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Emotional imagery and pupil diameter

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Abstract

Pupil diameter is enhanced in a variety of emotional contexts, including viewing pictures, listening to sounds, and during threat of shock. In this study, we investigated pupil diameter changes during emotional imagery. Participants imagined scenes describing pleasant, unpleasant, or neutral events while pupil diameter was continuously recorded. Second by second changes in pupil diameter were analyzed to determine whether, and when, modulation of the pupil as a function of hedonic content is found. Results indicated a significant effect of hedonic content beginning shortly after script onset, with enhanced pupil diameter when imagining emotional (pleasant or unpleasant), compared to neutral, scenes. Pupil diameter during imagery covaried with rated emotional arousal, consistent with an interpretation that changes in pupil diameter during emotional imagery reflect sympathetic nervous system activity. Because emotional imagery is a key element in clinical assessment and treatment, pupil diameter could prove a useful index of emotional engagement in a variety of clinically pertinent contexts.

KEYWORDS

emotion, eye tracking, imagery, pupillometry

1 | INTRODUCTION

Pupil diameter is modulated by emotional arousal in a number of different contexts, including picture viewing, in which larger changes in pupil diameter are found when viewing highly arousing pleasant or unpleasant, compared to neutral, scenes (Bradley, Miccoli, Escrig, & Lang, 2008; Ferrari et al., 2015; Henderson, Bradley, & Lang, 2014; Snowden et al., 2016). Pupil dilation has also been reported when participants listen to pleasant or unpleasant, compared to neutral, sounds (Partala & Surakka, 2003) and when participants anticipate the upcoming presentation of an aversive event. For example, Bitsios, Szbadi, and Bradshaw (1996) found that pupil diameter was enhanced when participants were under threat of shock exposure, compared to when no shock exposure was possible. In the current study, we investigated whether pupil diameter is similarly modulated by emotion during mental imagery. Because emotional imagery is a key component in the assessment (Lang, McTeague, & Bradley, 2016; Wangelin & Tuerk, 2015) and treatment of mental health disorders (Foa, Hembree, & Rothbaum, 2007; Lang, Melamed, & Hart, 1970), pupil diameter could prove to be a useful psychophysiological index in a number of clinical venues.

In this study, brief texts were presented visually that described a variety of emotional and neutral events. The participant was instructed to silently read each script and imagine the events described vividly, as an active participant. Previous studies investigating physiological and neural reactivity during narrative imagery found that modulation by emotion begins while the participant is reading the script, and is sustained during a subsequent imagery period. For instance, skin conductance is enhanced when reading emotional scripts, and the difference is sustained in the imagery interval following script offset (Henderson, Bradley, Mastria, Kroytor, & Lang, 2013). Relatedly, greater BOLD activation is found in the medial prefrontal cortex and nucleus accumbens when participants read pleasant scripts, which again continues during the imagery interval following script offset (Costa, Lang, Sabatinelli, Versace, & Bradley, 2010). These temporal parameters are reasonable, since reading a text, comprehending a text, and preparing to imagine the event

involve similar, if not identical, cognitive processes that can begin as soon as the constituent information becomes available.

An alternative imagery procedure that requires participants to first memorize to-be-imagined scripts (e.g., Vrana & Lang, 1990) eliminates the need for visual input, which could prove beneficial in studying pupil diameter, but imposes a relatively larger working memory burden on the participant, potentially affecting pupil diameter changes (e.g., Steinhauer, Condray, & Pless, 2015; Steinhauer, Siegle, Condray, & Pless, 2004). For this reason, scripts were presented visually in the current study. Importantly, scripts were selected to be of similar character length and did not differ in brightness. Moreover, each script was first read and rated prior to the imagery session specifically to facilitate rapid and immediate image construction during psychophysiological measurement (Costa et al., 2010; Sabatinelli, Lang, Bradley, & Flaisch, 2006).

Whereas previous studies have measured peripheral (e.g., skin conductance, heart rate) and central (e.g., BOLD) indices of affective engagement, in this study we explore pupillary changes occurring during emotional imagery. Pupil diameter changes are mediated by both parasympathetic and sympathetic action of the nervous system, which influence the sphincter and dilator muscles of the pupil, respectively. On the one hand, pupil diameter is greater when participants perform a difficult subtraction task compared to an easier addition task, and pharmacological manipulations suggest that this cognitive difference is likely modulated by inhibition of the sphincter muscle, mediated by parasympathetic activity, which reduces pupil constriction (Steinhauer et al., 2004). On the other hand, during emotional picture viewing, enhanced pupil diameter is found when participants view either highly arousing pleasant or unpleasant scenes, and this difference appears to be mediated by pupil dilation, probably due to differences in sympathetic action on the dilator muscle (Bradley, Sapigao, & Lang, 2017). Because of the sensitivity of pupil diameter to differences in emotional arousal, increased pupil diameter was expected during emotional (i.e., either pleasant or unpleasant), compared to neutral, imagery in the current study.

