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ORIGINAL ARTICLE

The pupil and myself: pupil dilation during retrieval of self-defining memories

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Abstract

Background There is a recent interest in pupil dilation during the retrieval of autobiographical memory. We pursued this line of research by measuring pupil diameter during the retrieval of self-defining memories, that is, memories that are highly vivid, emotionally intense, and are retrieved to reflect enduring concerns in a person's life.

Methods We invited 40 participants to retrieve self-defining memories while their pupil activity was recorder with eye-tracking glasses. We analyzed memories regarding specificity (i.e., specific or general) and emotional valence (neutral, positive, negative, or mixed).

Results Analysis demonstrated larger pupil diameter during the retrieval of specific than general self-defining memories. However, no significant differences in pupil diameter were observed across the four emotional categories of self-defining memories.

Discussion The increased pupil size during retrieval of specific self-defining memories can be attributed to the autonoetic experience during retrieval of these memories and/or to the cognitive load as required to construct these memoires. By investigating pupil dilation during the retrieval of self-defining memories, our study provides an original, ecological, and reliable physiological assessment of these memories.

Keywords Autobiographical memory · Pupil · Pupillometry · Self-defining memories

Introduction

Physiological changes in response to cognitive and emotional processing can be mirrored by the eye. While the human eye is quintessentially a vital sensory organ that serves to receive external visual information, it also mirrors and reflects cognitive and emotional processing. More specifically, cognitive and emotional processing can be mirrored by pupil dilation. The pupil (i.e., the opening area of the iris that allows light to reach the retina) is controlled by the sphincter muscles that decrease the diameter of pupil and dilator muscles that increase the diameter [1, 2]. These two muscles serve to optimize vision by modulating the amount of light that reaches the retina, whereas the pupil dilates in darker conditions, it constricts in brighter conditions. The pupil reacts to stimulation in about 200 ms. Pupil diameter typically varies from 1.5 to 9.0 mm, but in standard light conditions, this diameter is about 3 mm [3, 4]. The pupil does not only react to light, but also to emotional and cognitive effort [5, 6]. Based on this fact, in this study, we investigated whether pupil diameter can vary during the retrieval of self-defining memories, that is, memories that are highly vivid, emotionally intense, and are retrieved to reflect enduring concerns in a person's life [7, 8]. Our objective in this study was motivated by a wealth of research demonstrating how cognitive and emotional

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processing triggers pupil dilation, and how the retrieval of autobiographical memory triggers pupil dilation.

There is a wealth of research demonstrating how pupil diameter increases with cognitive load. Research on working memory has demonstrated that pupil diameter increases with each digit retained in digit span tasks until the length of the digits exceeds the capacity of working memory, at which pupil diameter begins to plateau or even diminish [9–13]. This research demonstrates that pupil dilation can be a reliable and valid psychophysiological marker of cognitive load, that is, that the measurement of pupil dilation can provide an online indication of the amount of cognitive effort devoted to a given task. The pupil does not only dilate in response to cognitive load but also due to emotional processing. A body of research has demonstrated how the pupil typically dilates in response to emotionally laden information compared to neutral information [14, 15]. This dilation has been observed for a wide variety of stimuli such as emotional video clips [16] and facial expressions [17, 18]. Taken together, pupil dilation can mirror cognitive and emotional processing. Critically, and as discussed below, pupil dilation also mirrors autobiographical memory processing.

Until recently, little was known about pupil dilation during the retrieval of autobiographical memory. This issue was addressed in a study by El Haj, Janssen[19] who invited participants to retrieve autobiographical memories freely (i.e., first memory that comes to mind) as well as positive and negative autobiographical memories (i.e., memories cued by, respectively, the words "happy" and "sad"). Participants were also invited, in a control condition, to count aloud. Pupil dilation was recorded with eye-tracking glasses during the autobiographical memory and control conditions. Analysis demonstrated no significance differences between pupil dilations across the retrieval of freely recalled, positive, and negative memories, which was attributed by the authors to the assumption that even freely recalled memories have triggered emotional content. However, and critically, results have demonstrated larger pupil diameter during the retrieval of autobiographical memories than during the control condition. El Haj, Janssen[19] attributed the larger pupil diameter, as observed during the autobiographical compared to the control condition, to the cognitive load required to reconstruct the context in which the retrieved autobiographical events were previously encoded. The cognitive load hypothesis was also proposed by El Haj and Moustafa[20] who recorded pupil dilation of participants during two conditions autobiographical retrieval and future thinking (i.e., imagining personal an event that may occur in the future). Results demonstrated a larger pupil size during future than past thinking. Results also demonstrated longer retrieval time during future thinking compared to past thinking, suggesting that future thinking perhaps involves more cognitive load, and thus larger pupil size, than past thinking. Although the studies of El Haj, Janssen[19] and El Haj and Moustafa[20] offer the first evaluations of pupil dilation during autobiographical retrieval, they did not investigate eye dilation for self-defining memories.

