Is the Pupil the Window to the Soul? —Application and Measurement of Pupil in Psychological Research

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Abstract

Pupil size is an important parameter in eye movement research that can, to a certain extent, reflect human psychological activity and influence others' psychology and behavior. On the one hand, pupil changes are influenced by top-down factors such as perception and attention, emotion and motivation, mental effort, and social cognition and development. On the other hand, large pupils can elicit more positive evaluations and behaviors from others. The neural mechanisms of the pupil (locus coeruleus-norepinephrine system) and adaptive gain theory explain the reasons for the close relationship between the pupil and psychology. Pupillometry, as an effective eye-tracking method, facilitates understanding of the relationship between the pupil and psychology. When measuring pupil, researchers need to attend to confounding variables (such as brightness, gaze position), raw data processing (such as baseline correction, blink handling), and the selection of pupil metrics (such as pupil diameter, tremor frequency). Future research should continue to explore the relationship between the pupil and other psychological phenomena, and investigate more effective methods for processing and utilizing pupil metrics.

Full Text

Preamble

Are pupils the window of the mind? The application of pupils in psychological research and pupillometry

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Abstract: Pupil size is a crucial parameter in eye-tracking research that can reflect mental activities and influence others' psychology and behavior. On one hand, pupil changes are influenced by top-down processes such as perception and attention, emotion and motivation, mental effort, and social cognition and development. On the other hand, larger pupils can elicit more positive evaluations and behaviors from others. The neural mechanism underlying the pupil (the locus coeruleus-norepinephrine system) and the adaptive-gain theory explain why there is a close connection between pupils and psychology. Pupillometry, as an effective eye-tracking method, helps us understand the relationship between pupils and the mind. When measuring pupils, researchers need to consider confounding variables (e.g., luminance, gaze position), raw data processing (e.g., baseline correction, blink handling), and the selection of pupil metrics (e.g., pupil diameter, oscillation frequency). Future research should continue to explore the relationship between pupils and other psychological processes and develop more effective methods for processing and using pupil metrics.

Keywords: pupil; pupillometry; top-down processing; neural mechanisms; adaptive-gain theory

> "In observing a person, nothing is more revealing than the pupils. The pupils cannot conceal one' s wickedness. When the heart is upright, the pupils are bright; when the heart is not upright, the pupils are dull. Listen to one' s words and observe one' s pupils—how can a person hide?"
> —*Mencius, Li Lou I, XV*

The exploration of the relationship between pupils and psychology dates back to ancient times, but scientific research using psychological methods has only a half-century of history (Laeng, Sirois, & Gredebäck, 2012). Although Kuntz proposed in 1929 that pleasant and fearful emotions are typically accompanied by pupil dilation (cited in Hess & Polt, 1960), this lacked empirical support. It was not until the early 1960s that Hess and Polt (1960) recorded pupil changes while six participants viewed a series of images—babies, mothers holding children, semi-nude males, semi-nude females, and landscapes—and found that pupil changes were influenced by individual interest. Most researchers consider this study the beginning of pupillometry applications in psychological research (Mathôt, 2018; Sylvain & Julie, 2014). Hess subsequently conducted a series of studies using pupil changes as an indicator for psychological variables such as emotion, motivation, taste preference, music preference, attitude, and attitude change, arguing that pupil change was an emerging sensitive indicator of human psychology, which sparked a boom in pupillometry research (Goldwater, 1972; Hess, 1965). However, due to methodological flaws in Hess' s research designs, some results could not be replicated, and his findings were questioned (Janisse, 1973). In the 1970s and 1980s, psychologists represented by Daniel Kahneman and Jackson Beatty discovered that pupils were also related to higher-level cognitive activities such as memory and mental effort (see Laeng et al., 2012). With the development of eye-tracking technology, pupil data have become more accessible and reliable, and with increasingly strict experimental controls, the fact that pupil changes can reflect psychological processing has once again attracted researchers' interest, and the relationship between pupils and psychology has received growing attention (Mathôt, 2018).

This review organizes and introduces recent applications of pupillometry in psychology, including how psychological factors influence individual pupil changes, how pupils affect others' psychology and behavior, an analysis of the neural mechanisms and related theories of pupil changes, and finally, a summary of methods for more effectively measuring pupils, aiming to provide references for researchers conducting pupillometric studies.

1. Do Psychological Factors Influence Individual Pupil Changes?

Researchers typically use task-evoked pupil responses (TEPRs) to study how specific psychological factors affect pupil size changes, treating overt pupil changes as one indicator of internal mental activity (Beatty, 1982). Factors influencing individual pupil changes mainly involve four aspects: perception and attention, emotion and motivation, mental effort, and social cognition and development.