Imagery was induced by presenting visual scripts for 6 s, followed by a 12-s imagery interval, while pupil diameter was measured continuously. Second by second changes in pupil diameter were analyzed beginning with script presentation and continuing through the imagery interval to determine whether, and when, changes in pupil diameter differed as a function of hedonic content. Because comprehending the events described by a linguistic text involves many of the same processes involved in active imagery, such as memory retrieval and development of a mental model of the described situation (e.g., Glenberg, Kruley, & Langston, 1994), we expected that pupil diameter changes prompted by differences in hedonic content would begin sometime during the initial read period.

An additional phenomenon reported in the pupil diameter literature is modulation of a transient constriction in response to a bright flash of light that is used as a probe during mental processing. Bitsios et al. (1996) report that the magnitude of pupil constriction (i.e., the "light reflex") elicited in response to a light flash is attenuated when the participant is under threat of shock compared to periods in which no shock will occur. To explore whether this fear-inhibited light reflex is found during aversive imagery, we presented brief light probes during imagery and assessed the amplitude of initial constriction as a function of hedonic content.

2 | METHOD

2.1 | Participants

Thirty-five (7 male, 18–29 years old) University of Florida general psychology students gave informed consent and participated for course credit. One participant arrived late and did not complete the ratings task.

2.2 | Materials and design

Stimuli were 45 brief scripts[1] that described pleasant (e.g., "You jump up and block the volleyball at the net, saving the game," "You raise a champagne glass and greet the new year with your lover"), neutral (e.g., "You run a brush through your hair and then put it on the counter," "You come home after a long day and take off your shoes and socks"), and unpleasant events (e.g., "You gasp when you lose control of your car and skid off the road," "You cringe as the dog leaps out at you, snarling in a crazy rage"), including 39 scripts selected from the Affective Norms for English Text (ANET; Bradley & Lang, 2007) and six neutral scripts used in previous imagery studies in our laboratory. Of the 45 scripts, 15 were pleasant (pleasure $M = 8.18$, $SD = 0.16$; arousal $M = 7.40$, $SD = 0.20$), 15 were neutral (pleasure $M = 5.41$, $SD = 0.16$; arousal $M = 4.0$, $SD = 0.26$), and 15 were unpleasant (pleasure $M = 2.31$, $SD = 0.13$; arousal $M = 7.52$, $SD = 0.20$). To minimize perceptual differences, scripts were similar in character length and format, with each script comprising two lines of text displayed in a black mono-spaced font (Courier New) over a light gray background (13 lux) in the center of the screen.

[1]The ANET scripts (Bradley & Lang, 2007) used in this study were pleasant: 2640, 4100, 4450, 4640, 4680, 4710, 7050, 7355, 7496, 8190, 8380, 8430, 8530, 8550, 8610; neutral: 2120, 2230, 2520, 2590, 2840, 2880, 7040, 7250, 7595; unpleasant: 1300, 1500, 2900, 3300, 5900, 6025, 6100, 6370, 6400, 7340, 8010, 9320, 9510, 9600, 9650.

In order to familiarize the participant with the content and to speed rapid image construction, each participant read the scripts and rated pleasure and arousal prompted by each script prior to the psychophysiological assessment using the Self-Assessment Manikin (SAM; Bradley & Lang, 1994). In the rating period, each script was visually displayed for 6 s, during which participants silently read the text. Following a 1-s intertrial interval (ITI), the SAM graphic ratings were presented, resulting in a rating of hedonic valence (9-point scale; 1 = *unpleasant*, 9 = *pleasant*) and arousal (9-point scale; 1 = *low arousal*, 9 = *high arousal*). After both ratings were made, a small fixation cross was displayed for 4 s until the next trial began.