Because our study aims at the evaluation of pupil dilation during the retrieval of self-defining memories, it would be of interest to highlight characteristics of these memories. Compared with typical autobiographical memories, self-defining memories are highly important for self-understanding and goal-seeking as they are typically activated to provide guidance and motivation to pursue important goals in life [21–23]. These memories provide us with a sense of continuity, meaning, and purpose, across situations, as well as with a significant understanding of both the self and the world [8]. Self-defining memories ground self since these memories allow us to update our self-concept by integrating these important experiences in our life story. This "meaning-making" process allows us to learn lessons from past events and to stand back from the past to realize how we have changed the way we see ourselves, others, or the world [8, 23, 24]. Considering their relevance to the sense of self, we investigated pupil dilation during the retrieval of self-defining memories. By doing so, we aimed to provide a cheap and ecologically valid tool to understand the characteristics of these memories.

To evaluate the characteristics of self-defining memories with pupil dilation, we evaluated the specificity of these memories. Specificity (i.e., the ability to retrieve memories situated in a specific time and space) can be considered a measure of cognitive effort during retrieval. The more specific the memories are, the more cognitive effort is required [25–28]. Besides specificity, we investigated emotional valence of self-defining memories as these memories do not evoke the same emotional valence. While some self-defining memories trigger positive emotions, other self-defining memories trigger fair negative emotions, especially when these memories are associated with ruminative thinking [29]. Furthermore, self-defining memories may involve mixed emotional valence as these memories sometimes trigger both positive and negative affective states [30].

To summarize, self-defining memories are highly important to the self and identity as these memories provide us with a sense of continuity, meaning, and purpose, across situations, as well as with a significant understanding of both the self and the world [21–23]. Considering their importance to the self and identity, we investigated pupil dilation during retrieval of self-defining memories, hoping to provide a cheap and ecologically valid tool to evaluate the characteristics of these memories. More precisely, we evaluated whether pupil diameter would vary following specificity and emotional valence of self-defining memories. We predicted larger pupil diameter for specific self-defining memories compared to general ones. We also predicted larger pupil diameter for positive, negative, and mixed self-defining memories compared to neutral ones.

Method

Participants

The study included 40 graduate/undergraduate students (23 females) from the University of Nantes (*M* age = 23.78 years, *SD* = 5.76, *M* education = 14.11 years, *SD* = 4.92). We found no significant differences regarding gender [X^2 (1, $N = 40) = 0.09$, $p = 0.76$]. Participants were native French speakers. The sample size was determined based on previous research on pupil dilation during autobiographical memory [19]. The original sample size included 50 participants. Four participants were, however, excluded as they declared having previous neurological or psychiatric disorders; three participants were excluded due to signal loss during recording, and three other participants were excluded as their pupil data exceeded typical ranges (i.e., outside the range of 1.5–9 mm) [3, 4]. Thus, the final sample size was 40 participants.

Procedures

Participants were tested individually in a quiet room at the Psychology Department of the University of Nantes. Participants were asked to retrieve three self-defining memories (see instructions, below) while they wore eye-tracking glasses and faced a white wall. To ensure that differences in pupil dilation were not caused by differences in retinal illumination, blinds were closed and the lightness of the room (60-W fluorescent lamp) was the same during the session. Prior to the experiment, participants were informed that the experiment was related to vision and memory in general. In order not to influence their performance, the participants were not provided with further details regarding pupil dilation and its relationship to self-defining memories.

The retrieval of self-defining memories

We invited participants to retrieve three self-defining memories using the following instruction: "You are invited to remember three events in your life. These events must be important in defining who you are. In other words, these memories should refer to events that help you understand who you are as an individual; these events should also be events that you would share with someone if you wanted that person to understand you in a basic way. The events may be positive or negative memories; the only important aspect is that they should lead to strong feelings. The memories should be events that you have thought about many times. They should also be familiar to you like a picture you have looked at a lot or a song you have learned by heart." These instructions replicated those used in previous research on self-defining memories [24]. The instructions were repeated when participants did not succeed to retrieve three memories. As mentioned in the "Results" section below, some participants only retrieved two memories.