1.1 Perception and Attention

Traditional views hold that the pupil light response (PLR) is a simple physiological reflex—pupils dilate in dark environments and constrict in bright environments (Loewenfeld, 1958). As research has progressed, however, studies have found that pupil changes are also influenced by subjective brightness perception. Although the effect of brightness perception on pupil changes (diameter change less than 0.5mm) (Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Sylvain & Julie, 2014) is much weaker than that of physical brightness (change range about 2-8mm) (Loewenfeld, 1993), this phenomenon has still attracted researchers' interest. Studies have found that even when viewing images with identical physical brightness, images subjectively perceived as bright (e.g., the sun, brightness illusions) elicit more pronounced pupil constriction (Laeng & Endestad, 2012; Naber & Nakayama, 2013). Moreover, imagining a brighter image results in smaller pupils than imagining a darker image, and hearing words with bright connotations (e.g., "daytime") produces smaller pupils than hearing neutral (e.g., "house") or dark-connotation words (e.g., "nighttime") (Laeng & Sulutvedt, 2014; Mathôt, Grainger, & Strijkers, 2017). These findings demonstrate that pupil changes are not merely physiological conditioned reflexes but are also influenced by higher-level cognitive processing; both physical light stimulation and brightness perception can induce pupil constriction (Mathôt, 2018).

Furthermore, research has found that selective attention to information also induces pupil changes. For example, in a study by Mathôt, Dalmaijer, Grainger, and Van Der Stigchel (2014), the screen was divided into bright and dark halves, with participants required to fixate on the center point while cues randomly appeared on either side to attract attention. Results showed that 476-893ms after cue presentation, pupils were smaller when cues appeared on the bright side, a phenomenon termed the "pupillary cuing effect." This effect has been replicated in other studies (Binda & Murray, 2015; Binda, Pereverzeva, & Murray, 2013; Mathôt, Linden, Grainger, & Vitu, 2015; Mathôt & Van Der Stigchel, 2015). These studies indicate that although the physical luminance entering the pupil remains constant, attention guided by cues can evoke pupil changes similar to the pupil light response. Additionally, the three components of the attention network—the alerting network, orienting network, and executive monitoring network—produce different temporal patterns and magnitudes of pupil dilation. For instance, Geva, Zivan, Warsha, and Olchik (2013) used the Attention Network Task (ANT) to compare differences among the three attention network components while recording pupil changes. They found pupil dilation 300ms after cue presentation (alerting network); spatially informative cues induced earlier pupil dilation than non-spatial cues (orienting network); and pupil changes in the executive control network were primarily influenced by mental effort (see Section 1.3). Therefore, pupil changes may serve as an indicator of attention network function (Geva et al., 2013; Petersen & Posner, 2012; Wang, Boehnke, Itti, & Munoz, 2014).

1.2 Emotion and Motivation

Emotional arousal activates the autonomic nervous system, thereby inducing pupil changes (Mathôt, 2018). Although Hess' s early research (1965) suggested that emotional stimuli produced bidirectional pupil changes—positive emotions causing dilation and negative emotions causing constriction—most subsequent research has refuted this finding. For example, emotional stimuli such as frightening images, pleasant or familiar music, and crying or laughing sounds all induce pupil dilation compared to neutral stimuli (Bradley, Miccoli, Escrig, & Lang, 2008; Laeng, Eidet, Sulutvedt, & Panksepp, 2016; Snowden et al., 2016). Moreover, people are more sensitive to negative emotional stimuli, showing greater and longer-lasting pupil dilation than to positive stimuli (Babiker, Faye, & Malik, 2013; Derksen, Van Alphen, Schaap, Mathôt, & Naber, 2018; Oliva & Anikin, 2018; 袁加锦, 李红, 2012). Additionally, tactile stimuli can also evoke emotions; studies have found that human touch produces greater pupil dilation than machine touch, and that touch speed is proportional to pupil dilation to some extent (Ellingsen et al., 2013; Van Hooijdonk et al., 2019). In flight simulations, pilots' reported anxiety levels correlate positively with pupil size (Tichon, Mavin, Wallis, Visser, & Riek, 2014). These results indicate that emotional stimuli such as happiness, sadness, and anxiety can cause pupil dilation regardless of emotional valence, though whether more complex emotions (e.g., contempt, melancholy, longing) also induce pupil dilation remains to be explored.