During the imagery procedure, each script was displayed for 6 s, followed by the presentation of an open black circle that signaled the event should continue to be vividly imagined as an active personal experience, which remained on the screen for 12 s following script offset. Brief light probes were presented 11, 12, or 13 s following the onset of each script. Each trial was followed by a varying ITI (10–12 s) consisting of a small fixation cross (plus sign) on a gray background.

The light probe was a brief (400 ms) background change in brightness from 13 to 20 lux, based on pilot data showing that this change in brightness reliably induced a clear light reflex. Fifteen light probes were presented during imagery of each hedonic content (pleasant, neutral, unpleasant), and 15 light probes were presented during the ITI (5 s following onset of ITI).

Script order was counterbalanced such that each block of three trials included one pleasant, one neutral, and one unpleasant script, with light probes presented in the imagery period at 5, 6, or 7 s following script offset. Light probes were also presented during the ITI on one third of trials, with these probes always occurring on trials in which light probes were presented 5 s after script offset. Within a block of nine trials, each content was paired with each probe delay. Three presentation orders were constructed that counterbalanced, across participants, whether a specific script was presented early, middle, or late in the experiment. Participants viewed scripts in one order when making evaluative ratings, and a different order during the imagery phase.

2.3 | Apparatus

Presentation of all stimuli was on an IBM-compatible computer running Presentation software (Neurobehavioral Systems, San Francisco, CA). Stimuli were displayed on a 19-in. monitor (Samsung SyncMaster 191T) at a distance of 30 in. (76.2 cm) from the participant's eye, subtending 8.9 × 9.1 degrees of visual angle.

Pupil diameter was continuously sampled at 60 Hz using an ASL model D6 desk mounted remote eye tracker (Applied Science Laboratories, Bedford, MA). This system consists of a video camera and an infrared light source, which is focused on the participant's right eye. Face recognition is used to track head movements and keep the pupil in focus. The recording video camera was located in front of the participant, situated just below the stimulus presentation monitor. During the imagery task, pupil diameter was continuously sampled at 60 Hz from 2 s before script presentation until 250 ms before the end of the ITI, for an average of 30.75 s per trial, at .01 mm resolution.

2.4 | Procedure

After arriving at the laboratory, each participant signed a consent form and was seated in an upright chair in a small, sound-attenuated, dimly lit room (approximately 70 lux). Participants were instructed to minimize body movements and to keep their gaze directed toward the screen during upcoming tasks.

A calibration procedure was first conducted in which the participant was instructed to sequentially look at nine dots that appeared one at a time on the screen. In the evaluative ratings task, each participant was instructed to read each script silently when it appeared on the screen and to rate pleasure and arousal when SAM appeared, using two arrows on a handheld response box.

During the imagery task, each participant was instructed to silently read and imagine actively engaging in the events described by each script, and to continue imagining until the imagery cue (circle) left the screen and was replaced with an intertrial cue (plus sign). In the ITI, the participant was instructed to relax and clear their mind until the next trial began.

The experimenter emphasized the importance of keeping the eyes open and gaze directed toward the screen at all times. Each participant was informed that brief changes in brightness of the screen would occur and could be ignored.

2.5 | Data reduction

Pupil diameter was converted offline from arbitrary units to millimeters. Linear interpolation was used to estimate pupil size for samples in which the pupil was occluded due to blinking with ASL Results software. Five participants were not included in the final analysis due to unsuccessful pupil discrimination on more than 15% of trials during the imagery task. For the remaining 30 participants, trials with insufficient pupil discrimination for over 15% of the trial were excluded from the analysis (mean percentage of trials excluded = 2%).

For each trial, pupil diameter in the 1 s prior to script presentation was subtracted from each of the following pupil samples. For each subject and trial, the mean change in pupil

diameter was then calculated in 1-s intervals for 11 s, which included the 6-s period in which the script was on the screen and the following 5-s imagery period prior to onset of the earliest light probe. Analyses of variance (ANOVAs) were conducted with hedonic content (pleasant, neutral, unpleasant) and time (1-s intervals) as repeated measures factors, and follow-up ANOVAs were conducted separately on each 1-s interval to decompose significant interactions.

2.5.1 | Script analysis

In this analysis, script, rather than participant, served as the unit of analysis in a regression that used the average pleasure and arousal ratings for each script (across participants) to predict pupil diameter change.

2.5.2 | Probe-induced light reflex

To estimate the pupil response to the brief light probes, pupil diameter in the 1 s prior to probe presentation was subtracted from each of the following pupil samples, and averaged over a 0.5- to 1.5-s postprobe window. Light probe responses were analyzed in an ANOVA with repeated measures of hedonic content (3: pleasant, neutral, unpleasant) and probe interval (2: imagery, ITI). Greenhouse-Geisser was used to correct for sphericity.

