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Differences in pupil size during self-reported experiences of disgust, sadness, fear, anger, and happiness

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ABSTRACT

Previous research has found pupil dilation associated with stimuli pre-assigned as positive and negative in their emotional valence; however, it is not yet clear how self-rated experiences of specific emotions may correlate with differences in pupil size. Using a novel methodology across two studies, 200 participants were presented with emotionally engaging images and sounds and then rated the extent to which they felt happy, sad, angry, fearful, and disgusted in response to these. Data were analyzed using linear mixed effects models to examine whether the participant's own emotion ratings predict pupil size. In 2 studies using standardized images and sounds, and varied 30-s audio clips, in trials with higher self-reported disgust and sadness there was a consistent relationship with pupil dilation. Disgust was most often the strongest predictor of pupil dilation. This effect emerged ~2 s after stimulus onset and remained present throughout stimulus presentation. Happiness had a weaker effect on pupil dilation and fear was associated with a late pupillary response. Anger was associated with pupil constriction, but only in Study 2. The present approach finds the most consistent relationship between pupil dilation and self-rated disgust and sadness, compared to other negative emotions. The findings thus suggest that measures of pupil size warrant further investigation as a potential indicative psychophysiological correlate of self-reported emotions, with implications for distinguishing negative emotions, such as disgust from anger.

Pupil dilation is a measure of autonomic activity that has been previously associated with emotional responses. Pupil dilation reflects sympathetic activation of the iris dilator muscle and parasympathetic inhibition to relax the iris sphincter muscle (with vice versa for pupil constriction). The emotional pupillary response is unaffected by light levels, reflecting that it is likely sympathetically driven activation of the iris dilator muscle (Widmann et al., 2018), separating it from a purely low-level visual response to light or viewing conditions. Early research linked pupil dilation to positive emotions (Hess, 1975), whereas later studies have shown dilation occurs during both positive and negative affect, when exposed to emotional stimuli such as sounds (Partala & Surakka, 2003) or greyscale images (Bradley et al., 2008). Notably, negative emotional stimuli are associated with even greater and more sustained pupil dilation than positive emotional stimuli (Babiker et al., 2015). Despite these findings, pupillometry remains understudied as a measure of discrete emotions such as anger, disgust, happiness, sadness, and fear. Most pupillometry studies have focused only on general positive or negative affect (Babiker et al., 2015; Bradley et al., 2008; Lichtenstein-Vidne et al., 2017; Partala & Surakka, 2003; Widmann et al., 2018), while research focused on discrete emotions has primarily used electrodermal and cardiovascular measures (see Kreibig, 2010 for a review). Previous research, therefore, only indicates that pupil dilation is elicited by both positive and negative affect but has not examined whether there are patterns associated with specific emotions, which this manuscript seeks to address.

A further limitation in existing pupillometry research is the frequent use of stimuli that has been pre-categorised as positive or negative by researchers (Bradley et al., 2008; Lichtenstein-Vidne et al., 2017) or where self-report ratings are only a manipulation check (Partala & Surakka, 2003). This does not address that emotional experiences are, inherently, individual and personal. Researchers from a variety of theoretical backgrounds argue that personal experience and perception constitutes a key part of emotion (Al-Shawaf et al., 2016; Barrett, 2006a, 2006b, 2013, 2017; Cosmides & Tooby, 2000; Ekman, 2016; Ekman &

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Cordaro, 2011; Lindquist, 2013). Because of this, it is argued that all self-reports are at least meaningful or, to the extreme, the only way of assessing affective experiences (Keltner et al., 2019; LeDoux & Hofmann, 2018; Robinson & Clore, 2002). However, while self-report remains an often-used and often-recommended approach to the study of emotion (e.g., Coan & Allen, 2007), in practice self-reports of emotional experiences have not been the focus in pupillometry. This is a potentially important gap as, in at least one study which relied on participant's own ratings of valence, it was highlighted that there was notable variation across participants (Babiker et al., 2015). Adopting the theoretical approach that personal reports of one's own experiences are valid and necessary, the present studies build on previous work by incorporating this framework to investigate whether self-reports for specific emotions are associated with differences in pupil size.

Another important consideration is that individuals can experience multiple emotions (such as both anger and disgust) or even mixed valence emotions (such as feeling both happy and sad) in response to a single stimulus (Larsen et al., 2001; Larsen & McGraw, 2014; Berrios, Totterdell, & Kellett, 2015). This is because differences in how stimuli are uniquely appraised by participants will lead to differences in measured emotional responses (Al-Shawaf et al., 2016; Scherer, 2001; Siemer et al., 2007). In previous research using self-reported emotional ratings, multiple emotions are often measured and then controlled for (Gutierrez & Giner-Sorolla, 2007; Molho et al., 2017; Russell & Giner-Sorolla, 2011; Simpson et al., 2006). Incorporating this theoretical approach to emotions results in an innovative methodology, using self-reports of multiple emotions for each stimulus to examine whether any emerge as key drivers for the resultant pupillary responses. Using linear mixed effects for analysis, we control for the covariance associated with the other emotions and with general participant-level emotional reactivity, adding further clarity.