Motivation, as an important psychological variable, influences both human drive states and pupil changes. Hess' s early research found that hungry participants showed pupil dilation when viewing food images (Hess, 1965, 1975). Recent studies have found that pupil dilation is related to sexual interest: heterosexual males show the strongest dilation to images of adult females, homosexual males to adult males, bisexual males to both male and female adult images, while none show significant dilation to images of male or female children (Attard-Johnson, Bindemann, & Ciardha, 2017), suggesting an association between physiological motivation and pupil dilation. Beyond physiological motivation, research on special populations has found that social motivation also affects pupil changes. For example, major depressive disorder (MDD) patients, whose primary symptoms include depressed mood, slowed thinking, and reduced volitional activity, show inhibited pupil dilation during problem-solving tasks due to anxiety; however, increasing motivation levels can promote pupil dilation in MDD patients (Jones, Siegle, & Mandell, 2015). Some researchers also suggest that low motivation may be one reason for blunted pupil changes in schizophrenia patients performing the double-step task (Thakkar et al., 2018). It should be noted that motivation can be categorized into various types in terms of dimension and intensity, and its effects on pupil changes may differ accordingly—for instance, whether approach and avoidance motivations both induce pupil dilation and whether they differ in intensity.

1.3 Mental Effort

Mental effort refers to the cognitive resources invested to achieve goals during task performance and is often accompanied by pupil dilation (Beatty, 1982; Van Der Wel & Van Steenbergen, 2018). On one hand, task difficulty affects pupil changes through its impact on mental effort (Beatty & Kahneman, 1966; Hess & Polt, 1964). More difficult tasks require greater mental effort and produce larger pupil dilation, but when task difficulty exceeds cognitive load, pupils no longer dilate. Therefore, the essence of previous research manipulating task difficulty to induce pupil changes may be that mental effort influences pupil changes (Van Der Wel & Van Steenbergen, 2018). Studies on children have also found that in short-term memory tasks, pupil diameter increases with digit span, but reaches its peak when children reach their maximum memory span (6 digits), indicating they have reached their cognitive limit; subsequent decreases in pupil diameter suggest reduced mental effort (E. L. Johnson, Miller Singley, Peckham, Johnson, & Bunge, 2014).

On the other hand, different task types induce different levels of mental effort, resulting in varying degrees of pupil dilation. For instance, in conflict task paradigms such as the Stroop, Flanker, and Simon tasks, incongruent conditions produce greater pupil dilation than congruent conditions (Diede & Bugg, 2017; Hershman & Henik, 2018; Van Steenbergen & Band, 2013; Wendt, Kiesel, Geringswald, Purmann, & Fischer, 2014). In goal-directed visual search tasks, the less conspicuous the target, the more cognitive effort required and the greater the pupil dilation (Kleberg, Del Bianco, & Falck-Ytter, 2019; Mathôt, Siebold, Donk, & Vitu, 2015); this phenomenon is even more pronounced in individuals with autism (Blaser, Eglington, Carter, & Kaldy, 2014). Decision-making studies have found that pupil dilation occurs before participants actively press a button to switch tasks, suggesting mental effort may be present during decision preparation (Katidioti, Borst, & Taatgen, 2014). Moreover, higher decision uncertainty (Urai, Braun, & Donner, 2017) and more cautious decision-making (Cavanagh, Wiecki, Kochar, & Frank, 2014) are associated with greater pupil dilation. In learning tasks, learners invest more mental effort in information they subjectively rate as more important, showing greater pupil dilation and better memory performance (Ariel & Castel, 2014). Overall, greater mental effort during task execution produces larger pupil dilation. However, most of the above studies rely on subjective reports of mental effort; future research could combine pupil measures with other physiological indicators of mental effort (e.g., heart rate, facial EMG) to better understand the relationship between mental effort and pupil changes (Van Der Wel & Van Steenbergen, 2018).