3 | RESULTS

3.1 | Evaluative ratings

As expected, evaluative ratings differed as a function of a priori hedonic content. For pleasure ratings, a main effect of content, $F(2, 27) = 1010$, $p < .0001$, indicated higher pleasure ratings for pleasant ($M = 8.01$, $SD = .15$), compared to neutral ($M = 5.31$, $SD = .23$) or unpleasant ($M = 1.92$, $SD = .15$) scripts, $F(1, 28) = 524$, $p < .0001$, $F(1, 28) = 1215$, $p < .0001$, respectively, and lower pleasure ratings for unpleasant scripts compared to neutral scripts, $F(1, 28) = 1050$, $p < .0001$.

For arousal ratings, a main effect of content, $F(2, 27) = 85.2$, $p < .0001$, indicated that, compared to neutral scripts ($M = 3.85$, $SD = .15$), rated arousal was higher for pleasant ($M = 7.41$, $SD = .18$; $F(1, 28) = 294.6$, $p < .0001$) and unpleasant scripts ($M = 7.30$, $SD = .22$; $F(1, 28) = 79.3$, $p < .0001$), which did not differ in rated emotional arousal.

3.2 | Emotional imagery

Figure 1 illustrates the change in pupil diameter for each second following script onset as a function of hedonic content. A repeated measures ANOVA indicated main effects of time, $F(10, 20) = 15.7$, $p < .001$, $\eta\rho^2 = .351$, and hedonic content, $F(2, 28) = 4.6$, $p < .05$, $\eta\rho^2 = .136$, as well as an interaction of time and content, $F(2, 28) = 3.3$, $p < .005$, $\eta\rho^2 = .103$. Simple main effects tests were conducted for each time bin, and indicated that pupil diameter varied with hedonic content beginning in the third time bin after script onset, which was then sustained across the imagery period (time bins 3–11: Fs(2, 28) = 6.6, 6.2, 4.4, 5.4, 2.4, 3.7, 4.8, 6.1, 6.5, ps $< .05$ except time bin 7, $p = .1$). Significant quadratic trends indicated that pupil diameter when imagining pleasant or unpleasant scenes was larger than when imagining neutral scenes at each time bin (time bins 3–11: Fs(2, 28) = 12.5, 11.9, 7.9, 5.4, 4.1, 6.3, 7.8, 9.4, 10.0; ps $< .05$, except time bin 7, $p = .05$). Consistent with this, when pupil diameter was averaged across the effective imagery interval (time bins 3–11), there was a significant main effect of content, $F(2, 28) = 5.4$, $p < .01$, and follow-up comparisons indicated enhanced pupil diameter when imagining unpleasant ($M = 0.23$, $SD = 0.19$; $F(2, 28) = 5.7$, $p < .05$) or pleasant ($M = 0.22$, $SD = 0.19$; $F(2, 28) = 10.2$, $p < .005$), compared to neutral ($M = 0.15$, $SD = 0.21$) events.

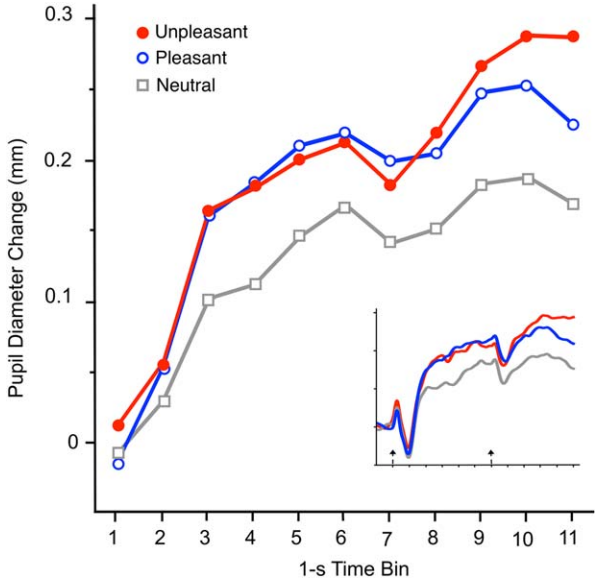

FIGURE 1 Pupil diameter change (mm) from a 1-s baseline interval during imagery of unpleasant, pleasant, and neutral scenes, averaged over 1-s intervals, shows enhanced pupil diameter for emotionally arousing (pleasant or unpleasant), compared to neutral, scenes. The inset shows pupil data at the acquired 60 Hz sampling rate, and the dotted arrows indicate script onset and offset