However, it should be noted that there have been many disagreements about the validity of measuring emotional states such as anger, disgust, happiness, sadness, and fear, rather than using a general emotional valence and arousal framework (Barrett, 2006a, 2006b, 2013, 2017; Lindquist, 2013). This includes debates about whether each emotion is measurable via differences in patterns of physiology, feelings, and behaviour (Al-Shawaf et al., 2016; Cosmides & Tooby, 2000; Ekman, 2016; Ekman & Cordaro, 2011; Lench et al., 2011). It has been argued that each emotion represents a culturally dependent, descriptive category with largely indistinguishable physiological underpinnings and is, therefore, impossible to distinguish physiologically from emotions of the same valence and arousal (Barrett, 2006a, 2006b, 2013, 2017; Lindquist, 2013). On the other hand, longstanding, commonly used (Ekman, 2016) approaches such as basic emotion theory (Ekman, 1992), argue for discrete emotions with differing underlying physiology. This debate is reflected in psychophysiological emotion research where evidence is conflicted, with some only finding psychophysiological distinctions based on emotional arousal (high or low) and positive or negative valence (Barrett, 2006a; Cacioppo et al., 2000) but others finding differences in specific emotions (Kreibig, 2010).

We do, however, expect that different emotions may influence pupil sizes due to their role coordinating behavioural and physiological responses to meet situational demands. Emotions like anger, disgust, happiness, sadness, and fear can be viewed as distinct "modes" that prepare the body for specific tasks, which could involve changes in pupil size to optimise vision (Al-Shawaf et al., 2016; Scherer, 2001; Tooby & Cosmides, 2008). Pupil constriction is associated with sharper, narrower fields of view, whereas pupil dilation widens the field of view but with less depth. Pupil constriction and the associated visual acuity provides fine visual discrimination when required, such as when optimising current, focused task performance (Campbell & Gregory, 1960; Mathôt & Van der Stigchel, 2015). Pupil dilation and the associated widened field of view and visual sensitivity, on the other hand, provides the ability to detect important environmental stimuli, typically associated with a vigilant state (Campbell & Gregory, 1960; Mathôt & Van der Stigchel, 2015). Different emotions are thought to motivate different behavioural responses, such as anger encouraging more focused, approach behaviours compared to fear or disgust which may encourage environmental vigilance (Al-Shawaf et al., 2016; Cosmides & Tooby, 2000; Tooby & Cosmides, 2008). Therefore, it is likely that these will require differences in pupil size associated with the different task demands.

While there is limited direct evidence of differences in pupil size associated with discrete emotions, there is self-report evidence. In one early study (Hess, 1975) which was more recently replicated (Kret, 2017), it was demonstrated that participants will draw smaller pupil sizes when finishing incomplete drawings of angry faces and larger pupil sizes on happy faces. Older participants also drew increasingly smaller pupils on angry faces; the correlation with age suggesting learning from repeated exposure to small pupils in angry individuals (Kret, 2017). Similarly, although happy faces, in general, are judged as more trustworthy than angry faces, angry faces with smaller pupils are rated as even less trustworthy as they look angrier (Kret & De Dreu, 2019). Importantly for this evidence, despite their apparent subtlety, differences in pupil size are noticed and reacted to by other humans (Brambilla et al., 2019; Hess, 1975; Kret, 2017). Given the evidence that pupil dilation is a cue noticed by conspecifics, self-reports of assumed emotional pupillary reactions may reflect actual pupil size displayed during those emotional experiences. Taken together this may reflect a genuine difference: that relatively smaller pupils have associations with anger, whereas larger pupils were associated with happiness. However, this has not been investigated with other emotions or using actual measures of pupil size.

The current study aims to build on prior research which supports pupil dilation as a measure of negative and positive emotional valence (Babiker et al., 2015; Bradley et al., 2008; Lichtenstein-Vidne et al., 2017; Partala & Surakka, 2003; Widmann et al., 2018). As discussed, prior work pre-categorised the stimuli as negative or positive, rather than using participant's own ratings, and did not consider the existence mixed emotional valence. In light of the lack of research examining pupil dilation in relation to self-reported, mixed, discrete emotions, we aim to explore the relationship between pupil size and emotions by presenting emotionally varied stimuli while measuring pupillary responses and participant's self-ratings of five emotions: fear, sadness, happiness, anger, and disgust.