1.4 Social Cognition and Development

Social cognition formed during complex social interactions also affects pupil changes. For example, playing a violent video game for 15 minutes impairs participants' perception of negative images such as violence victims, resulting in smaller pupil dilation compared to participants who played non-violent games (Arriaga et al., 2015). Furthermore, research has found that different levels of social cognitive development in infants and young children affect pupil changes. When watching videos showing consistent (smiling while gently patting a doll) or inconsistent (smiling while hitting a doll) emotion-action pairings, 14-month-old infants and 10-month-old infants showed no difference in looking time, but differed in pupil measures: 14-month-olds showed greater pupil dilation when watching inconsistent videos, whereas 10-month-olds showed no pupil differences between the two video types, suggesting that 14-month-olds can understand the relationship between emotions and actions (Hepach & Westermann, 2013). Twelve-month-old infants can form expectations about objects based on pointing gestures and show significant pupil dilation when these expectations are violated (i.e., when nothing is seen), whereas 8-month-olds cannot understand pointing gestures, showing no significant pupil differences between gesture and no-gesture conditions (Pätzold & Liszkowski, 2019). Additionally, regarding the development of social altruism, 2- to 3-year-old children show greater pupil dilation when seeing others in need, especially when they themselves caused the need, and their pupils become relatively smaller when they see others receiving help (Hepach, Vaish, Müller, & Tomasello, 2017; Hepach, Vaish, & Tomasello, 2012, 2016).

Overall, pupil changes result from the combined effects of bottom-up and top-down processing. Luminance changes cause rapid and pronounced pupil constriction or dilation, representing bottom-up processing, while psychological factors such as perception and attention, emotion and motivation, mental effort, and social cognition and development also influence pupil changes, representing top-down processing. Through clever experimental designs that control confounding variables, researchers have investigated how different psychological factors affect pupil changes, revealing the psychological significance of pupil changes.

2. Do Pupils Affect Others' Psychology and Behavior?

Recall the cartoon characters we have seen: wicked queens are often depicted with small pupils and eyes, while kind princesses have large pupils and eyes. Is there scientific basis for such portrayals? As discussed earlier, pupil changes are influenced by multiple psychological factors. In other words, pupil changes can reflect mental states to some extent. Can pupils, then, serve as a social cue that influences others' psychological perception and even overt behavior?

Existing research has confirmed that faces affect social perceptions and evaluations such as trust and attractiveness (Oosterhof & Todorov, 2008). Further studies have found that although pupils constitute only a tiny portion of the face and subtle pupil changes are difficult for people to detect, they still influence psychological perception (Hess, 1975; Kret, 2018; Kret & De Dreu, 2019). In subjective ratings, Hess' s early research found that men more frequently used terms like "gentle," "more feminine," and "beautiful" to describe images of women with large pupils, while using terms like "selfish" and "cold" to describe women with small pupils. Even when other facial features were identical, men still perceived women with large pupils as more sexually attractive (Hess, 1975). In real life, 17th-century Italian women used belladonna powder (containing atropine, which blocks parasympathetic influence on pupil muscles, thereby dilating pupils) to enlarge their pupils and increase their attractiveness. In a large-scale empirical study, 579 participants aged 4-80 years drew pupils on simple line drawings of faces with different emotions. Although 4- to 9-year-old children showed no significant difference in pupil size drawn on happy versus angry faces, with increasing age, participants drew larger pupils on happy faces and smaller pupils on angry faces (Kret, 2018). This unconscious behavior suggests that people gradually develop an association between "large pupils-positive" and "small pupils-negative" through socialization. In objective measures, Harrison et al. (2006) had participants rate the emotional intensity of faces with different emotions and pupil sizes while recording brain imaging data. Results showed that small pupils enhanced participants' perception of sadness intensity, and sad faces with small pupils significantly activated brain regions related to social cognition, such as the left amygdala, left frontal operculum, and right dorsal anterior cingulate, providing neurocognitive evidence that pupil size can affect others' emotion perception.

Moreover, pupils can influence others' overt behavior. Pupil mimicry, also known as pupillary contagion, refers to the phenomenon where an individual' s pupil size changes in response to observed changes in another' s pupils (Mathôt & Naber, 2018; Galazka et al., 2018). Hess first discovered pupil mimicry in 1975, and subsequent research has found this phenomenon in adults (Kret & De Dreu, 2017; Kret, Tomonaga, & Matsuzawa, 2014), infants (Fawcett, Arslan, Falck-Ytter, Roeyers, & Gredebäck, 2017; Fawcett, Wesevich, & Gredebäck, 2016), and even chimpanzees (Kret et al., 2014). Pupil mimicry is strongest when communicating parties achieve mental coupling (Kang & Wheatley, 2017) and helps people understand each other' s emotional states, playing an important social function in interpersonal communication. Recent research has found that although individuals with autism spectrum disorder (ASD) show significantly less fixation time on eyes than typical individuals, both ASD and typical individuals exhibit pupil mimicry (Galazka et al., 2018). This finding challenges the traditional view that ASD individuals are indifferent to social-emotional information, suggesting they can also perceive emotions conveyed by others and become aroused. Notably, although the above studies treat pupil mimicry as a manifestation of social communication, whether pupil mimicry constitutes socially meaningful imitation remains to be determined (Derksen et al., 2018; Mathôt & Naber, 2018; see Section 5.2).