3.2.1 | Script analysis

Pleasure and arousal ratings for each script were used to predict pupil diameter in the interval in which emotional modulation was significant (average of time bins 3–11). Rated emotional arousal accounted for significant variance in the amplitude of pupil dilation, $F(1, 44) = 5.8$, $p < .05$, $r = .35$,

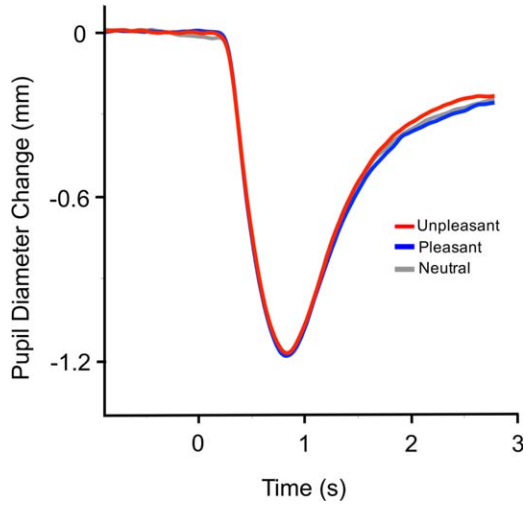

FIGURE 2 Pupil diameter change (mm) following presentation of a light probe consisting of a brief change in screen illumination in the context of imagining either unpleasant, pleasant, or neutral scenes. Pupil diameter is shown deviated from a 1-s preprobe baseline

but there was no relationship between rated pleasure and pupil dilation.

3.2.2 | Probe-induced light reflex

Figure 2 shows pupil diameter changes to the brief light probes presented during imagery. A large transient constriction is evident that was not modulated by hedonic content. A 3 Content (pleasant, neutral, unpleasant) × 2 Interval (imagery, ITI) repeated measures ANOVA found only a main effect of interval, $F(1, 29) = 5.2$, $p < .05$, with a slightly larger amplitude light reflex for probes presented during imagery ($M = .94$, $SD = .30$), compared to the ITI ($M = .88$, $SD = .32$). There was no interaction between hedonic content and interval.

4 | DISCUSSION

Mentally imagining active engagement in emotionally arousing scenes, whether pleasant or unpleasant, prompted an increase in pupil diameter compared with imagining neutral, everyday scenes, and these changes covaried with rated emotional arousal, consistent with cumulative data suggesting that emotional modulation of the pupil is due to enhanced dilation that may be mediated by sympathetic nervous system activation (Bradley et al., 2008, 2017). Because imaginal exposure is a key assessment and treatment modality in many clinical disorders, pupil diameter could be a sensitive measure of sympathetic nervous system engagement both pre- and posttreatment. On the other hand, the amount of pupil constriction to a brief light probe presented during emotional imagery was not enhanced during aversive imagery, as reported previously during threat of shock (Bitsios et al., 1996). Among the differences between the two studies are the task (e.g., anticipation or imagery), the degree of aversiveness (e.g., shock vs. imagery), and the physical properties of the light probe (i.e., LED diode near eye vs. change in screen brightness). Although the light probe was clearly sufficient to elicit a measurable light reflex, there was no evidence of changes in initial constriction due to hedonic content during mental imagery.

The analysis of second by second changes in pupil diameter during the read and imagery intervals indicated that hedonic content exerted a modulatory effect on pupil diameter starting soon after script onset, which was then sustained throughout the imagery interval. This is consistent with a previous study (Costa et al., 2010) in which enhanced functional activity in the medial prefrontal cortex and nucleus accumbens began shortly after the onset of a pleasant script and was sustained throughout the imagery interval. Importantly, pre-exposure to script content was a component in both of these studies, enabling relatively rapid comprehension and construction of the to-be-imagined event during the physiological assessment.

Measuring pupil diameter during emotional imagery reduces concerns regarding the impact of visual factors, such as brightness and contrast, on pupil diameter. In this study, mental imagery was induced using visually presented texts that were identical in brightness and contrast in order to minimize variation in physical parameters that could affect pupil dilation. The use of visual script presentation as an imagery cue was selected for study for a number of reasons. In the "memorize" paradigm (Vrana & Lang, 1990), participants memorize two scripts and are later cued via a tone to imagine one or the other. Although the lack of visual cues is advantageous for measuring pupillary responses, memory load can affect pupil diameter (Steinhauer et al., 2004, 2015) and the memorization requirement reduces the number of trials that can reasonably be included in a single session.

