreated from memory. The more prolonged the length is subjectively experienced, the greater the shifting experiences we encounter throughout time. Those are kept in memory and later recovered.

Therefore, the perception of a lengthy period of time is related to the behavior of an individual with varied experiences. It draws on the activation of regions like the medial temporal cortex, which has been found to be a component of episodic memory (Noulhiane, Pouthas, Hasboun, Baulac, & Samson, 2007).

Considering the time scales in time perception, the brain is expected to interpret intervals that reach just a couple hundred milliseconds in duration. The 50 ms time frame, which is unrelated to the motor and cognitive control, represents pure timing processes. The argument proposes that dopamine-driven systems, which are active in both longer and shorter time periods, are supplemented by further procedures, independent of time (namely working memory and attention) during longer intervals compared to a few hundred milliseconds (Rammsayer, 1997).

In Miyake et al. (2004)'s study, the processing of time periods within 0.45 and 1.5 s appears to be automated, unaffected by cognitive demands, but the processing of time periods around 1.8 and 3.6 s is impacted by attention and working memory operations that are driven by secondary activities (Miyake, Onishi, & Poppel, 2004). Gathering studies in neural timing methodologies, first, it is found that a cognitively regulated timing mechanism for supra-second periods is related mostly to the parietal cortical and right prefrontal regions. Second, an automated timing mechanism for short periods up to around 1 s that involves motor circuits throughout the brain consisting of basal ganglia, SMA, and cerebellum (Lewis & Miall, 2003).

Additionally, sensory modality is commonly suggested as a component determining time perception in addition to arousal and valence. In his book ”Psychologie du Temps,” Paul Fraisse made the argument that an interval's apparent length is influenced by the sensory qualities of its borders (Fraisse, 1957). Empty intervals with audible borders are seen as shorter than with visual bounds. On the other hand, auditory durations are often considered to be 20 percent longer than visual durations for entire intervals made up of several or continuous events

(Behar & Bevan, 1961). Numerous studies have proven that auditory tones are often regarded as being longer than visual flashes of identical objective length, hence supporting this idea (Ortega, Guzman-Martinez, Grabowecky, & Suzuki, 2014; Droit-Volet, Clément, & Wearden, 2001; Penney, Gibbon, & Meck, 2000; J. H. Wearden, Wearden, & Rabbitt, 1997; Lustig & Meck, 2011).

1.1.5. Time Perception from Physiological Perspectives

It is usually believed that time perception is accurate independent of the particular context being timed since exact timing is essential for efficient motor responses in a variety of tasks (Buhusi & Meck, 2005). According to one theoretical hypothesis, the larger amount of change people notice when they watch quicker motion or stimuli might be used as a marker of how much time has passed. Thereby, this might result in an overestimation of time periods. Also, Brown et al. (1995), Kanai et al. (2006), and Kaneko and Murakami (2009) have emphasized this topic in earlier research. Overall, these results are compatible with a directional link between the experience of time and motion.

Karsilar and Balcı (2018) tested these advocating that the physical properties of the occasions also have an influence on the modulation of time perception. In his experiment, he observed how different qualitative, such as walking forward and backward, and quantitative, such as walking speed, sides of the motion affect time sense via temporal discrimination tasks (Karşılar, Kısa, & Balcı, 2018). The findings demonstrated that irrespective of walking direction, faster walking speeds resulted in a sense of shorter periods. Although the direction of movement had minimal bearing, the effect of walking pace on perceived time was constant. According to these results, there is a considerable correlation between perceived biological motion, generated from the premotor frontal area (Saygin, 2007), occipital face area, and posterior superior temporal sulcus (Grossman & Blake, 2002) for example, speed and temporal perception.

1.2. Understanding of Time in Chronological Order

Since the perception of time is an abstract concept that is open to manipulation, it has been discussed in different concepts from the past to the present. As time can be interpreted subjectively, a significant comparison in contemporary timing research can be done between retrospective and prospective timing (J. Wearden, 2016). The prospective timing comes from situations where people are alerted just before the timing. This can be notifications such as ”Take it just for a second”. And the retrospective timing includes circumstances in which sudden inquiries about time are made. To exemplify, “How long ago it was as you are writing your thesis?”. The majority of contemporary opinion sees both of these forms of timing as separate, with prospective timing including some kind of internal timer and retrospective time judgments relying on the amount of something non-temporal (for example, the quantity of information processing, or ”contextual variation”) having arose while the time period evaluated (J. Wearden, Duncan, Phillips, McLeod, & Phillips, 2005). Thus, throughout time, literature about time” showed and will show variations when it is tried to be conceptualized.

At the beginning of 1864 and 1960, a simple psychological time unit was evaluated as an “indifference point” which was both under and over in equal respect forecasted (Woodrow, 1930; Nichols & Hall, 1891). Despite the fact that it is not connected to current research on time perceiving, Skinnerian psychology (Skinner, 2019) also played an important role in animal experiments on timing.

In the latest 1920s, people and animals exhibit their sense of time by providing from “internal clock-like tool” as a kind of organ for duration perception (Penton-Voak, Edwards, Percival, & Wearden, 1996). According to Treisman et al. (1963)’s model, periodic sensitization to excitation pacemakers is generated from the raw element for duration judgments and activates a timer with bursts. And he emphasizes terms called ‘comparator’ and ‘store’ which will create the judgments of time and behavioral output. Gibbon et al. (1984) extend their idea as a reference for the time and a particular comparison mechanism is required to produce behavior in terms of memory as a storage and decision mechanisms as a comparator. He also developed a theory named scalar expectancy theory (SET). This model was also based on an accumulator clock term consisting of the decision process different from reference and working memory stores. The discrepancy between the two inventions was while Treisman et al.(1963) were observing time perception in humans, large quantities of data about studies of animal timing had been gathered since the time of Gibbon et al, in the 1930s (Gibbon, Church, Meck, et al., 1984).

During the years between 1983 and 1996, psychopharmacological research has done by Meck et al. (1983), stating that dopamine levels influenced the pacemaker of the clock's rhythm, as opposed to acetylcholine levels controlling the reference memory storage (J. Wearden, 2016).

Relying on Weber's law, mathematical analyses were brought to the estimation of time in animal experiments. Toward the conclusion of the 1980s, terms like mean accuracy, real-time (t), and the standard deviation of time for the scalar property of variance were identified to make time perception more concrete.

Considering human time interpretation in the 1990s up to the present, cited by Gibbon and Allan (1991), SET's theoretical framework, specifically the clock, memory, and decision functions, explains how humans behave differently than animals on constraints like temporal generalization and bisection. Within this framework, in bisection, people make decisions on standard timing by comparing "short" and "long" time standards (e.g. 300 and 700 ms length, correspondingly) and whether durations are more alike.

The underlying process of timing behavior was tested and filled with visual and auditory judgments benefiting from the short/long comparison and speed calculation after the cumulative knowledge (Treisman et al., 1990; Penton-Voak et al., 1996). Wearden et al. (2004) exemplify that with this progress, the internal clock system must be positioned in a more complex cognitive scheme that includes attention, retention, and decisions in order to time behavior.

Besides, time perception creates distinctions when comparing children of different ages with adults. According to SET theory, researchers justify that older children and adults are better at timing than younger children. Multiple studies indicated that the instability of time depiction declines with age despite children's decision-making differs essentially from adults' and this contrast disappears around the age of 8 (Droit-Volet et al., 2001). For instance, modeling based on SET principles in Wearden et al.'s (1997) research showed that, at least in certain instances, the variability of time illustrations increased consistently with aging and declining IQ. However, in broad terms, the impacts of aging on prospective timing are relatively minor, with older individuals typically behaving in the same manner as younger individuals, albeit with greater performance inconsistency.

Due to the fact that the neural, and time perception could not be clarified with behavior and physical bases connected, their role in cognition is still investigated since 1990 up until now. For example, Meck et al. (1996) highlight that the parts of the basal ganglia gathered the output from the dopaminergically sensitive pacemaker neurons produced by the substantia nigra pars compacta, while other parts of the brain controlled decision-making and memory. Moreover, Nenadic et. al. (2003) and Macar et. al. (2004) emphasize that if specific brain regions are stimulated at the timing task, does that mean they are associated with timing or recalling and decision stages? Thus, varying degrees of delicacy and inventiveness, have been put forth.

1.3. Pupil Diameter to Assess Cognitive Functions

It is acknowledged that pupillometry is a well-established and frequently applied technique for evaluating behavioral reactions and gaining factual data on cognitive processes. Pupil diameter offers an objective, quantifiable measurement that is simple to record and interpret the underlying cognitive process. It refers to a change in pupil size and a physiological reaction that is impacted by a variety of cognitive and emotional variables (Laeng, Sirois, & Gredebäck, 2012; Partala & Surakka, 2003). Although it is quite hard to evaluate cognition as a concrete phenomenon (Goldinger, Papesh, Barnhart, Hansen, & Hout, 2016), it is possible to learn more about cognitive functions including attention, arousal, mental strain, and emotional processing by monitoring pupil dilation.

Considering the advantages the pupillometry in cognitive science, measuring pupil dilation is attainable in real-time and is non-invasive on a physical basis. Besides, it has been demonstrated that pupil dilation is responsive to variations in cognitive load and attentional demands (Beatty, 1982). Researchers can get insight into the cognitive functions at work by monitoring pupil size variations. It makes it possible to estimate the amount of cognitive effort and attentional resources dedicated to different tasks. Besides, individual variations in mental representation can be shown by tracking the pupil size change. Pupil reactions may differ between people, revealing differences in cognitive ability, attentional control, or information processing methods. The research of cognitive problems or the evaluation of cognitive abilities can both benefit greatly from this.

Behavioral responses have been discovered to be connected to temporal processing in regard to the synthesis of pupil dilation with time perception. The study of time perception and temporal processing has found great value in pupil constriction. Pupil dilating executes have been seen to correspond with time estimating tests, offering a view of people’s subjective experiences of time. Furthermore, in time perception tests, pupil dilation might represent a sense of anticipation and readiness for forthcoming events. Participants’ pupils often enlarge when they anticipate an event occurring at a given moment, demonstrating their temporal expectations. Additionally, the time dilation effect, where attention-demanding tasks can cause erroneous perceptions of time, appears to be related to pupil diameter. Pupil dilation patterns during these activities can be examined to get important knowledge about the underpinning cognitive mechanisms causing temporal distortions. Hence, researchers can acquire a deeper knowledge of how people perceive and feel time by combining pupillometry with time perception studies.

1.3.1. Physiology of Pupil Dilation

People may collect information from their environment through their pupil, which is located in the center of their eyes. Unknown to many, however, is that by carefully observing how the pupil contracts (gets smaller) and dilates (gets wider) in reaction to various stimuli, researchers may learn important things about what is happening in the brain. For instance, when it's bright outside, the pupil shrinks, and when it's dark outside, the pupil expands. Environmental reactions, however, matter. Additionally, the pupils react when someone uses particular drugs, when they experience powerful emotions, when they recall a memory, or when they are focusing or thinking extremely intently (Torres & Hout, 2019).

It is important to consider how pupils perform, how they react to their surroundings, and how these responses represent cognitive processing, or the internal calculations taking place in the mind.

Having looked at the function of the pupil, the iris responds to bright light by expanding (flexing), which causes the pupil to shrink and block less light from entering the eye. In response to low light, the iris dilates (relaxes), causing the pupil to enlarge in conditions when more light is required to see. *The pupillary light reflex* is what is meant by this (Sirois & Brisson, 2014). The pupillary light response is a function of the autonomic nervous system, referred to as the portion of the nervous system in charge of uncontrollable, unconscious, and involuntary functions including digestion and respiration. Therefore, pupillary responses to light might be partially interpreted as uncontrollable or unconscious bodily reactions.

The pupillary response mentioned earlier is a bottom-up process.*Bottom-up processing* may be defined as the ”up” interpretation of sensory input, such as light, noise, heat, pressure, or chemical compounds, from the body to the brain. The mouth, skin, ears, nose, and eyes are the sense organs via which information enters the body and is processed from ”the bottom up,” or ”the bottom.” The collected data is subsequently transported to the ”top” of the brain, where it is analyzed to produce an interpretation (i.e., a perception), a recollection, or other higher-order thinking. Pupillary reactions to light are thought of as bottom-up processing since they come about as a result of the internal processing in the brain of external input (a certain intensity of light entering the eye) and the subsequent perception (the magnitude of the light is interpreted as brightness).

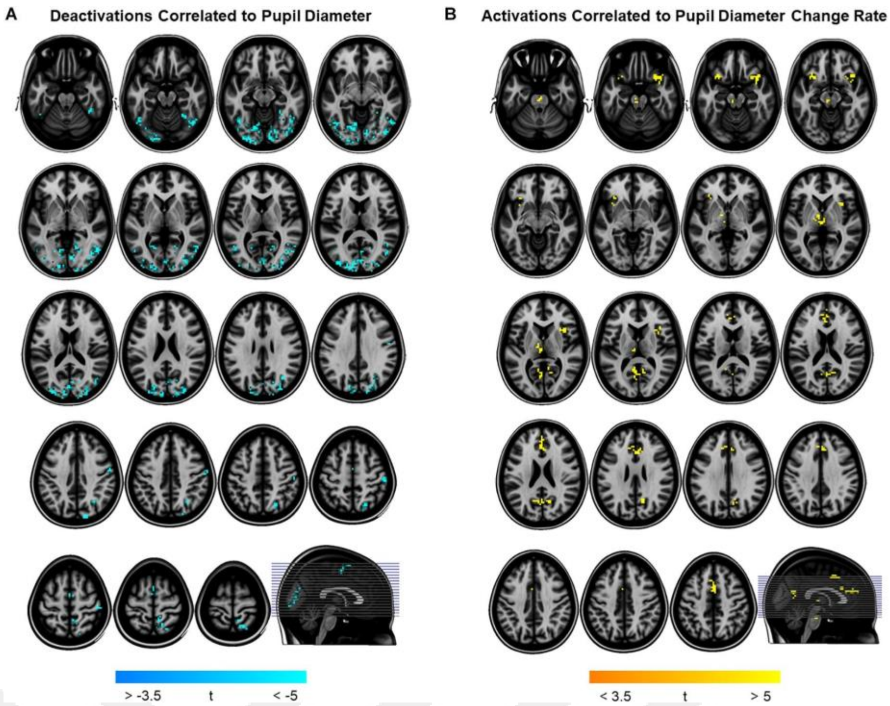
With respect to the intensity of the light, the brain then transmits messages right back to the iris, leading to either shrinking or dilating (Steinhauer, Siegle, Condray, & Pless, 2004). Therefore, it appears logical that the pupil ought to react solely to certain lighting circumstances as regulating the rate of light appears to be the pupil’s main objective. Unexpectedly, this is not totally accurate. It is now inevitably known that pupils may provide information about far more complicated brain activity by observing pupillary responses.