Furthermore, pupil size and changes can affect others' trust and dishonest behaviors. Kret, Fischer, and De Dreu (2015) manipulated partners' pupil sizes in a trust investment game and found that participants were more willing to trust partners with larger pupils and made more investments (Kret & De Dreu, 2017; Prochazkova et al., 2018). When partners' pupils dilated, participants' dishonest behaviors decreased significantly (Van Breen, De Dreu, & Kret, 2018). Interestingly, individuals with depression show greater trust in partners with smaller pupil changes, regardless of pupil size. One explanation is that pupil changes reflect a person' s emotional variability, and depressed individuals prefer emotionally stable partners. Another explanation is that pupil dilation is considered an emotional cue or expression (Bradley et al., 2008), and since emotion recognition abilities are impaired in depression, these individuals cannot, like healthy individuals, trust partners with larger pupils more (Wehebrink, Koelkebeck, Piest, De Dreu, & Kret, 2018). Similar to healthy individuals, depressed patients' mimicry of pupil dilation also promotes more trust behaviors (Wehebrink et al., 2018).

Why do people with larger pupils gain more trust from others and even reduce others' dishonest behavior? Prochazkova et al. (2018) found that partners' pupil dilation and participants' pupil mimicry activate brain regions related to theory of mind, such as the precuneus, temporoparietal junction, superior temporal sulcus, and medial prefrontal cortex, thereby influencing behavior. Practically speaking, compared to nonverbal cues such as facial expressions and gestures, pupils are less susceptible to conscious control and can more authentically reflect internal mental states, thus serving as an important and reliable source of information for trust and cooperation during communication (Kret et al., 2015; Kret & De Dreu, 2019). Although pupils are often overlooked as physiological and social cues, the above research demonstrates that pupils can affect others' psychological perception and even important social behaviors (primarily showing that large pupils elicit more positive evaluations and behaviors), indicating that the role of pupils in social communication cannot be ignored.

3.1 Neural Mechanisms of the Pupil

In terms of physiological structure, the pupil is a transparent circular opening in the center of the iris that is highly sensitive to luminance. Light passes through the pupil and projects onto the retina, stimulating smooth muscles in the iris that control pupil size: the circular sphincter pupillae and the radial dilator pupillae, which together regulate the amount of light reaching the retina to produce optimal vision. Pupil constriction is primarily influenced by light stimulation through a relatively simple neural pathway: light projected onto the retina generates neural impulses that, after passing through the Edinger-Westphal (E-W) nucleus, cause the sphincter muscle to contract and pupil diameter to decrease. Neural pathways for pupil dilation mainly include: (1) decreased light causing reflexive pupil dilation; (2) cognitive brain activity activating the locus coeruleus-norepinephrine (LC-NE) system, which acts on the dilator muscle to cause pupil dilation; and (3) activation of the locus coeruleus (LC) inhibiting information transmission from the E-W nucleus, thereby suppressing pupil constriction (Mathôt, 2018) (see Figure 1 [Figure 1: see original paper]).

Among these, the LC-NE system is the primary neurophysiological mechanism affecting pupil changes (Costa & Rudebeck, 2016; Elman et al., 2017; Joshi, Li, Kalwani, & Gold, 2016; Liu, Rodenkirch, Moskowitz, Schriver, & Wang, 2017). The LC exhibits two activity modes: tonic and phasic, releasing norepinephrine (NE) to act on the central nervous system (Aston-Jones & Waterhouse, 2016). During tonic activity, the LC is in a sustained and diffuse state, facilitating detection of novel stimuli, with pupil diameter changes during target search corresponding to LC tonic firing rates (Joshi et al., 2016; Murphy, O’ Connell, O’ Sullivan, Robertson, & Balsters, 2014; Murphy, Robertson, Balsters, & O’ Connell R, 2011). During phasic activity, the LC shows rapid and brief changes, with individuals exhibiting high-level task-related processing and pupils showing rapid and pronounced changes (Beatty, 1982). Overall, LC tonic activity corresponds to baseline pupil states, while task-related events affect pupil changes by eliciting LC phasic activity. Additionally, pupil changes are related to various neural mechanisms controlling mental activity, including hippocampal activity (McGinley, David, & McCormick, 2015), visual cortex activation (Reimer et al., 2014), and adrenergic and cholinergic activity (Reimer et al., 2016). As Lawrence Stark stated: “The pupil is a paradigm of a neurological control system, and pupillometry is the mathematics of physiology” (cited in Loewenfeld, 1993). Pupil changes serve as an indicator of LC-NE system activity and other intracortical states, indirectly yet intuitively reflecting mental activity under brain control (Murphy et al., 2014; Reimer et al., 2014).