Pupil recording

Self-defining memories were retrieved while pupil dilation was recorded using the Pupil Capture software. Participants wore eye-tracking glasses (Pupil Lab) consisting of a remote pupil-tracking system that uses infrared illumination with 200 Hz sampling rate and a gaze position accuracy of $< 0.1°$. Prior to retrieval, calibration was made by inviting participants to fixate on a black cross (a 5×5 cm cross, printed on an A4 white paper fixated at the wall center) that was used as a calibration reference; the cross was withdrawn after calibration. During retrieval, participants were seated in front of a white wall and the distance between the subjects and wall was approximately 30–50 cm. Participants were instructed not to look outside the wall, but were free to explore all parts of it. Needless to say, the wall did not display any visual stimuli (e.g., drawings, windows). Regarding dependent variables, we calculated the mean of pupil dilation (in mm) during the retrieval of the three memories.

The coding of self-defining memories

Memories were recorded with a smartphone throughout the experiment and were transcribed and evaluated a posteriori using the classification system and scoring manual for self-defining memories [30]. According to this classification system, memories were coded as specific if they depicted a specific brief and detailed event (i.e., situated in time and space) with a unique occurrence. In contrast, general self-defining memories referred to memories of long or repeated events. Exceptions were considered for categorizing specific memories: if memories seemed general but included a specific event associated with details and the expression of emotion, they were coded as specific. In addition, if memories seemed general but contained a speech or dialogue with precision about one person, these were also coded as specific. If the retrieved events lasted for more than 24 h but corresponded to a memory of a specific event, then the memories were also coded as specific. Regarding the emotional dimension, memories were coded as positive, negative, neutral, or mixed according to the emotional words expressed by the participants. If no emotional words were expressed, the memory was categorized as neutral. If the memory contained both positive and negative emotional vocabulary, it was coded as a mixed memory [30].

To avoid scoring bias, all memories were rated by independent judges who also followed the coding instructions of Singer and Blagov[30]. Inter-judge agreement was calculated with Cohen's kappa (K) [31], which demonstrated a substantial agreement score (K specificity = 0.82; K emotional valence = 0.81, K). Cases of disagreement were discussed until a consensus was reached.

Statistics

Following the objectives of the study, we carried out different analyses. We first analyzed differences between the number of specific and general self-defining memories, as well as between the number of positive, negative, mixed, and neutral self-defining memories. Afterward, we compared differences on pupil diameter between specific and general self-defining memories, as well as between positive, negative, mixed, and neutral self-defining memories. Because the Shapiro–Wilk test did not show normal distributions, we used non-parametric statistical tests: a Mann–Whitney test for two independent samples (specific vs. general self-defining memories) and a Kruskal–Wallis test for k samples (i.e., positive, negative, mixed, vs. neutral self-defining memories). For all tests, statistical significance was defined at $p < 0.05$, and effect sizes were reported; $d = 0.2$ can be considered a small effect size, $d = 0.5$ represents a medium effect size, and $d = 0.8$ refers to a large effect size [32]. The effect size was calculated for non-parametric tests following recommendations by Rosenthal and DiMatteo[33] and Ellis[34].

Results

More specific than general memories but no significant differences regarding emotion

Thirty-two participants retrieved, each, three self-defining memories while eight participants retrieved, each, only two memories. The total number of memories was thus 112. Table 1 describes the distribution of memories according to specificity and emotional valence. Analyses showed that participants produced more specific than general self-defining memories [X^2 (1, $N = 112$) = 22.32, $p < 0.001$, Cohen's $d = 1.00$]. Significant differences between the distribution of self-defining memories were observed regarding the four emotional dimensions [X^2 (3, $N = 112$) = 21.50, $p < 0.001$, Cohen's $d = 0.97$]. Participants produced more mixed than neutral [X^2 (1, $N = 60$) = 19.27, $p < 0.001$, Cohen's $d = 1.37$], positive [X^2 (1, $N = 75$) = 4.81, $p = 0.03$, Cohen's $d = 0.52$], and negative self-defining memories [X^2 (1, $N = 71$) = 7.45, $p = 0.006$, Cohen's $d = 0.68$]. Participants also produced more positive than neutral self-defining memories [X^2 (1, $N = 41$) = 5.49, $p = 0.02$, Cohen's $d = 0.78$]. However, no significant differences were observed between the number of negative and neutral self-defining memories [X^2 (1, $N = 37$) = 3.27, $p = 0.07$, Cohen's $d = 0.62$], or between negative and positive self-defining memories [X^2 (1, $N = 52$) = 0.03, $p = 0.86$, Cohen's $d = 0.05$].