1.3.2. Modulatory Systems in the Brain Stem

Movement, balance, attentiveness, sensory processing, respiration, and autonomic body functions are just a few of the crucial processes that the brainstem regulates. To control reflexes like coughing, swallowing, and vomiting, it gets instructions from higher brain areas and communicates with the spinal cord and cerebellum. Individual neurons may be changed to alter the activity of the brainstem, which then changes how tiny neural circuits and behavior function. This is accomplished by altering the way that synapses, which allow cells to communicate, and neural networks operate. These modifications enable the brain to adapt to changing circumstances and generate the necessary actions. acetylcholine, glutamate, glycine, and GABA are essential neurotransmitters regulating if the brain stem network is active or inactive. Additionally, neurotransmitters, involving acetylcholine, glutamate, noradrenaline, serotonin, dopamine, and GABA, may alter the electrical and synaptic characteristics of neurons by binding on certain receptors, affecting significant signaling pathways (Noga, Opris, Lebedev, & Mitchell, 2020).

Precisely, the brain stem consists of plenty much distinctive motor and sensory systems. They are second- and third-degree neurons of the somatosensory, auditory, and vestibular structures; lower motor neurons in the cranial nerve nuclei; preganglionic neurons of the parasympathetic nervous system; circuitry mediating autonomous reflexes (such as ones that regulate respiration and cardiovascular function); neurons providing the descending brainstem motor pathways (reticulospinal and vestibulospinal tracts); and neuronal glycine receptors (Steward & Steward, 2000).

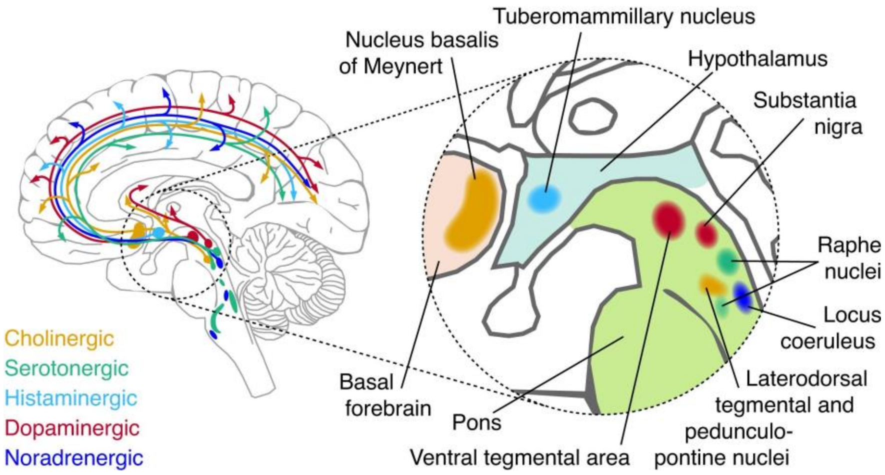
According to DiNuzzo et al., (2019) study's findings, variations in pupil size are linked to broad deactivation in the visual and sensory-motor regions of the brain(Figure 1.1, A). Activation in distinct subcortical and cortical areas, in contrast, is correlated with fluctuations in the range of pupil diameter (Figure 1.1, B). These regions include the right anterior insular cortex (rAIC), dorsal anterior cingulate and paracingulate cortex (dACC/PaCC), orbitofrontal cortex (OFC), posterior cingulate cortex (PCC), substantia nigra (TH), locus and coeruleus (LC).



(DiNuzzo et al., 2019)

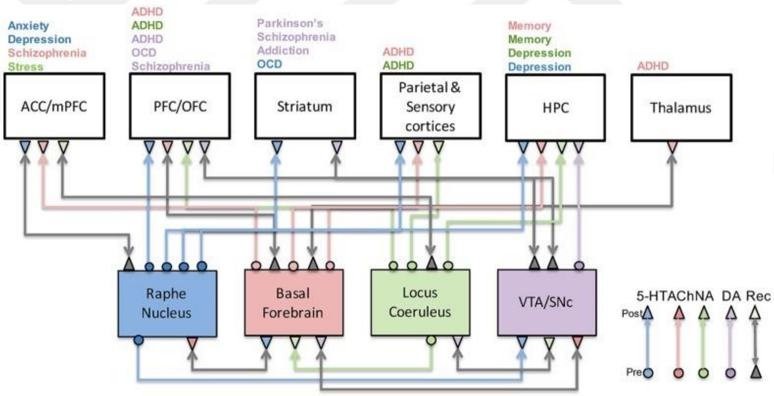
Figure 1.1: Areas of the brain connected to changes in pupil size.

As it is shown in Figure 1.2, small clusters of neurons found in the brainstem, pontine nucleus, and basal forebrain make up the human neuromodulatory system. Such neurons profoundly influence cognitive behavior. There are various kinds of ascending neuromodulatory networks connecting the brainstem and basal forebrain to different regions of the central nervous system, generated by noradrenergic (Figure 1.6), serotonergic (Figure 1.5), dopaminergic (Figure 1.4), and cholinergic (Figure 1.7) outputs. These neuromodulators provide communication through rewards, novelty, danger, and social interaction. They serve as the building blocks for many higher cognitive processes including focus, judgment, emotion, and action that is motivated by goals. These tasks are generated from the interaction of particular brain domains, like the anterior cingulate, frontal cortex, hippocampus, sensory cortex, and striatum, including the neuromodulatory systems (Avery & Krichmar, 2017). As it is indicated in Figure 1.3, neuromodulatory networks interplay with each other and play a role in the occasion of certain brain disorders.



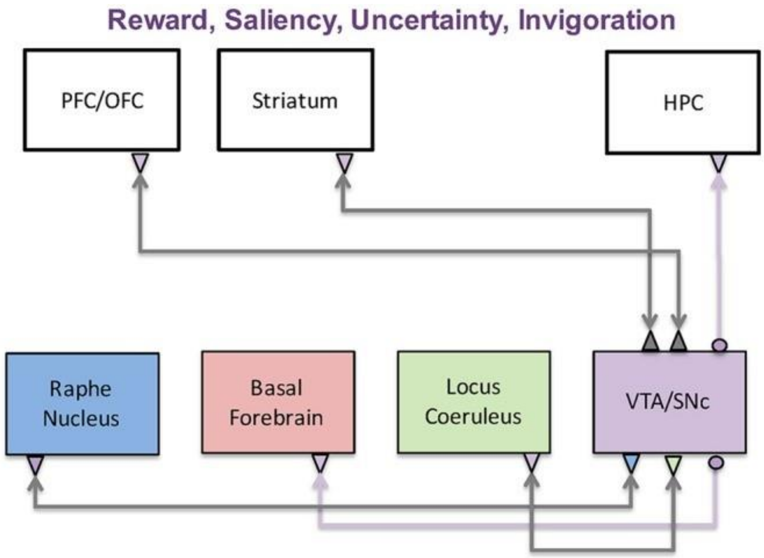
(van den Brink, Pfeffer, & Donner, 2019)

Figure 1.2: The main neuromodulatory circuits showed in a detailed diagram. For the aim of brevity, cerebellar, spinal, and temporal branches are excluded. The forebrain's principal afferent nuclei's probable anatomical locations are shown in the center.



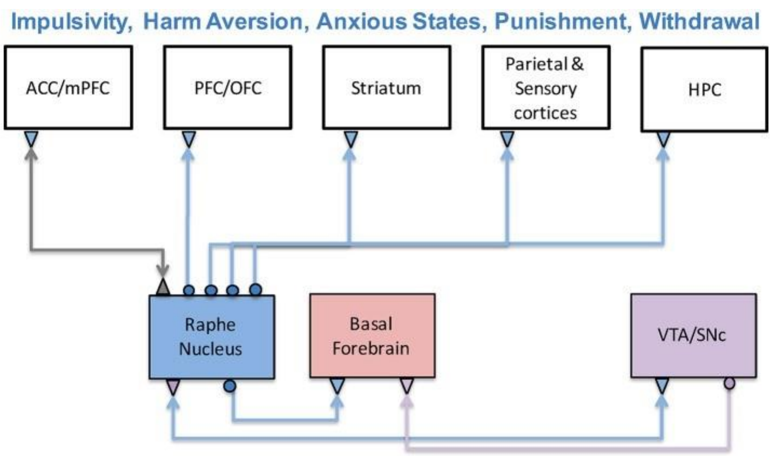
(Avery & Krichmar, 2017)

Figure 1.3: Interplay between neuromodulatory networks and how they influence disorders. The association between the noradrenergic (green), serotonergic (blue), dopaminergic (purple), and cholinergic (red), networks, through with the cortical and subcortical regions, are shown in this schema. As shown above, for each brain region, its dysfunction has been correlated to distinctive neurological and psychiatric diseases. Gray arrows indicate links that are repeated.



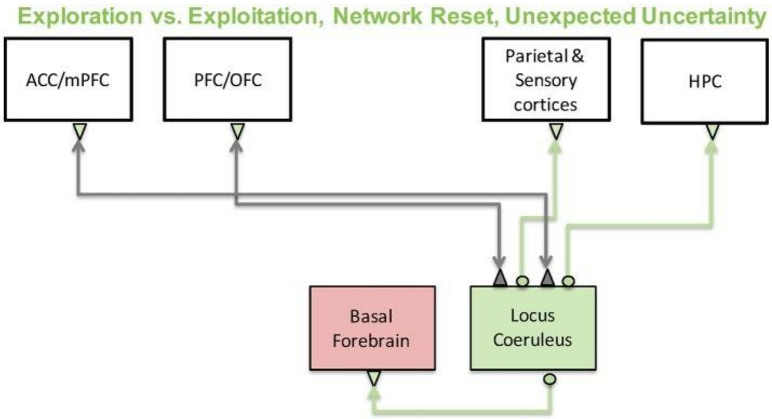
(Avery & Krichmar, 2017)

Figure 1.4: Role of the dopaminergic system. A wide range of activities, including reward, saliency, apprehension, and invigoration, have been connected to the dopaminergic system, which has its origins in the VTA and SNc. Links between the prefrontal cortex, striatum, and hippocampus enable these processes. Additionally complicated by its reciprocal connections to the other three neuromodulatory structures, its function in disease conditions



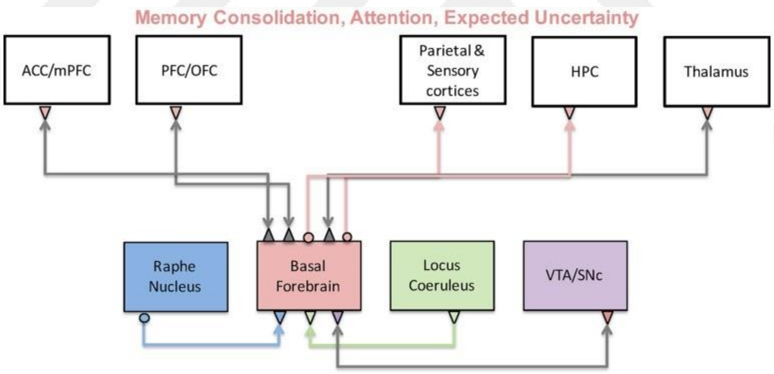
(Avery & Krichmar, 2017)

Figure 1.5: The functioning of the serotonin system. The prefrontal, sensory, limbic, and striatal regions are all related to the serotonergic system, which has its beginnings in the brain stem's Raphe Nucleus. Numerous behaviors, such as impulsiveness, trauma aversion, anxious moods, punishment, and withdrawal, have been linked to the serotonin hormone. It is thought to have a negative interaction with the dopaminergic system, according to experimental and theoretical investigations.



(Avery & Krichmar, 2017)

Figure 1.6: How the mechanism of noradrenergic neurons works. Management of neural pathways in the brain in response to unexpected stimuli has been related to the noradrenergic system, having its origins in the locus coeruleus. The prefrontal and cingulate cortexes regulate the neural activity of the locus coeruleus, which reflects among the cortex and adjacent neuromodulatory areas like the basal forebrain.



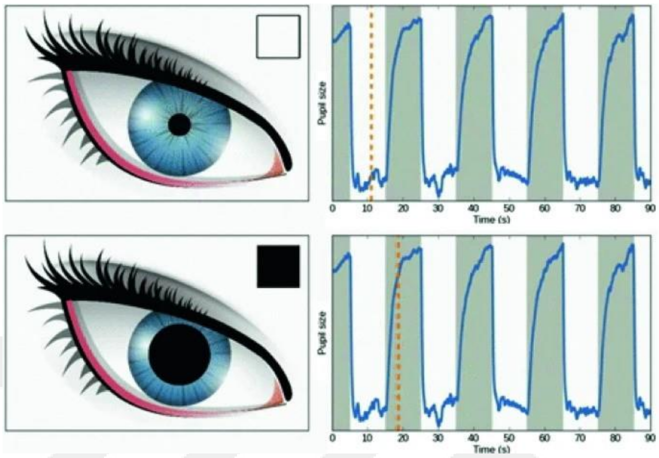
(Avery & Krichmar, 2017)

Figure 1.7: The roles of the cholinergic network. The cholinergic network has its starting point in the basal forebrain and projects several cortical and subcortical areas. Consequently, it has been linked to a number of cognitive processes, including uncertainty calculations, memory, and attention. Prefrontal cortices and other neuromodulatory brain areas are hypothesized to control the basal forebrain's activity.

1.3.3. Pupil Dilation and the Brain

To control the quantity of light reaching our eyes, the extent of our pupils continually adjusts in response to shifts in natural light levels. The pupillary light reflex

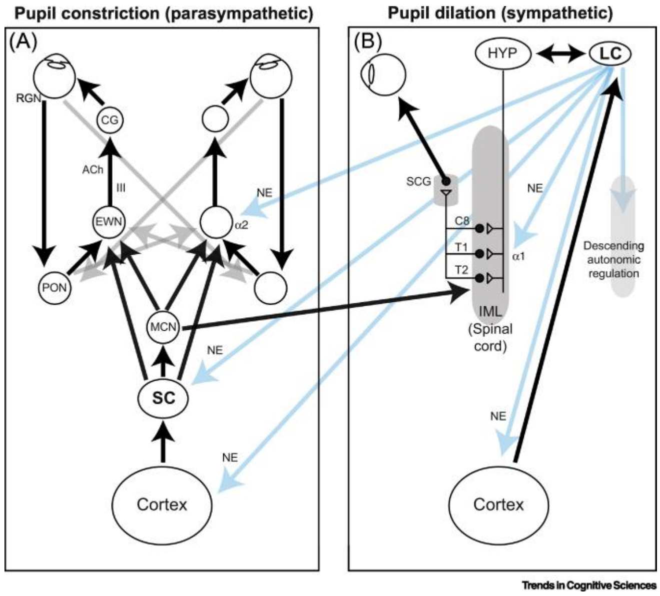
(PLR) is the name for this mechanism; however, it is not entirely responsive. As an alternative, working memory, attention, and other cognitive processes can all influence the PLR (Toates, 1972; Lowenstein & Loewenfeld, 1950). Referred to as "pupillary light reactivity" (PLR; Figure 1.8), an immediate contraction of the pupil, is triggered by abrupt spikes in lighting (for example, a flash of the camera).