3.2 Adaptive-Gain Theory and the Pupil

Aston-Jones and Cohen (2005) proposed the adaptive-gain theory to explain the relationship between pupils and behavior and the modulating role of the LC-NE system (see Figure 1). This theory posits that human behavior operates in two modes: exploitation and exploration, with individuals switching between these modes to maximize rewards. The LC-NE system plays a crucial role in this switching. Exploitative behavior is often accompanied by LC phasic activity, where different task difficulties and feedback activate different LC phasic responses, thereby affecting pupil changes (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010). When individuals cannot benefit from the current task, they disengage to search for new goals, a behavior often accompanied by LC tonic activity that affects baseline pupil levels (Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2011; Reimer et al., 2014). Consequently, researchers often use pupillometry to test the adaptive-gain theory (Thakkar et al., 2018), while this theory provides a theoretical framework and support for pupils reflecting cognitive processing, emotional arousal, and other mental activities (Mathôt, 2018).

4. How to Effectively Measure Pupils

Exploring the relationship between pupils and psychology depends on the development of pupillometry technology. Hess (1965) used a simple pupillary response device to record participants' pupils, initiating psychological research based on pupillometry. However, this device' s low sampling rate and inaccurate recording were obvious limitations (Janisse, 1973). With advances in eye-tracking technology, eye trackers can simultaneously record pupil changes during eye movements, and specialized pupillometers have been developed for measuring pupil changes. Pupillometry has gradually become an independent method in psychological research, revealing many mental activities (e.g., perception, attention, mental effort) and is considered an easy-to-operate, reliable, non-invasive, and visualizable method (Bradley, Sapigao, & Lang, 2017). Compared to commonly used behavioral measures (e.g., reaction time, accuracy) and neurophysiological indicators such as skin conductance and heart rate, pupil metrics can sensitively and dynamically reflect psychological changes. Compared to neurophysiological techniques such as event-related potentials and brain imaging, pupillometry is relatively inexpensive, simple to operate, and minimally intrusive to participants. However, pupillometry faces a particular challenge: the sensitive pupil metric is highly susceptible to interference from confounding variables (e.g., luminance, gaze position, blinks). Therefore, how to measure pupils effectively and accurately is a major concern for many researchers. Summarizing previous research experience, several aspects require special attention in pupillometric studies:

First, luminance control. Luminance is the primary physical factor affecting pupil changes (Mathôt, 2018); therefore, luminance must be strictly controlled when recording pupil data, and pupil metrics should be used cautiously in ecological environments (Peysakhovich, Vachon, & Dehais, 2017). To better control this factor, researchers recommend conducting cognitive task studies in moderate luminance environments (Eckstein, Guerra-Carrillo, Singley, & Bunge, 2017; Steinhauer, Siegle, Condray, & Pless, 2004). Compared to ambient luminance, screen luminance has a greater impact on pupils (screen luminance causes a pupil change threshold of 1mm; ambient luminance causes a threshold of 0.4mm) (Benedetto, Carbone, Drai-Zerbib, Pedrotti, & Baccino, 2014). Therefore, after controlling ambient luminance, stimulus luminance should be averaged to reduce interference.

Second, gaze position. Most eye-tracking research uses optical recording-based eye trackers (e.g., pupil-corneal reflection recording). When the camera is fixed but the eyes look at different positions, the recorded pupil area may change due to eye rotation even if the actual pupil size remains constant. Moreover, the effect of gaze position on pupil measurement varies across eye trackers. Brisson et al. (2013) had participants track a rotating blue dot to examine the effects of gaze position and eye tracker type on pupil size. They found that in Tobii systems, pupil diameter was more affected by horizontal position (pupil size at left gaze positions was overestimated), whereas in EyeLink systems, it was more affected by vertical position (pupil size at downward gaze positions was overestimated). Therefore, in practice, it is best to place experimental materials at the center of the screen.