Whereas auditory script presentation (e.g., Cuthbert et al., 2003) similarly reduces differences in visual stimulation, it is less feasible in a clinical setting, particularly when new (personal) scripts are added on the day of assessment. In this case, the need to record new scripts is not only time consuming but could result in differences in intonation and delivery across participants. In addition, choices must be made regarding gender (male, female) and voice (1st or 2nd person) of the delivery, which could impact initial comprehension as well as later imagery. Taken together, visual presentation of the text as a cue, following preprocessing of all scripts, was advantageous for a number of methodological and clinically relevant reasons.

Pupil diameter is determined by the net action of the dilator muscle, under control of the sympathetic nervous system, and the sphincter muscle, under parasympathetic control (Loewenfeld, 1999; Steinhauer et al., 2004), and data are

beginning to accumulate that the enhanced pupil diameter found during emotional processing probably reflects sympathetic nervous system activity (Bradley et al., 2017; Bradley & Lang, 2015). Thus, during free viewing of emotional scenes, pupil diameter covaries with sympathetically mediated skin conductance changes (Bradley et al., 2008, 2017), and skin conductance is also reliably heightened during imagery of emotional, compared to neutral, events (Miller, Patrick, & Levinson, 2002; Miller et al., 1987). Moreover, skin conductance covaries with emotional arousal during picture viewing (Greenwald, Cook, & Lang, 1989; Lang, Greenwald, Bradley, & Hamm, 1993), and, in the current study, rated arousal, but not hedonic valence, significantly predicted pupil diameter changes during emotional imagery, consistent with an interpretation of differential sympathetic nervous system activity.

Because emotional imagery has long been a key feature in both diagnosis (e.g., Lang & McTeague, 2009; McTeague & Lang, 2012) and treatment of clinical disorders (Craske, Antony, & Barlow, 2006; Foa et al., 2007; Zinbarg, Craske, & Barlow, 2006), the data encourage assessment of pupil diameter in an imaginal context. During picture viewing, Kimble, Fleming, Bandy, Kim, and Zambetti (2010) found that combat veterans reporting higher counts of posttraumatic stress disorder (PTSD) symptoms showed greater pupil diameter when viewing unpleasant pictures compared to veterans reporting fewer PTSD symptoms. Utilizing emotional imagery with this population not only allows construction of scenes that can be individually tailored to each patient (e.g., McTeague et al., 2010), but imaginal induction is also of clear utility when pictures or sounds of the clinically pertinent event cannot easily be recreated.

Measuring physiological reactivity during imaginal exposure has provided useful data in both assessment and treatment venues. For instance, McTeague et al. (2010) found different patterns of physiological reactivity during emotional imagery in PTSD patients with a history of single compared to multiple traumatic events. Although both groups reported elevated emotional arousal during trauma imagery compared to a trauma-exposed control group, single-trauma patients demonstrated exaggerated physiological reactivity, with heightened startle reflexes, increased heart rate, and greater facial expressivity, compared to the control or multiple-trauma patient group. Thus, variation in physiological reactivity provides useful information about the etiology of psychopathology, and future studies could determine whether variation in pupil diameter during imagery similarly reveals useful diagnostic information in an assessment context.

A number of studies report that patients who show emotional engagement during mental imagery have better treatment outcomes. Thus, patients who react physiologically during imaginal desensitization were more likely to have a successful therapeutic course of systematic desensitization (Lang et al., 1970; Levin, Cook, & Lang, 1982), and PTSD patients with enhanced skin conductance during prolonged exposure treatment reported greater symptom reduction by the end of treatment (Wangelin & Tuerk, 2015). It is tempting to speculate that individuals showing enhanced pupil diameter when imagining clinically relevant scenes may also show better response to treatment. In any case, the current data clearly show that pupil diameter is reliably heightened during emotional imagery, as previously reported in studies of emotional perception (e.g., Bradley et al., 2017) and anticipation (e.g., Bitsios et al., 1996; Bitsios, Szbadi, & Bradshaw, 2004), suggesting a task-independent modulation of the pupil by emotional arousal that could prove useful in a number of clinically relevant contexts.

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