(Laeng & Alnaes, 2019)

Figure 1.8: A and B are the pathways that regulate pupil dilation and constriction, respectively.

The regions of the brainstem and spinal cord include brain circuits controlling pupil dilatation and constriction. The pretectal olivary nucleus (PON)in the brain-stem, largely regulating pupil size, receives retinal inputs that encode variations in brightness and relay them straight into these circuits represented in Figure 1.9 (Joshi & Gold, 2020).



(Joshi & Gold, 2020)

Figure 1.9: Pupil dilation as a room's brightness is changed from being completely black to being highly lit (top vs. bottom). The curve in blue shows the equivalent size of the pupil at every moment, and the dotted line designates a certain point in time when the room is either dark or lit up.

In Figure 1.9, at the base of the brainstem, hemisphere-crossing linkages are shown by gray arrows. The brainstem and cortex are shown with blue arrows to receive locus coeruleus (LC) information. Segments of the intermediolateral cell column (spinal cord) are referred to as C8, T1, and T2. Descriptions of the abridgment transmitters are as follows: ACh, acetylcholine; CG, ciliary ganglion; HYP, hypothalamus; III, third cranial nerve; IML, intermediolateral cell column; NE, norepinephrine; PON, pretectal olivary nucleus (midbrain); RGN, retinal ganglion neuron; SCG, superior cervical sympathetic ganglion (Joshi & Gold, 2020).

It is clear that pupils reveal more beyond merely brightness. By monitoring variations in the pupil's size in response to different forms of stimulation, a technique known as pupillometry is used to analyze pupillary reactions. The examination and measurement of pupil size as well as the way it responds to cognitive and environmental stimuli. A further top-down association between pupil responses and a number of, occasionally extremely complicated, mental functions has been found via pupillometry (Sirois & Brisson, 2014). *Top-down processing* may be described as the ”down” transmission of higher-level data received from the brain to the body.

It is possible to think of top-down processing as the ”down” transmission of higher-level information from the brain to the body. Thus, it can be asserted that changes in pupil size are directly correlated with changes in perception, emotional reactions, and cognitive load which is the quantity of mental effort expended during the cognitive process.

Scientists have recently discovered that pupils react to stimuli suggesting changes in lighting conditions, even if there is no actual change in brightness (Torres & Hout, 2019). Put simply, pupils can get smaller when exposed to stimuli that typically imply bright lighting, regardless of the actual brightness. For example, participants viewed equally bright images of the sun and the moon, as well as scrambled images with no identifiable form. The scrambled images were intentionally devoid of meaning, allowing any pupillary response to be solely attributed to brightness. The findings revealed that pupils shrink in response to the sun images associated with brightness, but not to the moon images or the meaningless images, despite their equal brightness. Similarly, based on Mathot et al. (2017)’s study, when participants encountered words conveying the concept of light or darkness, their pupils contracted for light-related words and dilated for darkness-related words. This indicates that pupils can respond not only to external stimuli but also to internal processes originating from the brain.

1.3.4. Pupil Dilation and Cognition

Engaging in unfamiliar tasks or those requiring higher mental effort entails increased cognitive load, necessitating greater mental exertion or ”harder thinking.” This heightened cognitive load is associated with augmented pupillary dilation, which serves as an indicator of the increased effort invested in the task. Sustained pupillary dilation indicates continued attention and cognitive processing in response to prolonged cognitive load. The frontal lobe of the brain, located behind the forehead, is believed to be involved in sustained attention and exhibits greater activation during periods of heightened cognitive load. Such patterns of increased pupillary dilation are observed when individuals tackle challenging tasks, such as solving complex math problems, memorizing extensive information, or performing backward counting by sevens (Steinhauer et al., 2004; Sirois & Brisson, 2014).

Pupillary dilation, serving as a marker for increased cognitive load, has also been investigated in memory studies. These studies demonstrate that cognitive load escalates during the processes of memorization, recall, and recognition, with higher difficulty levels leading to greater cognitive load. For example, research by Papesh et al. (2012), revealed a significant increase in cognitive load when participants were tasked with memorizing and recalling fictitious words (e.g., ”garp”) compared to real words. Interestingly, pupil dilation aligned with memory performance, indicating that stronger memories were associated with more pronounced pupil dilation.

Beatty and Kahneman (1966) found major pupillary changes for the task addressed to both short-term and long-term memory (Beatty & Kahneman, 1966). These findings extend to children’s utilization of short-term memory, which is employed when remembering information for a brief duration. For example, in a study by Johnson et al. (2014), participants were required to memorize long sequences of numbers and immediately recite them. Monitoring participants’ pupils allowed researchers to identify periods of increased and sustained dilation, indicating active memorization. After memorizing six numbers, children’s pupils typically began to constrict, while adults’ pupils remained dilated. This suggests that children reach their memory capacity threshold at six numbers, leading to discontinued memorization, whereas adults do not. Hence, pupillometry confirmed that children possess a smaller short-term memory capacity compared to adults.

Moreover, in the study on memory for prior remembering, Aftab (2023) found that pupils were significantly greater when participants remember the words incorrectly, as opposed to correctly remembered words (Aftab, 2023).

In contrast to pupillary responses during perception and emotion, both pupil dilation and constriction occur during cognitive load (Torres & Hout, 2019). Pupils dilate during information processing and encoding due to the demanding nature of these cognitive tasks. Subsequently, pupils often constrict upon reporting the information, signifying reduced cognitive load once successful memorization has taken place. Finally, pupil size returns to an intermediate level once mental processing is done (Steinhauer et al., 2004). Thus, monitoring pupillary changes is a valuable tool for tracking variations in cognitive effort, ranging from the initial processing of information to the subsequent reporting stage.

1.3.5. Pupil Dilation and Emotion

Higher-level cognitive and emotional brain structures have been found to exert an influence on pupillary activity. These regions of the brain associated with emotions and cognitive processes are capable of inducing changes in pupil size. Environmental stimuli that evoke emotional responses can lead to pupillary dilation. For example, Partala and Surakka (2003) conducted a study where participants were exposed to a series of sounds, and their pupillary responses were monitored. Subsequently, participants rated the sounds based on their emotional valence, categorizing them as positive, negative, or neutral. It was observed that sounds rated as positive (such as the laughter of a baby) or negative (such as the crying of a baby or a couple arguing) elicited an increase in pupil dilation, in contrast to neutral sounds (such as background office noises) which had minimal impact on pupil size (Torres & Hout, 2019).

In another study, it was looked into how lyrical language affects human pupillary dilatation. The results demonstrated that reading comic poetry (CP) caused early and considerable pupil dilation, which indicated a rapid and powerful arousal in reaction to hilarious lines. Larger pupil dilations were similarly elicited by aesthetic poetry (AP), albeit with a somewhat longer delay, suggesting significant but gradual shifts in arousal owing to the more subtly emotive and implicit impacts of aesthetic characteristics (Niikuni, Wang, Makuuchi, Koizumi, & Kiyama, 2022). As a result, tasks with high emotional load lead pupils to enlarge.

1.3.6. Pupil Dilation and Sustained Attention

Sustaining attention is a process that can be impacted by the demand of the task. Prevailing theories propose that performance decline in such tasks can be assigned to either excessive task demands that deplete cognitive resources (Grier et al., 2003) or insufficient task stimulation leading to decreased arousal (Manly, Robertson, Galloway, & Hawkins, 1999). Hence, these theories underlie the effect of external task factors on sustained attention.

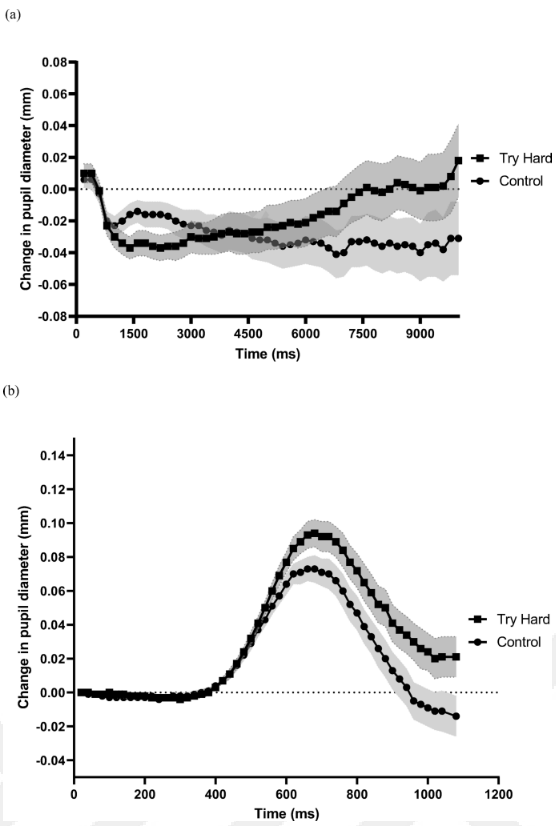
Based on resource theories, maintaining optimal performance requires a limited amount of cognitive resources that decline over time. When individuals need to stay alert for enhanced timelines, attentional failures occur due to the depletion of these cognitive resources. On the contrary, underload models suggest that in repetitive sustained attention tasks, unrelated thoughts can intrude and hinder the detection of critical signals (Warm, Parasuraman, & Matthews, 2008; Manly et al., 1999).

Levels of desire, arousal, and alertness have a significant impact on sustained attention (Samuels & Szabadi, 2008). Extreme changes in these levels cause interruptions in attention, which cause the person to lose focus on the activity at hand. Failures to pay attention can occur due to mind-wandering (thoughts irrelevant to the task at hand or daydreaming), mind-blanking (periods of zoning out or lack of thought), or exterior distraction (having one's focus diverted from the task by external sources, such as starvation or loud noises in the surroundings) (Unsworth & Robison, 2016). Thereby, the internal process shows an influence on an attention-required task.

There are plenty of sustained attention studies that are associated with pupil dilation. Evaluating the internal process, Massar et al. (2016) found that offering higher rewards resulted in better performance and greater allocation of attentional effort, as evidenced by changes in pupil diameter. Furthermore, in the experiment, participants assigned less value to rewards that necessitated maintaining vigilance for extended periods. These findings prove that motivation can enhance sustained attention by promoting increased effort, while individuals take into account the perceived costs associated with maintaining performance when evaluating the value of rewards.

With respect to beliefs about how the locus coeruleus norepinephrine (LC-NE) system works, Unsworth et al. (2016) looked into whether pupillary responses, including baseline and phasic responses, might efficiently identify attention gaps. During the experiment, both on-task and off-task conditions were used. It was found that pupillary responses accurately distinguished between on-task and off-task states. Notably, the pretrial baseline pupil responses were able to differentiate various types of attention lapses. Besides, mind-wandering and inattentive states were associated with smaller pretrial baseline pupil size on average, whereas distracted states were linked with greater pretrial baseline pupil size on average than the focused states. Thereby, these findings support that pupil size is sensitive to different types of attention lapses (Unsworth & Robison, 2016).

Considering the study by Unsworth et al. (2022), it was analyzed that the influence of effort on sustained attention and attention lapses. In his study, participants were either in an effort or a control condition. In the effort condition, participants were instructed to ”Try Hard” during specific trials, whereas the control condition had no specific instructions. Although there was no behavioral difference between the two conditions, larger pupil sizes were examined in the ”Try Hard” condition (Figure 1.10). Comparing the effort and control conditions, participants in the effort condition performed faster and had fewer very long reaction times (Unsworth, Miller, & Aghel, 2022; Aghel, 2020).



(Unsworth et al., 2022)

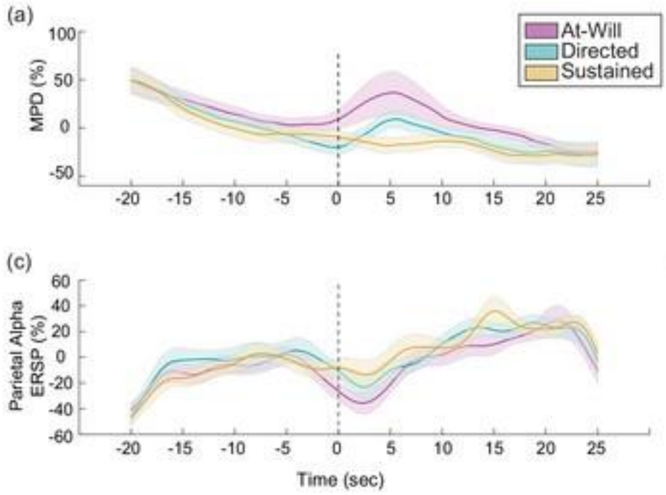
Figure 1.10: a) Pupil size change during the conditions. b) Pupil size change after stimulus onset and the conditions. Shaded regions represent one standard error of the mean

Moreover, selective attention also takes part depending on the level of perceptual load in the task. As a task involves a high perceptual load, for instance, more stimuli, or increased demand on perception, it allows for greater attentional engagement. In regard to this, it is expected that selective attention can be seen greater in individuals with ADHD and typically developing children, who are typically more susceptible to distraction compared to healthy adults (Hobbiss & Lavie, 2023).

Numerous studies have indicated that individuals can effectively concentrate their attention on a task when engaged with a high perceptual load (Lavie, Hirst, De Fockert, & Viding, 2004; Lavie & Cox, 1997). This phenomenon has been observed among various research findings and has been found to enlarge focused attention even in individuals with ADHD and during childhood (Forster, Robertson, Jennings, Asherson, & Lavie, 2014; Huang-Pollock, Carr, & Nigg, 2002). It can be interpreted that high perceptual load tasks require more concentration and attention even for the population who have focusing problems. Hence, pupil enlargement in high perceptual load tasks should be an indicator of increased sustained attention as well.