Third, pupil baseline correction. Considering the influence of pupil oscillations and individual differences in pupil size, researchers must perform baseline correction or comparison to increase statistical power. Baseline can be selected as the 0.5s or 1s before stimulus presentation (e.g., Binda & Murray, 2015; Olmos-Solis, Van Loon, & Olivers, 2018; Peysakhovich, Causse, Scannella, & Dehais, 2015; Chen & Westermann, 2018; Laeng & Sulutvedt, 2014) or 0.5s after stimulus presentation (e.g., Galazka et al., 2018). This depends on the experimental task and purpose, and there is currently no unified standard. After determining the baseline, researchers need to process pupil size under experimental conditions based on the baseline. The main processing methods are two: division correction (corrected pupil = pupil size / baseline value) and subtraction correction (corrected pupil = pupil size - baseline value). Mathôt et al. (2018) compared the advantages and disadvantages of these two methods using simulated and experimental data, finding that subtraction correction is less affected by noise such as blinks and is a more ideal pupil correction method. Additionally, Mathôt et al. (2018) proposed five recommendations for more effective pupil correction: (1) preprocess data (e.g., handle missing values, outliers; correct pupil diameter errors caused by different gaze positions); (2) use subtraction correction; (3) directly observe and compare differences between corrected and raw data to ensure no essential changes; (4) if corrected pupil size increases significantly within 220ms (the latency of pupil changes), baseline outliers may exist; and (5) plot histograms of baseline pupil values and delete abnormally small baseline values. Baseline-corrected pupil values can more objectively reflect changes induced by experimental manipulations, supporting the application of pupillometry in scientific research.

Fourth, blink processing. Participants' blinks during experiments may cause data loss. One processing method is to interpolate pupil measurements before and after each blink (100 or 150ms before and after) (e.g., Kloosterman et al., 2015; Knapen, Gee, Hoppenbrouwers, & Theeuwes, 2016; Olmos-Solis et al., 2018). However, luminance entering the retina after a blink is stronger than during the blink, causing slight and rapid pupil constriction that may take 5 seconds to return to baseline (Knapen et al., 2016). Knapen et al. (2016) designed a finite impulse-response deconvolution (FIR) algorithm to estimate blink-induced pupil changes using a general linear model (GLM), helping reduce measurement errors caused by blinks. The former method is simpler and more widely used, but the latter is more rigorous as it accounts for pupil constriction caused by sudden luminance increases.

Regarding other aspects, such as left-right eye selection: since differences between left and right pupils are minimal (Brisson et al., 2013), most studies select data from either eye or average both eyes' pupil sizes. For pupil metric selection, the most commonly used are baseline-corrected (typically by subtracting baseline mean) average pupil diameter or peak values (Van Hooijdonk et al., 2019; Wendt, Koelewijn, Ksiazek, Kramer, & Lunner, 2018), sometimes with additional Z-score standardization (Derksen et al., 2018). Researchers can refer to commonly used pupil metrics in their field.

5.1 Summary

In summary, pupils are influenced not only by bottom-up effects of physical luminance but also by top-down processing such as perception and attention, mental effort, emotion and motivation, and social cognition and development. Pupil metrics can serve as important indicators for detecting mental activities when confounding variables are well controlled. During social communication, pupils affect others' psychological perception and overt behavior. Research has confirmed that larger pupils can elicit more positive evaluations and behaviors from others. The close connection between pupils and psychology originates from the neural mechanisms of pupils, primarily the role of the locus coeruleus-norepinephrine system. Additionally, the adaptive-gain theory reveals the correspondence among pupil changes, physiological mechanisms, and behavioral patterns. Finally, this paper organizes existing literature on how to exclude or control confounding variables and process pupil data, offering operational recommendations.

5.2 Future Directions

Future research can continue in the following areas:

First, the greatest challenge facing pupillometry applications in psychology is how to interpret the psychological meaning behind pupil changes (Hepach &

Westermann, 2016). For example, most studies consider pupil mimicry a social phenomenon of emotional communication (Prochazkova & Kret, 2017; Prochazkova et al., 2018). However, some researchers propose that pupil mimicry is merely a simple light reflex without social significance, because pupils are darker than the iris, and pupil dilation reduces luminance in the eye region, causing reflexive dilation in others. Therefore, whether pupil mimicry can serve as an indicator of social communication remains debatable (Derksen et al., 2018; Mathôt & Naber, 2018). More importantly, pupil dilation cannot directly tell us which psychological process is being aroused. Therefore, experimental designs should minimize interference from irrelevant factors, especially spontaneously generated emotions, cognitive load, orienting responses, and fatigue during experiments, and results should be interpreted cautiously. Research reports must also detail data collection (e.g., luminance, gaze position, equipment) and data processing methods (e.g., baseline, blinks, invalid pupil data) to ensure rigor.