Table 1 Distribution of the self-defining memories ($n = 112$) according to their specificity and emotional valence

Specificity	Specific	81
	General	31
	Total	112
Emotion	Neutral	13
	Positive	28
	Negative	24
	Mixed	47
	Total	112

Larger pupil diameter during retrieval of specific than general memories

As illustrated in Fig. 1, larger pupil diameter was observed during retrieval of specific than general memories ($Z = -2.43$, $p = 0.015$, Cohen's $d = 0.47$).

No significant differences in pupil diameter regarding emotional processing

As illustrated in Fig. 2, no significant differences in pupil dimeter were observed across the four emotional categories of self-defining memories (i.e., positive, negative, mixed, vs. neutral self-defining memories) [X^2 (3, $N = 112$) = 1.98, $p = 0.58$, Cohen's $d = 0.26$].

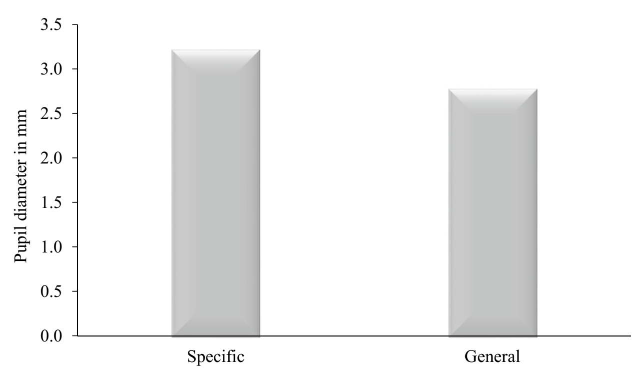

Fig. 1 Means of pupil diameters during retrieval of specific and general self-defining memories

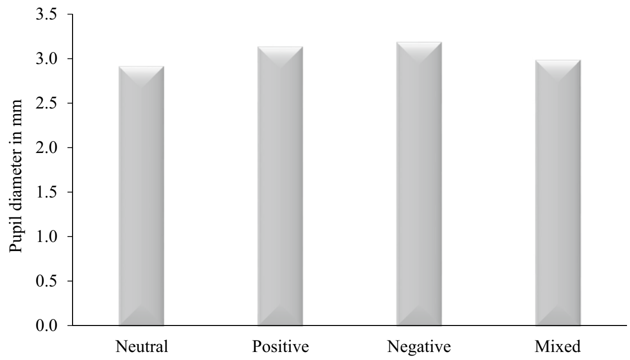

Fig. 2 Means of pupil diameters during the retrieval of neutral, positive, negative, and mixed self-defining memories

Discussion

We evaluated pupil diameter during the retrieval of specific and general self-defining memories, as well as during the retrieval of neutral, positive, negative, and mixed self-defining memories. Analysis demonstrated larger pupil diameter during the retrieval of specific than general self-defining memories. However, no significant differences in pupil diameter were observed across the four emotional categories of self-defining memories.

The increased pupil diameter during the retrieval of specific self-defining memories can be attributed to the contextual richness of these memories. In our procedures, specific self-defining memories referred to those describing detailed events (i.e., situated in time and space) with a unique occurrence, whereas general memories referred to those describing long or repeated events without contextual details. Beyond the contextual account, the increased pupil diameter during the retrieval of specific self-defining memories can be attributed to the subjective experience of these memories. Our assumption can be supported by the typical definition of episodic memory [35] according to which the retrieval of unique and specific (i.e., episodic) memories triggers a subjective state of mental time travel. This mental time travel, or autonoetic consciousness [35], refers to the ability to mentally project oneself backwards in time to relive the past. Autonoetic consciousness, as induced by episodic retrieval, is distinguished from noetic consciousness which refers to the general awareness of the past or the general feelings of familiarity or knowing [35]. Thus, the increased pupil diameter during the retrieval of specific self-defining memories can be attributed to the autonoetic experience of these memories. This assumption can be supported by research demonstrating how pupil size increases with the conscious recollection on recognition memory tests [36, 37].