Unsworth et al. (2018) investigated how fluctuations and lapses of sustained attention can be identified through pupillary responses. In their study, participants engaged in a sustained attention task with either a fixed interstimulus interval (ISI) or varied stimulus, while pupil size was measured throughout the experiment. The results revealed that performance was poorer when the ISI was varied or fixed at a longer duration (8 seconds) compared to a shorter duration (2 seconds). Thus, this suggests that tasks with varied or longer ISIs require higher levels of intrinsic alertness compared to tasks with constant short ISIs. Regarding pupillary responses, slower responses (indicating lapses of attention) were linked with greater distinctiveness in the baseline pupil diameter, smaller dilation responses during the ISI, and relatedly smaller dilation responses to the onset of stimuli. His findings demonstrate that lapses of attention are associated with reduced intrinsic alertness, resulting in a diminished level of attention to task-relevant stimuli. Yet, after a lapse of attention, performance, baseline pupil diameter, and pupillary responses all rose, revealing that attention was reoriented back to the task. As a result, Unsworth et al. (2018) and his colleagues showed the idea that pupil dilation can reflect fluctuations in sustained attention.

When sustained attention was also examined in the auditory task, Haro et al. (2022) found that pupil sizes were again greater in the effortful, which was the endogenous attention switch condition than the sustained attention. Thus attention switching was associated with an effortful task that leads pupils to increase as is seen in Figure 1.11.



(Haro, Rao, Quatieri, & Smalt, 2022)

Figure 1.11: Parietal alpha event-related spectral perturbation (ERSP) and mean pupil diameter (MPD) are presented. (a) shows the grand-mean MPD across time. (c) shows the grand-mean parietal alpha ERSP across time.

These findings show that while pupillary response reveals a higher cognitive level of performance on attentional tasks, internal processes have an influence on the attentional process.

1.3.7. Pupil Dilation and Continuous Performance

Recent studies have begun to investigate whether people may intentionally increase their effort levels and how this affects performance. Previous research has demonstrated that attentional lapses are associated with alterations in the tonic and phasic activity of the LC-NE system and that people often perform worse and have smaller pupillary responses during these lapses. Researchers have started looking at people's abilities to consciously increase their effort levels in order to see whether these mistakes may be avoided.

According to preliminary research, when participants were told to exert more effort, they were able to accomplish the job better. It indicates that people have a pool of energy that may be called upon when necessary. These studies, however, have mostly concentrated on the effect of instructions to try harder on performance, without carefully exploring the underlying processes of this improvement or its connection with variations in pupil dilation.(Steinborn, Langner, & Huestegge, 2017; Aghel, 2020).

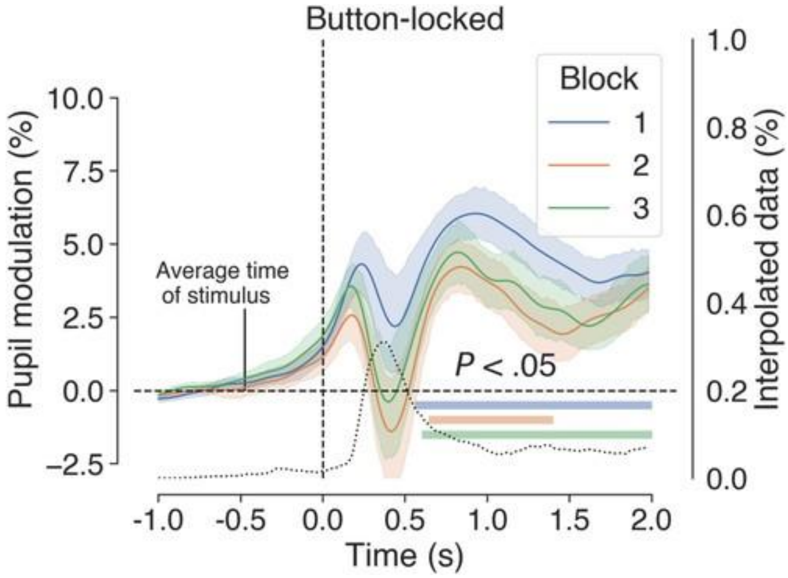
The study set out to investigate if performance is improved when participants are told to exert more effort and whether such gains are connected to changes in pupil dilation in order to shed light on these elements. In order to determine the extent to which effort levels may be raised while completing a task, Steinborn et al. (2017) carried out the research. Prior to certain trials, participants were occasionally prompted to put forth harder while still being encouraged to reply promptly and accurately. The results showed that explicit directions to exert more effort increased processing speed, but did not significantly affect the mistake rate. This demonstrates that people may increase the amount of effort they devote to an activity, especially when specifically told to do so.

A related idea was investigated in a different research by Kleinsorge et al. (2001) by determining if higher effort mobilization led to a trade-off in mistake rate. The purpose of the study was to determine if participants were responding more quickly because they were working harder or whether they were just trying to react more quickly, accurately, or no. The duration of the pre-cuing interval (PCI), which is the period between the instruction to speed up reaction time and the task presentation, was also investigated by the researchers to see how it affected response time. According to the findings of the two tests, participants were able to raise their effort levels in accordance with instructions, and the degree of that increase was influenced by how long the PCI was. Additionally, faster replies were often the result of faster instructions, especially for shorter PCIs.

Additionally, ”Vigilance” is a word that may be used to describe sustaining performance. The ability of a person to pay attention continuously for a lengthy period of time is referred to as vigilance. It is possible to trace a long line of systematic studies on alertness and continuous work activities to Mackworth (1948) (Mackworth, 1948; Mackworth et al., 1950). These studies illustrated the vigilance decrement, showing that human detection ability declines with task duration. According to a systematic review by Mackie et al. (1987), there are several factors that might contribute to failures to pay attentive attention that are related to the activity, the person, and the environment. The signal detection theory (Swets, Green, Getty, & Swets, 1978), which considers metrics like hits, misses, false alarms, and accurate rejections, has been used to assess a number of vigilance investigations. Detection delay and biometric technologies like EEG and fMRI have also contributed to our understanding of the neurophysiological principles underpinning continuous attention (Fortenbaugh, DeGutis, & Esterman, 2017).

Cognitive pupillometry, which measures the size and reactivity of the pupils following exposure to relevant stimuli(Joshi & Gold, 2020), is a valuable technique for exploring continuous monitoring. Variations in pupil size provide information about the central arousal systems of the brain, particularly the locus coeruleus noradrenergic system, regardless of changes in lighting. According to Berridge et al. (2012), this system is crucial for controlling arousal, upholding healthy attention levels, and improving performance (Berridge, Schmeichel, & España, 2012).

When doing visual vigilance tasks, Martin,et al. (2022) investigated the connection between pupil size and behavioral performance. The researchers discovered that despite real-world vigilance tasks being mostly visual, the majority of earlier research in this field concentrated on aural challenges. They thus performed two visual vigilance tests to investigate the relationship between performance and pupil size, both at baseline and in response to tasks. The trends in the pupil data were inconsistent with the hypothesis that lower performance would be represented in smaller pupils at baseline. As opposed, they were consistent with the general hypothesis that pupil size would decrease as time on task increased (Figure 1.12).



(Martin, Whittaker, & Johnston, 2022)

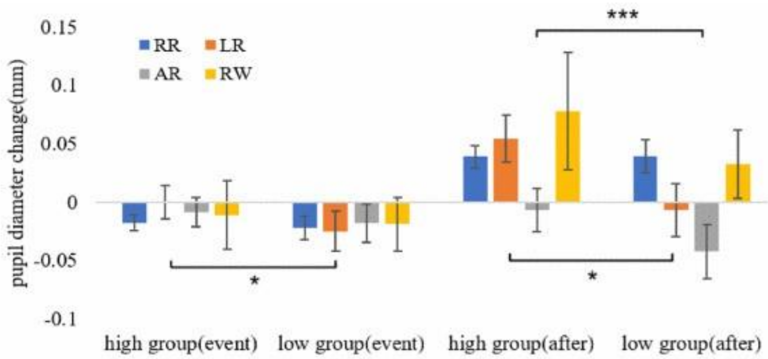
Figure 1.12: Pupil dilation after participants completed 3 sequenced blocks in a single test session. For every block, the mean button-locked pupil tracks. The proportion of interpolated data is shown on the black-dotted track, demonstrating task-correlated blinking. The standard error of the mean (SEM) for the colored tracks is displayed in shaded regions around them. Additionally, colored horizontal bars indicate clusters with significant modulation above baseline, as determined by non-parametric permutation tests (1,024 permutations, p .05, cluster adjusted across various testing).

While the second task of Martin, et al. (2022) was a psychomotor vigilance task, the first task required continuous and uninterrupted execution over a lengthy period of time. Their findings, which are consistent with the body of literature on the vigilance decrement, show that participants' behavioral performance decreased as they spent more time on the tasks.

Moreover, they examined the relationship between pupil size and behavioral performance in visual vigilance tasks. The researchers realized that most previous research in this domain focused on auditory tasks, despite real-world vigilance tasks being predominantly visual. Therefore, they conducted two visual vigilance tasks to explore how pupil size, both at baseline and in response to tasks, relates to performance. Remarkably they also saw a drop in the reactions that the assignment elicited from the students' performance (Martin et al., 2022).

Meanwhile, Qiao et al. (2022) developed a virtual reality (VR) game with two tasks: target-tracking and color-discrimination, in order to research how individuals perform in multitasking training games while monitoring players' pupil change as an indicator of their mental exhaustion.

By comparing the average change in pupil diameter between several groups, they discovered some surprising patterns. The high-performing group's pupils dilated after the event, demonstrating that they were actively engaged in the psychological processing of the color discrimination task at the time. For a portion of the post-event stage, the low-performing group, on the other hand, exhibited no pupil dilation, suggesting a probable disdain for how the Color-discrimination test appeared. This behavior is concerning since it demonstrates a lack of concentration and might negatively impact training outcomes. As a result, the study found that when different groups are subjected to the multitasking paradigm, the variations in the mean pupil diameter properly reflect their actual behavior (Qiao, Tahara, Nakphu, & Iramina, 2022). However, as in Figure 1.13, they did not find significant differences between groups.



(Qiao et al., 2022)

Figure 1.13: Mean pupil size change in the high and low group throughout various times of various events. The high group (event) refers to the mean pupil size change during the high group's event time. The high group(after) refers to the mean pupil size change between the event's conclusion and 1600 msec.

In the Redondo et al. (2020)'s study, they conducted an experiment on children who have attention deficit hyperactivity disorder (ADHD) to asses their relationship with behavioral performance. Their aim was to observe ocular accommodation (ability to adjust focus) and pupil size dynamics in both groups during the continuous performance task. Having looked at the results, compared to the control group, children with ADHD showed reduced accommodative behavior (increased lags of accommodation). Thanks to Redondo et al. (2020), it was found that the dynamics of ocular accommodation and pupil size have a role in potential predictors of behavioral performance (Redondo et al., 2020).

As a result, recent studies have demonstrated that people may improve their performance by actively exerting more effort. The relevance of pupil dynamics as a measure of cognitive processes and possible task performance predictors are highlighted by such results, which overall advance our knowledge of the link between effort, attention, and performance.

1.4. Pupil Dilation in Time Perception

As it was investigated so far, pupillometry is an adequate method to assess behavioral responses. It was mostly used to create concrete outputs of cognitive and internal processes like attention, perception, memory, learning, and so on. Based on the recent literature, such experiments related to task difficulty, performed effort, cognitive load, sustained attention, and maintained performance were used to describe and discriminate these internal processes. However, when it comes to time perception, there is no solid and single certain strategy or description to make a generalization which creates a gap in ”time perception” literature. Besides, the sense of time is a domain that is quite open to get manipulated by varied factors.

Age, gender, familiarity, anxiety, fearfulness, psychopathology, mood, memory, task difficulty, cognitive load, and attentional demands have been noted as variables that may affect assessments of event duration (Block, Hancock, & Zakay, 2010; Droit-Volet, Meck, & Penney, 2007; Lake, 2016; Lustig & Meck, 2011; Allingham et al., 2021). The characteristics of the stimuli themselves can have an impact on how long events seem to last, causing either time compression or time expansion. The apparent duration of events appears to be compressed by non-salient, well-known, and high-probability material when compared to a baseline. On the other side, the sense of duration can be lengthened by greater stimulus complexity, amplitude, quicker tempos, and higher repeat rates (Allingham et al., 2021; Droit-Volet et al., 2013; Jones & Boltz, 1989; Matthews, 2015; Tse et al., 2004; Van Wassenhove, Buonomano, Shimojo, & Shams, 2008).

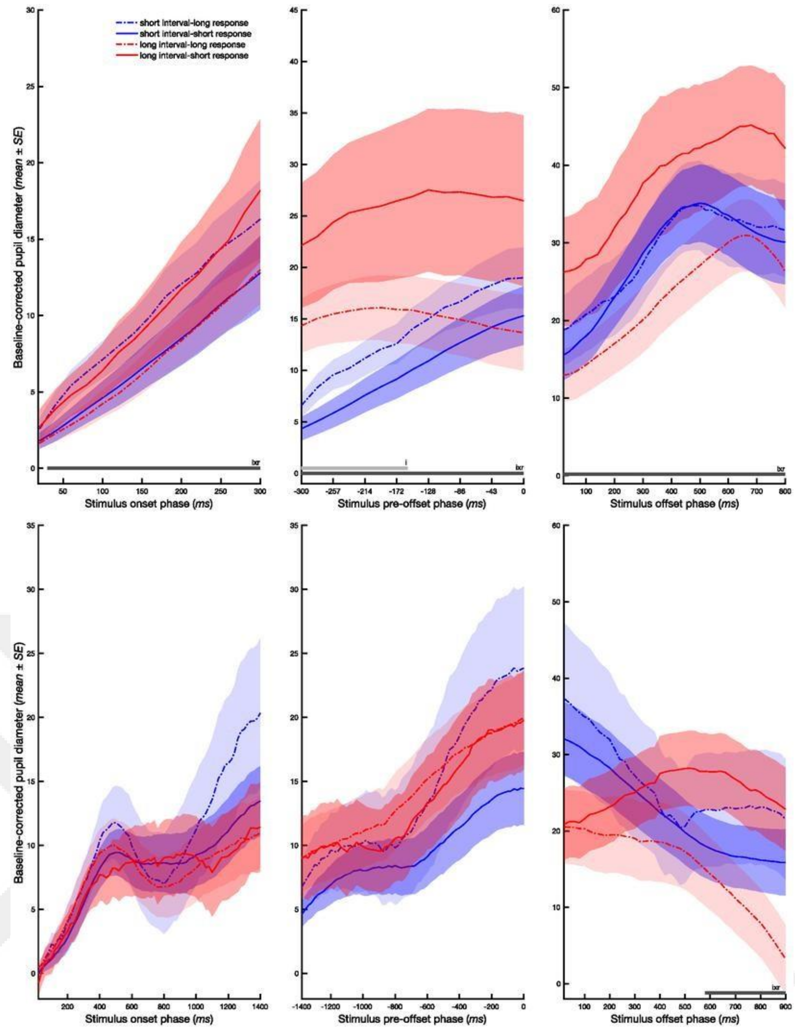
The ability to perceive time accurately over a range of time scales is essential for behavior and learning (Mauk & Ruiz, 1992). While an external clock keeps time at a constant rate, our perception of time can be distorted by a variety of circumstances, including concentration and arousal (Mattes & Ulrich, 1998; Penton-Voak et al., 1996). A possible biomarker for assessing human attention and arousal levels is pupil size (Mathot, Van der Linden, Grainger, & Vitu, 2013). It acts as a marker of cognitive processes, which include activities like decision-making and visual processing. The idea that variations in the size of pupils reflect cognitive performance across a wide variety of functions is supported by the convergence of research findings.