Second, investigate how pupil size and changes affect others' psychological perception and behavior. Hess (1965, 1975) began studying how pupils affect subjective evaluations, but subsequent research progressed slowly. In recent years, psychologists led by Kret have found that large pupils can promote trust behaviors in others and have conducted related studies (Kret et al., 2015; Kret & De Dreu, 2019). They have primarily explored whether pupil size effects on trust investments are moderated by partner characteristics (e.g., partners' pupil dynamics, gaze direction, in-group status) and task contexts (e.g., whether conflicts of interest exist between participants and partners) (Kret & De Dreu, 2017; Kret & De Dreu, 2019; Van Breen et al., 2018). However, human psychology and behavior extend far beyond these domains. Exploring how pupils affect other psychological processes (e.g., attention, emotion, motivation) and social behaviors (e.g., helping, aggression, conformity) will be a future research direction. Additionally, cultural factors may be influential, and future studies could compare the effects of pupil size on others' psychology and behavior across Eastern and Western cultural contexts.

Third, future research should continue exploring ways to enhance the explanatory power of pupil metrics. At the technical level of measurement and data analysis, researchers have designed the Pupil© platform, providing low-cost and convenient hardware and software (see Picanco & Tonneau, 2018), and developed CHAP (Cohen and Hershman Analysis Pupil), an open-source MATLAB-based software for independently analyzing pupil data from various eye trackers including EyeLink and Tobii (Hershman, Henik, & Cohen, 2019). At the theoretical level, researchers should elevate pupillometry to a theoretical level to explain pupil changes. For example, the adaptive-gain theory combines neural physiological activity, overt behavioral patterns, and pupil changes to explore their relationships, though it does not distinguish specific mental activities. Additionally, domestic research often uses pupil size as a supplementary indicator to reflect psychological factors such as cognitive load (陈庆荣, 邓铸, 谭顶良, 2008), interest (王福兴, 侯秀娟, 段朝辉, 刘华山, 李卉, 2016), and fatigue (李勇, 阴国恩, 陈燕丽, 2004). Future research could combine pupillometry with other techniques, especially electrophysiological methods, to broaden its application and help understand the relationships among pupils, psychology, and neurophysiology.

Fourth, use different pupil metrics for data analysis. Most studies use pupil size and its changes as metrics (闫国利 et al., 2013). However, since pupil size is affected by objective factors such as luminance, distance, and equipment, some research has adopted methods from MEG/EEG studies of steady-state visual evoked potentials, analyzing pupil oscillation frequency using Fast Fourier Transform (FFT). This research found that in visual search tasks, the flicker frequency of attended stimuli synchronizes with pupil oscillation frequency—the higher the flicker frequency of attended stimuli, the stronger the pupil oscillation (Naber, Alvarez, & Nakayama, 2013). This study shows that pupil oscillation, like pupil size, can reflect attention, providing a new method for pupillometry and attention research. Future research could also use pupil oscillation as an indicator of other mental activities, helping researchers more comprehensively understand the relationship between pupils and psychology.

Fifth, broaden the application of pupillometry in scientific research and daily life, especially in experiments and clinical studies with special populations. Research has found that pupil size can reflect mental effort in schizophrenia patients during decision-making (Reddy, Reavis, Wynn, & Green, 2018). Choi et al. (2017) designed a pupillometry-based neurofeedback cognitive training program that adjusts task difficulty in real-time based on mental effort reflected by pupils, helping improve processing speed and social functioning in individuals at clinical high risk for psychosis. Additionally, recent research has used pupil changes during task performance to reflect psychological dysfunction, considering abnormal pupil changes as one of the diagnostic and risk prediction indicators for depression, schizophrenia, and autism (Burley, Gray, & Snowden, 2018; Kudinova et al., 2016; Nystrom et al., 2018). However, it should be noted that most studies use medicated patients as participants, and medication can also affect pupils. Future research could use unmedicated patients to explore how diseases affect psychological functions using pupillometry (Thakkar et al., 2018). Pupillometry also provides an important window for understanding social cognition and language development in preverbal infants (Hepach & Westermann, 2016; 王福兴, 童钰, 钱莹莹, 谢和平, 2016). Overall, as a non-invasive, complementary cognitive measurement method with high temporal resolution and solid neural foundations, pupillometry holds promise for application in clinical, developmental, and neuroscientific research (Bradley et al., 2017; Eckstein et al., 2017).

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Note: Figure translations are in progress. See original paper for figures.