Besides the autonoetic account, the increased pupil diameter during the retrieval of specific self-defining memories can be attributed to the cognitive load as required to construct these memoires. The retrieval of contextual details typically requires high cognitive processing (e.g., retrieving these details, retrieving the temporal order of these details, binding or creating associations between these details) [38]. Furthermore, in pathological populations, a decline in these cognitive processes has been associated with autobiographical overgenerality, as observed in depression [25], alcohol dependence [28, 39], or Alzheimer's disease [26, 27]. Therefore, the increased pupil diameter during the retrieval of specific self-defining memories can be attributed to the cognitive load as typically required to retrieve specific memoires. Importantly, pupil diameter typically increases with cognitive load and effort during remembering, as reported by research on working memory [9–13].

While our findings demonstrated significant differences in pupil diameter regarding specificity of self-defining memories, no significant differences were observed regarding emotional content of these memories. The lack of significant differences in pupil diameter regarding emotional processes mirrors a previous study demonstrating no significant variations in pupil diameter across neutral, positive, and negative autobiographical memories, regardless of their self-defining nature [19]. The lack of significant differences regarding emotional valence of self-defining memories, as observed in our study, may mirror that, regardless of their emotional valence, these memories hold similar affective value. More specifically, regardless of their emotional valence, self-defining memories may yield similar affective valence as all these memories are highly important for self-understanding, goal-seeking, and meaning-making. These affective processes (e.g., self-significance, meaning-making), as may be equally involved in all self-defining memories regardless of their emotional valence, may result in the no significant differences in pupil diameter regarding emotional processes.

Although our study demonstrates no significant differences in pupil diameter regarding emotional valence of self-defining memoires, it would be of interest to investigate whether significant differences can be observed in pathological populations. A significant tendency to retrieve negative self-defining memoires has been reported in both patients with alcohol use disorder [40] and in patients with schizophrenia [41]. It would be of interest to investigate whether differences in pupil diameter can be observed in these populations during the retrieval of negative self-defining memories compared to positive, mixed, or neutral ones. Another suggestion for future research is the comparisons between self-defining memoires and non-self-defining memories. Also, future research can assess whether pupil changes during retrieval of self-defining memories can be influenced by eye movements, especially by saccadic planning. This in light of research demonstrating how eye movement influences pupil activity [42, 43].

By investigating pupil dilation during the retrieval of self-defining memories, our study provides an original, ecological, and reliable physiological assessment of these memories. Pupil dilation is closely tied to activity of the autonomic nervous system [44, 45]. While activity of the autonomic nervous system can be evaluated with skin conductance reactivity or heart rate, there are a number of advantages for measuring this activity regarding changes in pupil diameter. For instance, cognitive/emotional changes in pupil diameter occur more rapidly (after approximately 500 ms) compared to skin conductance reactivity (after approximately 1000–5000 ms). Thus, pupillometry offers a time-sensitive measure of activity of the autonomic nervous system. Critically, and unlike measures of skin conductance reactivity or heart rate, pupillometry does not require attaching wires to the participant. The same thing can be said for research using facial expressions to evaluate physiological responses during retrieval self-defining memories. A study by Gandolphe, Nandrino[46] evaluated facial expressions during retrieval of self-defining memories, this to demonstrate more emotional than neutral facial expressions during retrieval of these memories. However, Gandolphe, Nandrino[46] did not evaluate the emotional valence of self-defining memories. Together, like research on facial expressions, research on pupil dilation offers a great potential for the study of self-defining memories, especially in pathological populations.

To summarize, our study paves the way for a new era in the study of self-defining memories in which the subjective experience of these memories can be indexed with pupil dilation. Although self-defining memories are still fueling empirical research, the characteristics of these memories remains enigmatic probably because their study mainly relies on subjective evaluation. We address this need by offering the first study on pupil dilation during retrieval of self-defining memories. Because pupillometry can be embedded into eye-tracking technology, which will soon be available in everyday life, we believe that the study of self-defining memories, and memory in general, should take advantage of this technology to offer an ecological and reliable physiological assessment of memory processes.

Declarations

Conflict of interest None.

Ethical approval Informed consent was obtained in accordance with the Helsinki Declaration principles.

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