Potentially influencing neural activity relevant to time monitoring are pupil-linked brain states, which are largely linked to the locus coeruleus-norepinephrine (LC-NE) system yet additionally involve other neurotransmitter systems (Joshi, Li, Kalwani, & Gold, 2016; Reimer et al., 2016; de Gee et al., 2017; Suzuki & Tanaka, 2017). Previous studies have shown a relationship between pupil size and perceived duration, showing a negative link between pupil size and the delay of self-timed saccades in monkeys (Suzuki, Kunimatsu, & Tanaka, 2016). It’s still not apparent, though, if these results apply to human tasks that require manual time evaluations.

The attentional processes behind subsecond timing were investigated in pupillometry research by Toscano-Zapién et al. (2016). Intriguingly, they discovered that participants’ pupils became bigger when they misjudged the length of stimulus intervals, in spite of if they thought they were shorter or longer compared to what actually were. The relationship between pupil size and the processing of temporal information has also been supported by research on temporal expectations. Studies have specifically demonstrated that pupil size may track temporal regularities, demonstrating various levels of preparation depending on the conditions of the anticipated delay. The pupil widens more rapidly, for instance, when targets are expected to emerge after a shorter delay period than after a longer one (Akdoğan, Balcı, & van Rijn, 2016). Additionally, it has been suggested that pupil dilation is a useful indicator of newborns' capacity for interval timing. These results emphasize the connection between pupil size and numerous elements of processing temporal information (Addyman, Rocha, & Mareschal, 2014).

Nuthmann et al. (2005) employed a relatedness assessment test to examine how people cognitively perceive the direction of time in commonplace situations. The findings demonstrated that participants processed the elements in chronological order as opposed to reverse order. This implies that everyday experiences have a mental encoding of the direction of time. In addition to observing variations in pupil dilation, the researchers found evidence of top-down impacts during the processing of temporally relevant information (Nuthmann & Van Der Meer, 2005).

The association between pupil size and perceived duration was examined using two temporal bisection tasks (Warda, Simola, & Terhune, 2022). When shorter intervals were overestimated in the subsecond task, pupil size rose, and when longer intervals were underestimated, it stayed bigger both during and after stimulus offset. As longer intervals were underestimated in the supra-second task, a bigger pupil diameter was seen in the late stimulus offset period prior to reaction prompts (Figure 1.14). These results indicate a relationship between pupil size and error monitoring in interval timing, demonstrating disparities between perceived and actual lengths of time.



(Warda et al., 2022)

Figure 1.14: The relationship between pupil size and temporal judgments. Baseline corrected pupil diameter as a result of stimulus interval (short vs. long) and reaction (short vs. long) during stimulus onset, stimulus pre-offset, and stimulus offset phases of subsecond (top row) and supra second (bottom row) temporal bisection tasks. 0 represents the stimulus onset (left), offset (center), and offset (right) in each of the three stages. Significant interval effects (light gray) and interval-response interactions (dark gray) are shown by horizontal bars. The stan- dard error is sometimes referred to as standard error.

1.5. Present Study

The subjective way we feel and understand the length, order, and rhythm of events in our environment is referred to as time perception. It involves combining data from several senses and using higher-order cognitive processes including decision-making, memory, and attention. It is well established that particular demands, such as those involving attention, working memory, decision-making, and difficult perceptual or memory tasks, cause pupil size to rise. Two categories of task demands have been identified by prior research, Farooqui and Manly (2018).

Type I demands involve higher attention, working memory, and complex decision-making and are tied to the current task. These demands cause dilated pupils and engage fronto-parietal areas involved in cognitive regulation (Figure 1.15), (Farooqui & Manly, 2018).

The lengthier and more complex cognitive experiences that are processed as a single component, on the contrary, are connected to Type II demands. These requirements result from tasks that must be ordered and regulated holistically across long periods of time in cognition. Farooqui and Manly hypothesized that Type II demands have the opposite psychophysiological impact from Type I demands in that they deactivate the fronto-parietal areas linked to cognitive regulation. The objective of the current investigation was to test this theory.

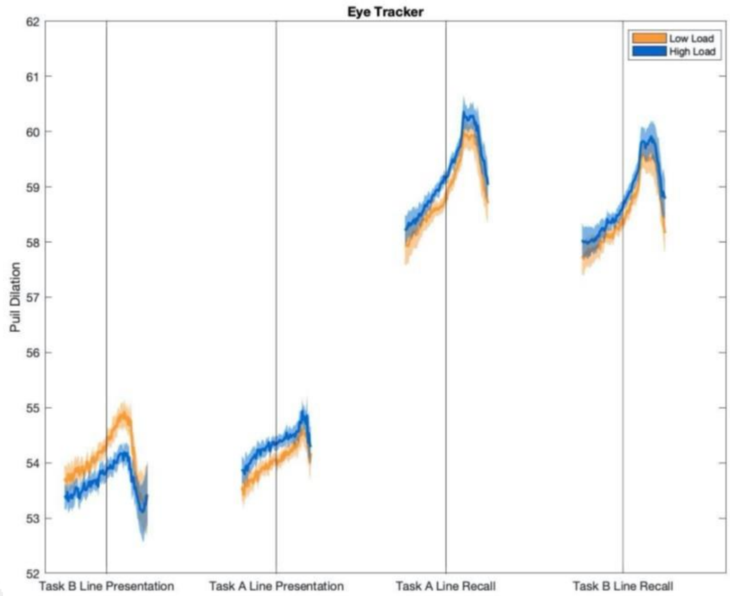


Figure 1.15: Pupil size change in different kinds of loads. While the Y-axis indicates pupil dilation in arbitrary units, the X-axis demonstrates different subtasks.

In this work, we used a new kind of task, especially a time-interval replication task, to evaluate these ideas.

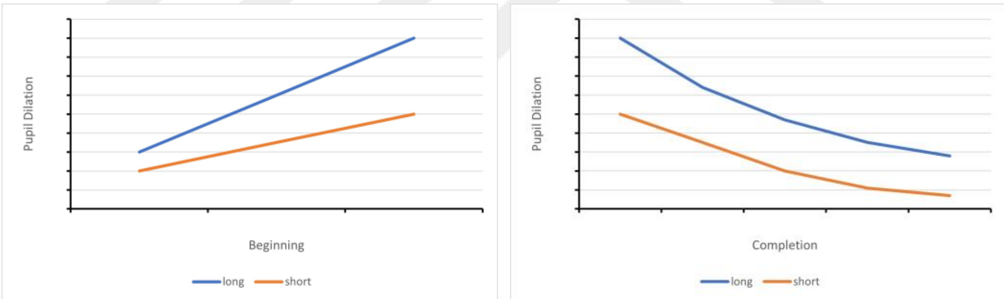
Besides, considering recent studies, time itself was not treated as a task. Therefore, in order to make a comparison in perception, we have given ”time” itself as a task in the present study. Regardless of the cognitive mechanism used by the participants in the specified time intervals (this could be an internal task they performed), we behaviorally examined how much change they experienced when perceiving *long* and *short* time intervals, and whether there was a noticeable difference between *real-time* and *perceived time*.

In our study, we examined the participants while they were engaging in an internal task in which their pupil diameter was measured. Along with receiving feedback after each trial, their predictions on *long* and *short* time intervals were compared while pupil dilation was examined via an eye-tracker.

In recent studies, it was suggested that people are struggling more when they have to perform difficult tasks which may require extended cognitive effort, working load, or sustained attention. Therefore, in terms of behavioral performance, making predictions on longer time intervals may lead to generating larger cognitive effort.

In this study, participants performed a task that was requested to replicate various time intervals by clicking a button at the beginning and end of each interval. We used both short (8–12 seconds) and long (14–18 seconds) intervals since we hypothesized that longer intervals would be more demanding and might result in more errors.

We measured whether pupil size would change when longer replication times were compared to shorter repetition times. Pupil size should be higher throughout the repetition of longer durations if the common idea that pupil size grows with any form of task load is correct, see Figure 1.16.



(a) Pupil size change at the beginning of the task

(b) Pupil size change at the completion of the task

Figure 1.16: Estimated Pupil Dilation at the Beginning and Completion of the Task in the Short and Long Time Intervals

However, if the psychophysiological response to Type II demands, requiring the structuring of longer cognitive episodes, is really the reverse of Type I demands, then pupil size may be lower for longer periods. Indeed, we found the results in favor of this theory, showing that the task demands associated with structuring longer cognitive episodes differ from the widely accepted demands for enhanced attention and working memory.

CHAPTER 2

METHODS

2.1. Participants

The experiment was conducted at National Magnetic Resonance Research Center (UMRAM), Aysel Sabuncu Brain Research Center, to 12 male and 22 female young adults who were aged between 18 to 27 (M= 23.49 SD= 4.16), and studying at Bilkent University, Turkey. 50 TL was paid to every participant and participation credits were assigned to students studying at Bilkent University. The participants signed consent forms and payment forms and the glasses were removed. Its screen size was increased to a certain font size when it was needed. The light in the room and the computer screen were all the same for the whole subject. 4 participants' data could not be used in the analysis since their pupils could not be detected by the eye tracker clearly.

2.2. Assessments

Since any kind of substance and psychiatric medication deviate from the pupil size change, participants' demographic is obtained and ones who are under the influence of any substance were discarded from the study. Participants having vision-related health problems were also eliminated. In order to calibrate the eye tracker, participants' less dominated eye (21 right eyes dominated, 8 left eyes dominated and 1 both eyes equally dominated) was detected before starting the experiment.

2.3. Eye Tracker

ASL Eye-Trac 6, manual version 3.03, was used at the Bilkent University National Magnetic Resonance Research Center (UMRAM), Ankara, Turkey to measure participants' pupil dilation change throughout the specified time intervals. The measurement was captured digitally on the Eye Tracker Interface PC as a crosshair or mouse overlaid on a video picture of the setting being seen by the subject. *Chin rest* was set as 57 cm away from the computer screen.

The D6 Desk Mounted Optics illuminates the pupil by employing a bright pupil approach and offers reliable gaze tracking for indoor use.*The Eye Tracker Optics* part includes the eye illuminator, eye camera, and a tracking mirror. In order to follow the movements of the subject's head/eye, these contents automatically move the illuminator and the camera.*The D6 Desk Mounted Eye Tracker* may monitor the eye from twenty to thirty inches away and is best used at a distance of 24 inches. About a 30-35 degree vertical and 40-45 degrees horizontal vision angle may be tracked by the eye tracker. The frequency of the eye camera output was 50 Hz (CCIR), (Figure 2.1,b).

Furthermore, this manual version of the tracker consists of *ASL Control Unit*(CU). With this unit, the entire system processing comprising gaze computation was carried out. It has been fitted with scene and eye detectors to give the operator real-time feedback.

Two *LCD* video screens installed atop *the EYE-TRAC 6 Control Unit* are part of the typical setup. One was used to show the eye picture captured by the D6 optics module's telephoto eye camera, while the other was used to enter scene imagery for projection. A broad-angle locating camera in the D6 optics module may also display its picture on the scene monitor. The picture captured by the eye camera was shown on the eye monitor. In the event the eye tracker was working adequately, a black outline is overlaid on the picture which is the corneal reflection (CR), and an outline of white was placed above the image which is the pupil. The display of the monitors was 1600 x 1200 resolution (Figure 2.1, a).

In Figure 2.2, you can see how the participant doing the experiment by putting the head in the chin rest and following the task in the monitor.

(a) Eye-tracker Setting *(b)* Chin Rest, D6-DMET *(c)* LCD, ASL

Figure 2.1: Experiment Room

Figure 2.2: Participant

2.4. Cognitive Paradigm and Procedure

The experiment consisted of 1 practice and 4 main sessions including baseline measurement at the beginning and end of the experiment, short-long time intervals, and rest phases. Whereas participants could only give small breaks between 4 sessions, they were not allowed to move during the rest phases. Each participant was exposed to 26 episodes which were designed as 13 long and 13 short time intervals; thus, the study was designed as within-subjects. While long time intervals lasted within 14 to 18 seconds, and short time intervals lasted within 8 to 12 seconds. There were 2.5 seconds between each short and long interval within a session. These intervals were counterbalanced.

Participants' pupil dilation was measured both in short and long time intervals via an eye tracker. Their pupil size changes were obtained during the study. The experiment was coded on Python, PsychoPy 2021.2.3, and conducted with the eye tracker to participants who had no defect of vision. All participants' time perception in pupils was measured in the same lighting conditions and they were set at a 57 cm distance from the computer screen. When participants' non-dominant eye was assessed, their pupils are calibrated on an eye tracker and followed throughout the experiment. There was no gender or age difference investigated in the study.

Participants were instructed not to move as possible and to focus on the center of the screen during the experiment. Participants first encountered a timer (baseline period) before starting the experiment. Their pupil size change was observed in 15 seconds baseline period. After it finished, they saw a screen written "rest". In this stage (rest beginning), participants could rest without leaving the eye tracker. After they pressed to "space" button, the task started and they saw one or two-digit numbers which were called "cue screens". The number represented the amount of the second. When they saw the number, they had to press the "space" button and focus on the fixation cross. Participants perform at this stage and it was named the "replication" screen.

The aim of the task was while participants were focusing on the fixation cross, they had to press the “space” button if they thought that the number of seconds they just saw on the cue screen passed. According to their estimate, at the “feedback screen”, they receive feedback showing how milliseconds late or early they guessed and pressed the button (Figure 2.3).

Feedback duration was coded as 0.5 seconds. This phase also shows how their timing of reply deviated from the exact target of timing. After participants completed all 26 episodes during each session, their pupil size change for 15 seconds, which was measured again at the baseline period, and end of the experiment. Participants did all the same processes 4 times, in other words, 4 sessions in total.

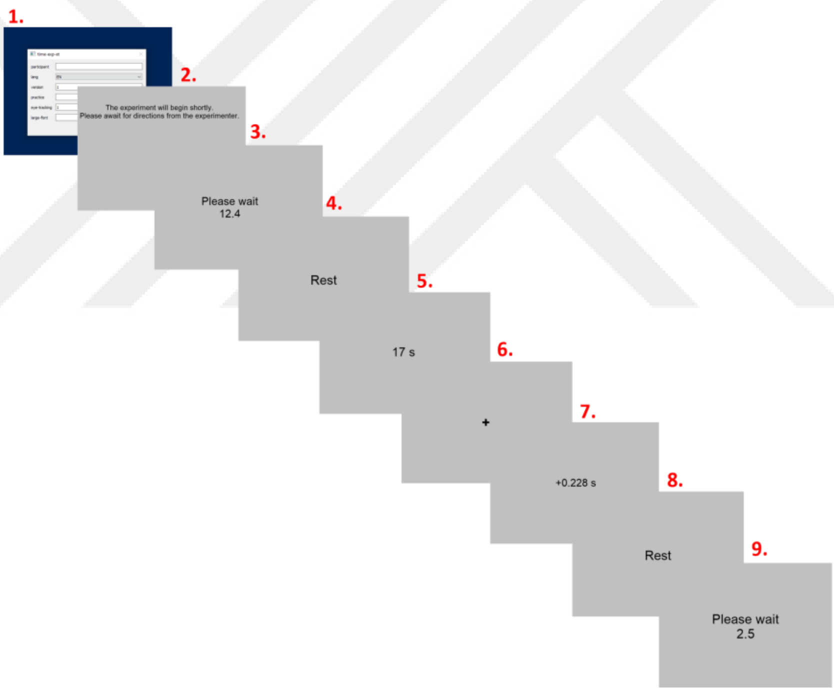


Figure 2.3: Experiment Stimuli: the red numbers represent the order of the experiment as follows: 1. is starting screen, 2. is the instruction screen, 3. is the beginning baseline screen, 4. and 8. are the rest screens, 5. is the cue screen, 6. is the replication screen, 7. is the feedback screen, and 9. is the end baseline screen.

2.5. Analysis

The analysis of behavioral and eye tracker data was preprocessed in Python Pandas Library and run in R-studio 2022.12.0 Build 353.

Preprocessing of pupil diameter included the smoothing of data with a window size of 5. In this algorithm, the value of each pupil diameter value is iteratively set to the average of the two data points back and the two data points forward from the current value. The other preprocessing steps included the removal of extreme values. Pupil diameter readings were four standard deviations above and below the mean, incorrect readings and suspected eyeblinks were set to NaN.

Replication Screen (Figure 2.3, 6): First and the last 400-time points were analyzed to assess the pupil size change at the beginning and end of each replication phase. The Two Way Mixed ANOVA was conducted into the mean values of each time point in the replication phase.

Feedback Screen (Figure 2.3, 7): The deviation data was assessed by the feedback screen participants encountered after their performance in the replication phase. Deviation indicates how much less or more the participant deviates from the target number they see on the cue screen while fulfilling the replication part. Thus, via Python, the mean deviation of all participants in each session was assessed in both short-long intervals. Paired t-test was conducted in the R-studio to asses the mean deviation difference of participants in the short and long time periods.

In order to understand whether participants' prediction on target timing at replication task is made on time, late, or earlier than the target timing they saw at the cue screen, the mean deviations of them are categorized as "accurate (Acc)", "high negative errors (Hne)" and "high positive errors (Hpe)".

Participants' pupil dilation was reached in Python at the first and the last 800 time points when their predictions deviated positively, negatively, or on time. One-Way

ANOVA and post hoc pairwise comparisons using Tukey’s method were conducted on R-studio to compare the deviation groups (Acc, Hne, and Hpe).

Cue Screen (Figure 2.3,5) : After participants completed the replication task and received their feedback, their pupil size changes were measured before they started to see the next cue screen. Thus, their mean pupil dilation in 125 time points (2,5 seconds) before the cue screen onset was assessed in Python. Repeated Measures of ANOVA and posthoc tests were conducted on R-studio to observe the pupil size difference both in long and short time intervals after participants completed the task and before starting the next one.

Data: The raw data was formatted and graphs of both analyses were created in Python, Jupyter Pandas Library. All the analyses were made on R-Studio. During these processes, participants’ mean pupil dilation was obtained considering the four sessions together on eye-tracker data. Behavioral data were used to calculate and categorize the mean deviations with the evaluations of four sessions.

CHAPTER 3

RESULTS

3.1. Less Accuracy in the *Long Time Intervals* When Participants Perform at the Replication Phase

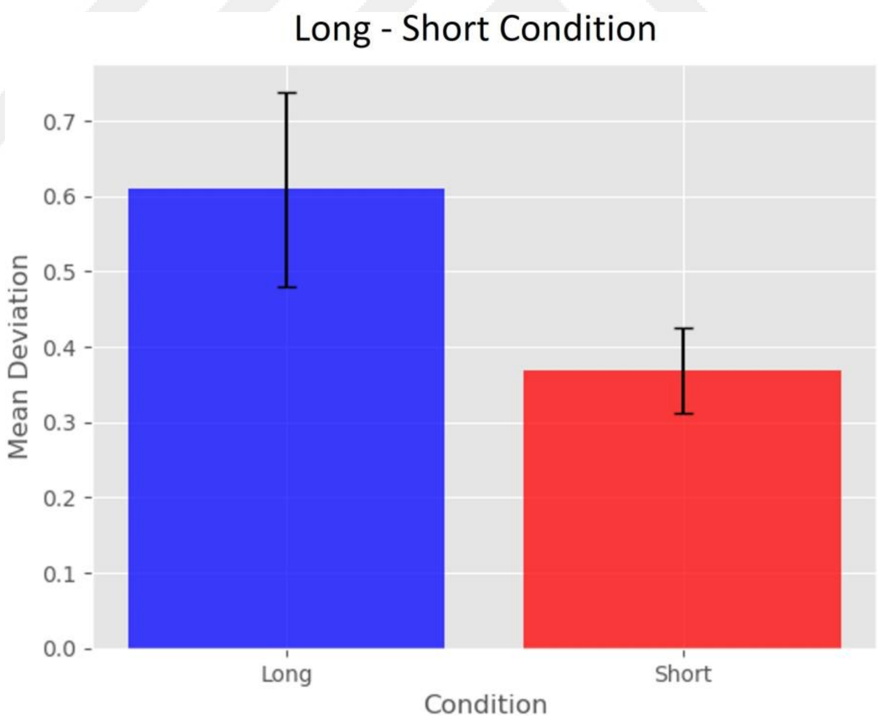


Figure 3.1: Mean Deviation from the Cue Target

The target time of the participants was measured in which time interval they were replicated more accurately. Therefore, standard deviations of their guesses on the target timing were calculated.

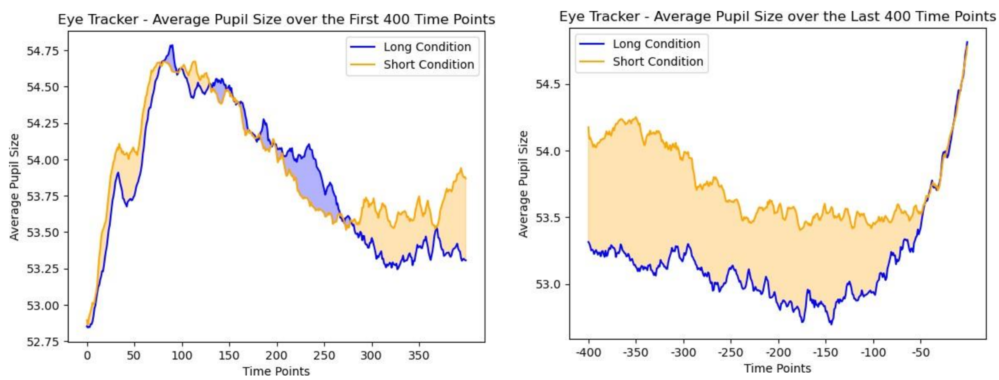
Relying on the results of the paired t-test in Table 3.1, whereas participants were replicating the target timing they saw at the cue screen, a statistically significant difference was found between the mean deviations in the long and short time interval conditions, $t(119) = 4.23$, $p < .001$, $d = 0.36$. The mean deviation was significantly greater in the long time interval condition ($M = 2.13$, $SD = 0.94$) as opposed to the short time interval condition ($M = 1.89$, $SD = 0.95$), Figure 3.1, with a mean difference of 0.24 seconds, 95% CI [0.13, 0.35].

Table 3.1: Paired t-test Results

Statistic	Value
t	4.2286
df	119
p-value	4.641e-05
Confidence Interval	(0.1278113, 0.3529248)
Mean Difference	0.240368

3.2. Pupil Dilation When Participants Perform at the Replication Phase

3.2.1. Larger Pupil Size in the First 8 Seconds (400 Time Points) of *Short Time Intervals*



(a) The filled region shows the pupil size range between the two conditions

(b) The filled region shows the pupil size range between the two conditions

Figure 3.2: Pupil size time-series (1-time point = 20 ms) for the first and last 8 seconds in the replication task.

In the analysis, the dependent variable was mean pupil dilation, and the independent variables were conditions (short and long time intervals) and time (400-time points).

In Table 3.2, the analysis represents participants' performance in the replication phase for the first 8 seconds (400-time points). An analysis of variance (ANOVA) and a two-way mixed ANOVA were conducted to observe the impacts of both short and long-time-interval conditions and time points on mean pupil dilation in participants.

The ANOVA found a significant main effect of short and long time interval conditions, $F(1, 23171) = 41.67$, $p < .001$, with a mean square of 53.55, showing that the mean pupil dilation varied significantly between the two-time intervals. There was also a significant main effect of time found, $F(399, 23171) = 9.16$, $p < .001$, with a mean square of 11.77, indicating that mean pupil dilation varied significantly across time as it is seen in Figure 3.2.

However, the interaction effect between conditions and time was not significant, $F(399, 23171) = 0.63$, $p = 1.00$, with a mean square of 0.80.

Thus, the results suggest that both short and long conditions and time have a significant effect on mean pupil dilation, but there was no significant interaction effect between them in the first 8 seconds of the replication phase.

Table 3.2: ANOVA Results

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Between	29	1797191	61972		
Within	23171	29773	1.28		
Conditions	1	54	53.55	41.674	1.1e-10 ***
Time	399	4696	11.77	9.160	< 2e-16 ***
Conditions:Time	399	321	0.80	0.626	1
Residuals	23171	29773	1.28		

Note. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$.

3.2.2. Larger Pupil Size in the Last 8 Seconds (400 Time Points) of *Short Time Intervals*

Table 3.3 the results of a two-way mixed-design ANOVA with the factors ”conditions” (short vs long time intervals) and ”time” (last 8 seconds, 800-time points) while participants were performing during the replication stage of the experiment.

The main effect of conditions was significant, F (1, 23171) = 2090.134, $p < .001$. Participants showed significantly different pupil dilation between the short and long conditions in the last 8 seconds.

The main effect of time was also significant, F (399, 23171) = 6.372, $p < .001$. This suggests that in the last 8 seconds of the replication phase, there was a significant change in pupil dilation over time across all participants and conditions.

Furthermore, there was a significant interaction effect between conditions and time, F (399, 23171) = 1.554, $p < .001$. Thus, this reveals that the change in pupil dilation over time differed significantly between the short and long-time interval conditions as shown in Table 3.3.

There were no significant effects for the ”Residuals” source of variance.

Table 3.3: ANOVA Results

Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Between	29	1865062	64312		
Within	23171	22656	1.0		
Conditions	1	2044	2043.6	2090.134	$< 2e-16$ ***
Time	399	2486	6.2	6.372	$< 2e-16$ ***
Conditions:Time	399	606	1.5	1.554	$1.35e-11$ ***
Residuals	23171	22656	1.0		

Note. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$.

3.3. Pupil Dilation After Participants Perform at the Replication Phase and Received Their Feedback

3.3.1. Larger Pupil Size within the 2.5 Seconds (125 Time Points) in the *Long Time Interval* Before its Cue Screen Onset, After its Feedback Screen

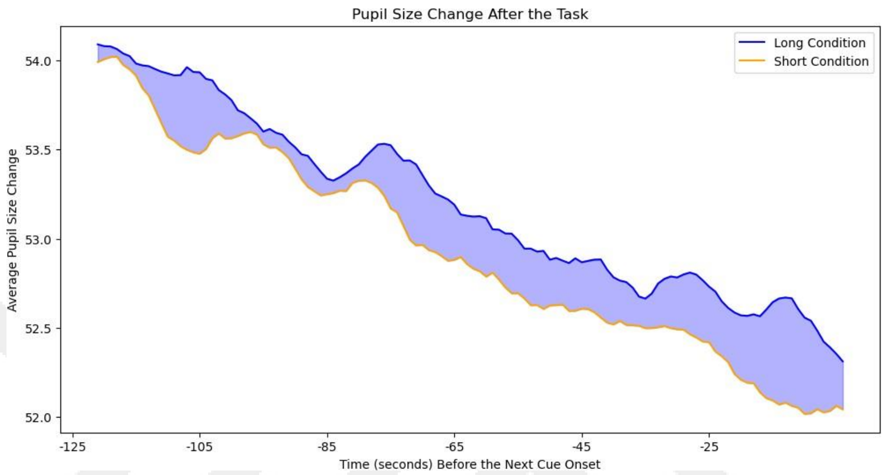


Figure 3.3: The filled region shows the pupil size range between the two conditions

A repeated measures analysis of variance (ANOVA) was conducted to examine the effects of condition (short-long time intervals) and time (125-time points) on mean pupil dilation after participants completed the task in the replication phase and got their feedback (Table 3.4).

The main effect of the condition was found significant, $F(1, 7467) = 99.52$, $p < .001$, implying that after participants performed either in the short or long time interval conditions, there was a significant difference seen in mean pupil dilation between the short and long conditions. Furthermore, the main effect of time was significant either, F (1, 7467) = 1710.74, $p < .001$, suggesting that mean pupil dilation differed significantly across different time points. Besides, there was a significant interaction between conditions and time, F (1, 7467) = 7.20, $p = .007$, demonstrating that the effect of conditions on pupil dilation relied on the time point.

In Table 3.5, Post hoc pairwise comparisons using Tukey's adjustment were conducted to further examine the differences in mean pupil dilation between the two-time intervals. The mean pupil dilation after participants completed the task, after the feedback screen, was significantly higher in the long time interval condition (M = 54.2, SE = 1.49) compared to the short time interval condition (M = 53.9, SE = 1.49), $t(7467) = 9.976$, $p < .001$ (see Figure 3.3.)

In the current analysis, a confidence level of 0.95 was provided. This means that the confidence intervals reported for the estimated marginal means and contrast have a 95 probability of containing the true population values. A higher confidence level, such as 0.99, would result in wider intervals, providing a higher level of certainty but sacrificing precision.

Table 3.4: ANOVA Results

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Between	29	485494	16741		
Within	7467	10211	1.4		
Conditions	1	136	136.1	99.518	$< 2e-16$ ***
Time	1	2339	2339.4	1710.736	$< 2e-16$ ***
Conditions:Time	1	10	9.8	7.202	0.0073 **
Residuals	7467	10211	1.4		

Table 3.5: Post Hoc Analysis: Estimated Marginal Means and Contrast

Condition	EMMean	SE	df	Lower.CL	Upper.CL
Long	54.2	1.49	29	51.1	57.2
Short	53.9	1.49	29	50.8	57.0

Post Hoc Contrast	Estimate	SE	df	t-ratio	p-value
Long - Short	0.269	0.027	7467	9.976	< 0.0001

3.4. Pupil Dilation Comparisons When Participants Replicate the Target Time Intervals as Accurate (Acc), Early (Hne) or Late (Hpe)

In this section of the results, the relationship between behavioral responses and eye-tracker responses of the participants was focused.

The behavioral data in section 3.1 and Figure 3.1, participants' mean standard deviation was compared within the long and short conditions. And it was understood that participants' guesses on target timing in the long condition were noticeably not accurate to the number of seconds which was presented on the cue screen during the experiment.

In order to determine whether participants' predictions were on time, early, or late, we described their mean deviations as "accurate (Acc)", "high negative errors (Hne)" and "high positive errors (Hpe).

If participants' mean deviations from the target timing deviated between -0.5 and 0.5, they did their task accurately and represented in the analysis as an Acc condition. At the Hne condition, if the deviations were lower than -1, they guessed the target timing earlier. If they deviated more than 1, then participants' guesses were later than the target timing, which was represented in the analysis as Hpe condition.

3.4.1. Pupil Dilation Comparisons When Participants Replicate the "*Long Time Intervals*" as Accurate (Acc), Early (Hne) or Late (Hpe)

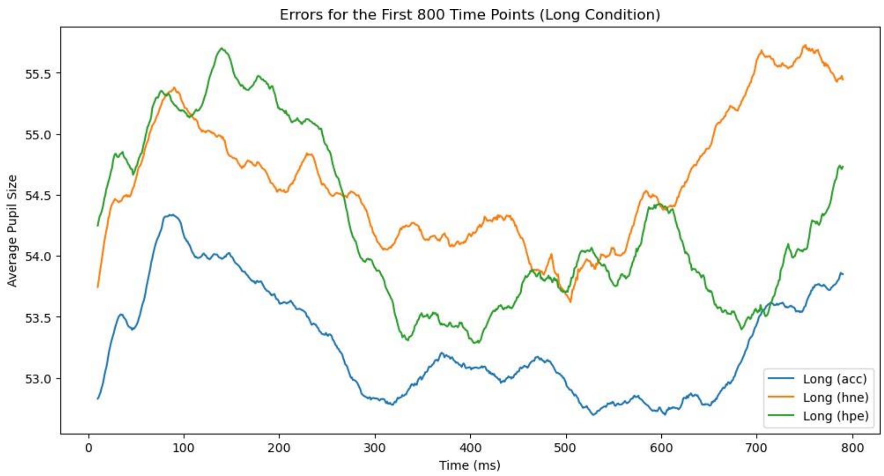


Figure 3.4: Pupil size change during the accurate (Acc), high positive errors (Hpe), and high negative errors (Hne) conditions in the first 800 time points of the long time interval.

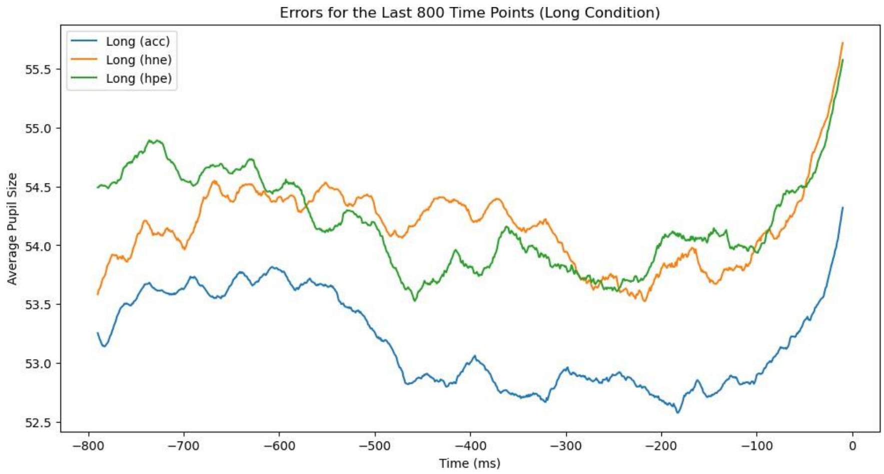


Figure 3.5: Pupil size change during the accurate (Acc), high positive errors (Hpe), and the high negative errors (Hne) conditions in the last 800 time points of the long time interval.

During the *First* 16 Seconds (800 Time Points)

In Table 3.6, the findings of the one-way ANOVA demonstrated a significant main effect of error type on pupil dilation in the first 800 time points, F (2, 70370) = 151.7, $p < .001$. Post-hoc pairwise comparisons benefiting the Tukey method showed significant differences between accurate (Acc) and early (Hne) conditions ($p < .001$) and accurate (Acc) and late (Hpe) conditions ($p < .001$), as well as between early (Hne) and late (Hpe) conditions ($p < .001$) as participants replicate the first 16 seconds of the specified long time interval, Table 3.8.

These findings reveal that in the long condition of the experiment, participants' pupil size changed significantly depending on the type of error made during the replication phase. Pupil dilation was significantly higher in the early (M = 54.62, SE = 0.05662) and late error conditions (M = 54.26, SE = 0.05665) compared to the accurate condition (M = 53.28, SE = 0.05567) at Table 3.7.

Hence, the results represent that the timing errors made during the replication phase of the *first* 16 seconds long time interval influenced participants' physiological responses, as reflected in their pupil dilation.

You can see the change in the figure above (Figure 3.4).

Table 3.6: ANOVA Summary for Pupil Dilation by Error Type in the Long Condition

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Error Type	2	22570	11285	151.7	< 0.001
Residuals	70370	5233647	74		

Signif. codes: * < 0.05, ** < 0.01, *** < 0.001

Table 3.7: Mean Estimates of Error Type on Pupil Dilation in the Long Condition

Error Type	Mean Estimate	SE	df	Lower CL	Upper CL
Accurate	53.28	0.05567	70370	53.17	53.39
Early	54.62	0.05662	70370	54.50	54.73
Late	54.26	0.05665	70370	54.15	54.37

Table 3.8: Pairwise Contrasts of Error Type on Pupil Dilation in the Long Condition

Contrast	Estimate	SE	df	t-ratio	p-value
Accurate - Early	-1.334	0.0794	70370	-16.797	< .0001***
Accurate - Late	-0.975	0.0794	70370	-12.275	< .0001***
Early - Late	0.359	0.0801	70370	4.480	< .0001***

During the *Last* 16 Seconds (800 Time Points)

The one-way ANOVA results for the long time interval condition, specifically considering the last 800 time points, revealed a significant main effect of error type on pupil dilation, F (2, 70352) = 105.8, p < .001 in Table 3.9. This indicates that the type of error made during the replication phase had a significant impact on participants' pupil dilation at the last 16 seconds.

In Table 3.11, Post-hoc pairwise comparisons using the Tukey method were applied to further examine the discrepancies between the error conditions. The results showed significant differences between the accurate and early error conditions (p < .001) as well as between the accurate and late error conditions (p < .001). Yet, there was no significant difference between the early and late conditions (p = .8725).

Specifically, in the long condition during the last 800 time points, participants' pupil dilation was significantly higher in both the early error condition (M = 54.18, SE = 0.05673) and the late error condition (M = 54.22, SE = 0.05676) when it was compared to the accurate condition (M = 53.20, SE = 0.05577). Nonetheless, there was no significant difference in pupil dilation between the early and late error conditions as can be understood from Table 3.10.

As a result, these findings suggest that timing errors made during the replication phase influenced participants' physiological response, as reflected in their pupil dilation during the *last* 800 time points of the long condition. Participants exhibited larger pupil dilation when making timing errors (early or late) in comparison to accurate timing judgments (see Figure 3.5).

In summary, the ANOVA results and post-hoc pairwise comparisons indicate a significant effect of Error Type on pupil dilation during the last 800 time points of the long condition. Pupil dilation was significantly higher in the early and late error conditions compared to the accurate condition. However, there was no significant difference in pupil dilation between the early and late error conditions.

Table 3.9: ANOVA Results for Pupil Dilation by Error Type

Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Error Type	2	15791	7895	105.8	< .001***
Residuals	70352	5250878	75		

Signif. codes: * < 0.05, ** < 0.01, *** < 0.001

Table 3.10: Mean Estimates of Error Type on Pupil Dilation in the Long Condition

Error Type	**Mean Estimate**	**SE**	**Lower CL**	**Upper CL**	**p-value**
Accurate	53.20	0.05577	53.09	53.31	-
Early	54.18	0.05673	54.06	54.29	<.001
Late	54.22	0.05676	54.10	54.33	<.001

Note: Pairwise comparisons using the Tukey method with p-value adjustment.

Table 3.11: Pairwise Contrasts of Error Type on Pupil Dilation in the Long Condition

Contrast	Estimate	SE	df	t.ratio	p-value
Accurate - Early	-0.9788	0.0795	70352	-12.304	< .0001
Accurate - Late	-1.0187	0.0796	70352	-12.802	< .0001
Early - Late	-0.0399	0.0803	70352	-0.497	0.8725

3.4.2. Pupil Dilation Comparisons When Participants Replicate the ”*Short Time Intervals*” as Accurate (Acc), Early (Hne) or Late (Hpe)

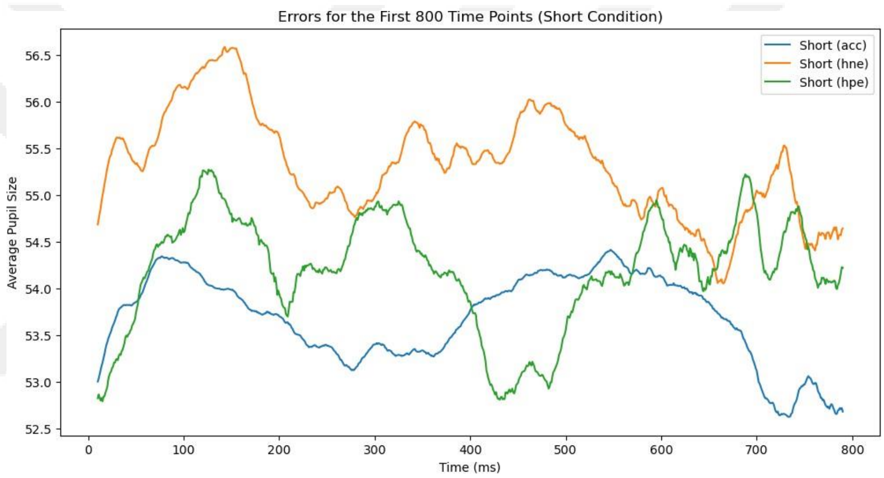


Figure 3.6: Pupil size change during the accurate (Acc), high positive errors (Hpe), and the high negative errors (Hne) conditions.

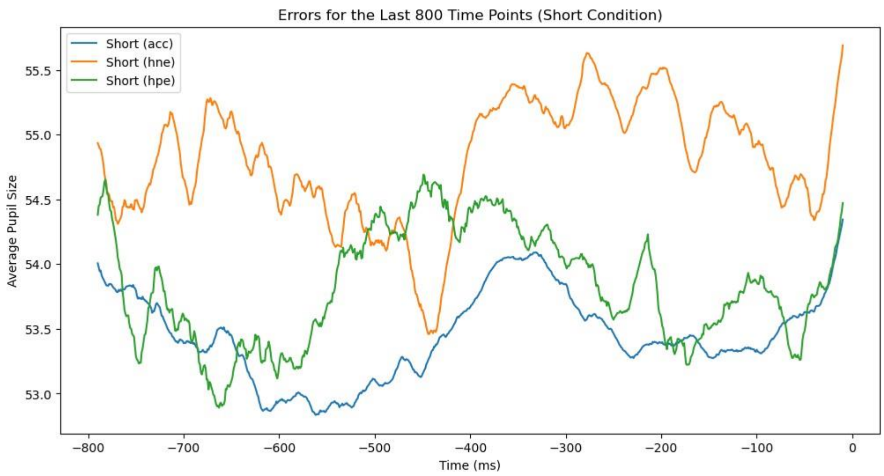


Figure 3.7: Pupil size change during the accurate (Acc), high positive errors (Hpe), and the high negative errors (Hne) conditions.

During the *First* 16 Seconds (800 Time Points)

In the short condition of the experiment, the one-way ANOVA results revealed a significant main effect of Error Type on Pupil Dilation, $F(2, 68748) = 185.7$, $p < .001$. This indicates that the type of error made during the replication phase had a significant influence on participants' pupil dilation in the first 800 time points (Table 3.12).

Post-hoc pairwise comparisons using the Tukey method were conducted to further analyze the differences between the error conditions (Table 3.14). The results showed significant differences between the accurate and early conditions ($p < .001$), accurate and late conditions ($p < .001$), as well as between the early and late conditions ($p < .001$).

Particularly, in the short condition, participants' pupil dilation was significantly greater in the early error condition ($M = 55.31$, $SE = 0.06287$) than in the accurate condition ($M = 53.67$, $SE = 0.05984$, $p < .001$). Likewise, pupil dilation was significantly greater in the late error condition compared to the accurate condition ($M = 54.18$, $SE = 0.06111$, $p < .001$). Moreover, there was a significant difference in pupil dilation between the early and late error conditions, with the early condition indicating higher pupil dilation ($p < .001$, Table 3.13).

These findings suggest that similar to the long condition, the timing errors made during the replication phase in the cue screen influenced participants' physiological response in terms of their pupil dilation. Participants exhibited larger pupil dilation when making timing errors in comparison to accurate timing judgments both at the beginning and end of the task as can be seen in Figure 3.6 and Figure 3.7.

Therefore, in the short condition, the type of error made during the replication phase significantly affected participants' pupil dilation, which was demonstrated by the ANOVA results and the post-hoc pairwise comparisons.

Table 3.12: ANOVA Results for Error Type on Pupil Dilation in the Short Condition

Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**p-value**
Error Type	2	31908	15954	185.7	<.001
Residuals	68748	5907769	86		

Note: p-values are rounded to three decimal places.

Table 3.13: Mean Estimates of Error Type on Pupil Dilation in the Short Condition

Error Type	**Mean Estimate**	**SE**	**df**	**Lower CL**	**Upper CL**
Accurate	53.67	0.05984	68748	53.55	53.79
Early	55.31	0.06287	68748	55.19	55.44
Late	54.18	0.06111	68748	54.06	54.30

Table 3.14: Pairwise Contrasts of Error Type on Pupil Dilation in the Short Condition

Contrast	**Estimate**	**SE**	**df**	**t-ratio**	**p-value**
Accurate - Early	-1.642	0.0868	68748	-18.920	< .0001
Accurate - Late	-0.507	0.0855	68748	-5.929	< .0001
Early - Late	1.135	0.0877	68748	12.947	< .0001

During the *Last 16* Seconds (800 Time Points)

In the short condition, specifically considering the last 800 time points, the one-way ANOVA results revealed a significant main effect of Error Type on Pupil Dilation, F (2, 69162) = 132.3, $p < .001$. This indicates that the type of error made during the replication period had a significant effect on participants' pupil dilation during the last 16 seconds of the short time interval (see Table 3.15).

Post-hoc pairwise comparisons benefiting the Tukey method were conducted to further examine the differences between the error types. The results revealed significant differences between the accurate and early conditions ($p < .001$) as well as between the accurate and late conditions ($p < .001$). Similarly, a significant difference was observed between the early and late conditions ($p < .001$) (see Table 3.17).

Precisely, in Table 3.16 in the short condition (last 800 time points), participants' pupil dilation was significantly larger in both the early error condition ($M = 54.82$, $SE = 0.06167$) and the late error condition ($M = 53.84$, $SE = 0.06045$) than the accurate condition ($M = 53.47$, $SE = 0.05922$). Furthermore, the pupil dilation was significantly higher in the early error condition compared to the late error condition.

These findings indicate that timing errors made during the replication phase in the cue screen influenced participants' physiological response, as reflected in their pupil dilation during the last 800 time points of the short condition. Participants exhibited larger pupil dilation when making timing errors (early or late conditions) compared to accurate timing judgments. Moreover, pupil dilation was higher in the early error condition compared to the late error condition. (see Figure 3.7).

To summarize, the ANOVA results and post-hoc pairwise comparisons indicate a significant effect of error type on pupil dilation during the *last* 800 time points of the short condition. Pupil dilation was dramatically higher in both the early and late error conditions compared to the accurate condition, and the early error condition indicated the highest pupil dilation.

Table 3.15: ANOVA Results for Pupil Dilation in the Short Condition

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**p-value**
Error Type	2	22271	11135	132.3	$< 2e-16$*
Residuals	69162	5821095	84		

Signif. codes: * < 0.05, ** < 0.01, *** < 0.001

Table 3.16: Pairwise Comparisons of Error Type on Pupil Dilation in the Short Condition

Error Type	Mean Estimate	SE	df	Lower CL	Upper CL
Accurate	53.47	0.05922	69162	53.35	53.59
Early	54.82	0.06167	69162	54.70	54.94
Late	53.84	0.06045	69162	53.72	53.96

Table 3.17: Pairwise Contrasts of Error Type on Pupil Dilation in the Short Condition

Contrast	Estimate	SE	df	t.ratio	p-value
Accurate - Early	-1.354	0.0855	69162	-15.832	< .0001
Accurate - Late	-0.373	0.0846	69162	-4.406	< .0001
Early - Late	0.981	0.0864	69162	11.357	< .0001

3.5. General Interpretation

Overall, considering the behavioral results, participants had higher deviations from the target timing in the long time interval condition compared to the short time interval. Thus, this shows that whereas participants were performing in the replication phase, they could make more accurate guesses or predictions on the specified second which belonged to the *short time interval*.

Examining the physical responses of participants, it was found that both short and long time intervals had a significant impact on pupil dilation throughout the experiment. Specifically, regardless of the beginning and end of the experiment, participants' pupils were more likely to enlarge in the *short time interval* while they were performing the replication phase.

Besides, participants' pupil dilation after they complete each trial, which means when they perform the replication phase at the specified timing and received feedback about their predictions were observed as well. It is noticeable that, even though their pupil sizes tended to get smaller until the next cue screen for both time periods, their pupils dilated more after they were out of the *long time interval* conditions.

When both the behavioral and physical responses of the participants integrated together, it can be generalized that both at the beginning and the end of the experiment, their pupil size were noticeably smaller whereas participants' guesses were more or less accurate on the given time in the *short* and the *long time intervals*. Regardless of the minimal differences, participants' pupils dilated greater when they made *early* guesses on the given time in all beginning and the end of the time periods. Yet, solely in the *last* 16 seconds of the *long time interval*, pupil sizes were slightly larger when the participants performed later than the specified timing.

CHAPTER 4

DISCUSSION

Pupilometry, the measurement of pupil dilation, has become a useful tool for comprehending cognitive functions, like attention, and performance. Researchers can learn more about numerous facets of human behavior by observing variations in pupil size and its behavioral response. Besides, pupillometry has been used in studies examining sustained attention, perceptual load tasks, continuous performance, and time perception.

Pupillometry and Cognitive Load:

The amount of mental effort necessary to complete a task is reflected by pupillometry, a tool that has been frequently used to quantify cognitive load. Pupil dilation is responsive to changes in cognitive load across various activities, tasks, and fields, according to recent studies. For instance, Ahern and Beatty (1979) discovered that during a digit-span test, pupil size rose as working memory demand increased. Similarly to this, Krummenacher et al. (2019) found that participants' pupils dilated more when engaging in activities that required more working memory. These results imply that pupillometry can act as an accurate and immediate measure of cognitive demand.

Pupillometry and Sustained Attention:

The research field of vigilance proceeds by emphasizing the significance of pupil dilation as a sign of elevated sustained attention. It cites research that points out how challenging activities with a high perceptual load demand enhanced concentration and focus, particularly among those with concentrating difficulties like ADHD. In these activities, pupil expansion is thought to be a sign of better-sustained attention.

Evaluating the study by Unsworth et al. (2018), which analyses how fluctuations and lapses of continuous attention can be defined through pupillary reactions. Thus, the findings demonstrate that slower responses and lapses of attention are strongly linked with reduced intrinsic alertness and diminished attention to task-relevant stimuli. Yet, after a lapse of attention, performance and pupillary reaction increase, stressing the reorientation of attention back to the task. Hence, this indicates that pupillary responses can serve as markers of attentional lapses and fluctuations in sustained attention.

Pupillometry and Task Difficulty:

Extensive research has additionally been done on the association among task difficulty and pupil dilation. Pupil diameter has a tendency to rise along with task demands, studies have indicated, signifying increased effort and allocation of cognitive resources (Beatty, 1982; Beatty & Kahneman, 1966). This shows that pupillary outcomes can be used as an assessment of mental effort put out when completing an assigned task.

Furthermore, a similar outcome has been seen while considering the relation between effort level and pupil size. It makes reference to research that shows how explicit instructions to exert greater effort can enhance performance because people will exert more effort when expressly instructed to do so. Additionally, the length and guidance for raising effort may have an impact on reaction times and performance, as studies have shown that increased effort mobilization may result in a trade-off in error rate.

Pupillometry and Time Perception:

Although knowledge of pupillary responses in connection to time perception is still developing, evidence points to the involvement of pupil dilation in temporal processing. Gathering the previous studies, they point out that there is no reliable method for describing and generalizing the time perception or sense of the time phenomena.

Studies have revealed a negative link between monkeys' delayed performance on self-timed tasks and their pupil size. Pupil dilation, which is related to the processing of temporal information, has also been seen to grow when participants estimate stimulus intervals incorrectly, regardless of whether they believe them to be either longer or shorter (Toscano-Zapién, Velázquez-Lopez, & Velázquez-Mart´ınez, 2016). Thereby, these findings indicate the fact that attentional mechanisms involved in the duration of the time intervals may be connected to pupillary responses.

Integration with Findings:

In our study, we focused on the connection concerning time perception and pupil dilation. The results suggested that the length of time between intervals had an impact on the participants' pupil dilation. Participants showed more pupil dilation in the short time interval condition during the replication phase as opposed to the long time interval condition. The larger pupil dilation seen in the short time interval condition may illustrate increased attentional focus and cognitive engagement during the replication phase. This is consistent with other studies that suggested task difficulty and the level of cognitive load affects pupillary responses. However, it is debatable whether participants put too much effort into the short condition or they experienced difficulty while interpreting the short time intervals compared to the long interval.

Additionally, after every trial, when they completed the replication phase at the designated time and got feedback about their estimations, we also watched the participants' pupils dilate. For both time intervals, participants' pupils have a tendency to become smaller till the next cue screen, yet after leaving the long time interval setting, their pupils tended to dilate greater. This would suggest that the replication phase of the extended time gap condition required more mental work or cognitive load.

Meanwhile, our results showed that when participants made early predictions on the provided time, particularly in the final 16 seconds of the long time span, their pupils tended to dilate more. This result supports the idea that pupillary responses reflect variations in long-term concentration and might signal attentional failures. The higher pupil dilatation in this situation can indicate that attention has been brought back to the task after wandering.

Recent Advances and Related Fields:

In order to develop a thorough knowledge of human behavior, recent research has investigated the integration of pupil dilation studies with other physiological and cognitive variables. An understanding of the neurological mechanisms controlling attention and cognitive processes has been gained, for instance, by integrating pupillometry with electroencephalography (EEG) (Knapen, Rolfs, & Cavanagh, 2009). Additionally, the research of visual attention and perceptual processes has been made easier by the combination of pupillometry over eye-tracking technologies (Hoeks & Levelt, 1993).

Moreover, in addition to psychology and neuroscience, pupilometry methodology has also been used in a variety of disciplines, including human-computer interface, and clinical research. It is a useful instrument for researching attention problems, fatigue, and cognitive stress in real-life circumstances because of its non-invasiveness, simplicity of use, and sensitivity to cognitive processes (Kahneman, Sibony, & Sunstein, 2021; Vimalajeewa, McDonald, Bruce, & Vidakovic, 2022).

Additionally, combining pupillometry with other measurements like electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) has allowed researchers to get a deeper knowledge of the brain mechanisms driving pupillary responses (Eldar, Niv, & Cohen, 2016; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010). Thanks to the help of these multimodal techniques, it is possible to examine the temporal dynamics and spatial localization of the brain activity linked to pupil size changes.

Pupillometry and Emotion:

Numerous studies have been done on the connection between emotion and pupillometry. It has been discovered that emotional arousal and valence influence pupil size. Irrespective of the valence, studies have demonstrated that emotionally triggering stimuli frequently result in an increase in pupil dilation (2008). Likewise, the distinction between positive and negative emotional states has been demonstrated using pupillary reactions. For instance, Knapen et al. (2014) discovered that in contrast to either neutral or positive emotional stimuli, individuals' pupils dilated greater in reaction to negative emotional stimuli (de Gee, Knapen, & Donner, 2014). These results demonstrate the significance of pupillometry in comprehending emotional processing.

Pupillometry and Neurotransmitter Systems:

Recent research also has concentrated on investigating the underlying neural mechanisms of pupillary reactions by analyzing the role of neurotransmitter systems. The locus coeruleus-norepinephrine (LC-NE) system has been precisely implicated in modulating pupil size. The LC-NE system is included in controlling arousal, attention, and cognitive processes. Aston-Jones and Cohen (2005) advocated that phasic alterations in LC activity impact pupil dilation, with increased noradrenaline release resulting in pupil dilation (Aston-Jones & Cohen, 2005). This proposes an association between pupillometry and the LC-NE system, contributing insights into the neural correlates of emotional and cognitive processes.

Limitations

A greater limitation in our study is the dependence of time perception on various facts including the age, psychopathology, emotional states, intellectual ability of the participants, and the valence of the stimuli (Noulhiane, Mella, et al., 2007; Noulhiane, Pouthas, et al., 2007; Block et al., 2010; Lake, 2016; Droit-Volet et al., 2001; Lustig & Meck, 2011; Allingham et al., 2021). Whereas our stimuli can count as ”neutral”, participants' emotional and mental situations could be called confounding variables.

Additionally, it is not known from which cognitive mechanisms participants benefited. Those, who have the greater intellectual ability (e.g. memory, attention, learning) may be made better estimations throughout the experiment (Noulhiane, Pouthas, et al., 2007; Lake, 2016; Lustig & Meck, 2011). Besides, the sense of time can be influenced by concentration and arousal even the internal clock provides a stable state (Mattes & Ulrich, 1998; Block et al., 2010; Penton-Voak et al., 1996; Brown, 1997; Zakay, 2005; Wöllner & Hammerschmidt, 2021)

Also, the type of stimuli whether audial or visual, create changes in perception which may directly be associated with pupil dilation. (Ortega et al., 2014; Penney et al., 2000; Lustig & Meck, 2011)

Recent Advances and Future Directions:

Rather than a concrete task, our study involved the internal process of the participants. They had to monitor themselves while doing the given task. Thereby, they chose their own strategy and methodology throughout the experiment. With the ”Pupil Dilation in Time Perception” research, we understood that time is perceived significantly differently when short and long duration is compared. However, we do not know which cognitive mechanism they are benefited from whether they are predicting, sensing, or guessing the specific time interval. Therefore, as a next step, in terms of the internal task process, the mind-wandering activity could be assessed and compared throughout replicating the target timing and in the resting phases.

Besides, pupil responses may now be monitored in real-time outside of a lab environment because of the advent of wearable and portable eye-tracking systems (Chen, Wang, Hung, & Hsueh, 2022; Rajendran, Rai, Shetty, & Mathangi, 2022). This creates possibilities for investigating pupil size change under ecologically plausible circumstances and for applications in human-computer interaction (Kosch et al., 2023; Rogers, Sharp, & Preece, 2023; Modi & Singh, 2023; Schneider et al., 2023), educational settings (Bao & Liu, 2023), and clinical diagnosis (Raschellà, Scafa, Puiatti, Martin Moraud, & Ratti, 2023; Pauszek, 2023).

Additionally, based on pupil dilation-behavior outcomes, the combination of pupillometry and machine learning approaches has demonstrated potential in the prediction of cognitive states and mental workload (Heimerl et al., 2023; Kaczorowska, Plechawska-Wojcik, & Tokovarov, 2021). Researchers may deduce more detailed information through pupillary data, increasing the likelihood of it serving as a useful tool in a variety of domains, by fusing pupillometry with cutting-edge analytical techniques.

In conclusion, the study reveals that the length of the time interval affected participants' timing accuracy, with a higher deviation shown in the long time interval condition. Despite pupils were prone to widen throughout the replication period of the short time interval condition, pupil dilation trends during the replication phase of the long time interval condition imply higher cognitive load. Hence, the study demonstrates the intricate connection between temporal perception, mental operations, and physiological reactions.

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