1. Study 1

To investigate whether increases in disgust, anger, sadness, fear, and happiness were significantly associated with either increases or decreases in pupil size, we measured pupillary responses and collected emotional reactions to 18 images sourced from the International Affective Picture System (IAPS) database and 18 sounds taken from the International Affective Digitised Sounds (IADS) database (Bradley & Lang, 1999; Lang et al., 1999). As both positive and negative emotional valence have been associated with pupil dilation (Babiker et al., 2015; Bradley et al., 2008; Partala & Surakka, 2003), we expected that there would be pupil size increases associated with both negative and positive emotions – but more so for negative emotions (Babiker et al., 2015). As previous pupillometry research had only investigated emotional valence, we had no additional hypotheses about whether specific negative emotions would be associated with differences pupillary responses.

2. Methods

2.1. Participants

A power analysis for multiple regression with five predictors was conducted in G*Power to determine a sufficient sample size to detect a medium effect size ($f2 = 0.15$) given alpha of 0.05, 1-β of 0.80 (Faul et al., 2013). Based on these assumptions, the desired sample size is 94; thus, we collected data from a convenience sample of 98 participants recruited via the University of Essex's participant pool, an additional 4 participants were recruited to allow for potential missing data during data cleaning. Of these participants, 65 were female and 33 were males. Ages ranged from 18 to 46 years (M = 23.09, SD = 4.75). Data was collected between May and August 2017.

2.2. Ethics

This study was reviewed by the University of Essex Science and Health Ethics Sub-committee and was approved under the ethics code McC1701.

2.3. Materials

The materials used as stimuli for this study were 18 images sourced from the International Affective Picture System (IAPS) database and 18 sounds taken from the International Affective Digitised Sounds (IADS) database (Bradley & Lang, 1999; Lang et al., 1999). The specific stimuli were chosen through a preliminary survey where we rated a subset of stimuli from the IAPS and IADS databases for the targeted study emotions (see Supplemental Materials for details and analysis of this survey). While acknowledging these stimuli may be differently appraised in the main study, we chose to take this step as the IAPS and IADS stimuli database is split by affective valence, thus we conducted the survey to choose stimuli which seemed to best elicit the range of emotions needed. We also aimed to choose those stimuli where, even when multiple emotions were elicited, the negative emotions did not correlate too highly, with the aim of allowing increased variation across stimuli in emotion appraisal and avoiding potential multicollinearity in the main study. Previous research has categorised the IAPS and IADS in a similar manner (Mikels et al., 2005; Stevenson & James, 2008), but not with all image stimuli we wished to include nor providing the correlations between emotion ratings per image.

Based on the survey, we selected the following negative IAPS images (with the IAPS identifier number in brackets) depicting a snake (1110), tarantula (1200), mutilated face (3000), slit throat (3071), baby with facial tumor (3170), beaten naked woman (3191), injured dog (9183), dirty toilet (9300), vomit (9322), man being thrown into fire (9428), bird in oil (9560), and the KKK (9810). Using the survey, we also chose three neutral images: an empty plate (7006), a pole (7161), and a filing cabinet (7705). For positive stimuli, we used the original IAPS scores (positive valence above 7) to choose three positive images: puppies (1710), rabbits (1750), and a beach (5833).

We also selected the following IADS sounds (with the IADS identifier number in brackets) where you could hear a sound of bees (115), coughing (242), blowing nose (251), vomit (255), a baby crying (261), a scream (275), a baby being hit by a man (278), arguing (282), a woman being beaten by a man (290), car horns (420), shooting noise and the 'Last Post' (611), and a belch (702). Using the survey, we also chose three neutral sounds: a radio tuning (723), chickens clucking (132), and a yawn (262). For positive stimuli, we used the original IADS scores (positive valence above 7) to choose three positive sounds: a baby laughing (110), a crowd laughing (226), and rock music (815).

2.4. Image stimulus preparation

For images, low-level stimulus properties such as luminance, contrast, or the colours of the image can affect pupil size (e.g., Barbur et al., 1992; Kimura & Young, 1995; Watson & Yellott, 2012). Using MATLAB (MATLAB, 2010), all images were edited to have the same mean pixel intensity, and the same root mean squared contrast, which is the mean pixel intensity divided by the standard deviation. As such, it is not affected by angular frequency distribution or spatial distribution of the image (Bex & Makous, 2002). As a further precaution, we created Fourier-phase scrambled versions of each image (referred to as *scrambled images* henceforth). These scrambled images maintained the frequency spectrum and the colours of the original image, but the content could not be perceived.

Luminance of each image was measured from the perspective of a participant, fixating on the image centre. Luminance for the original images was on average 22.56 cd/m^2 (SD = 6.80 cd/m^2), and 60.93 cd/m^2 (SD = 32.10 cd/m^2) for the scrambled images. This is a large discrepancy, and we corrected for this by including image state (original vs. scrambled) in models which can be found in the supplementary materials. There was no correlation between luminance profile and average emotion ratings for stimuli.

2.5. Procedure

Before the study began, each participant signed a paper consent form containing information about the upcoming experiment. For the duration of the experiment, participants' head motion was restricted using an SR Research head support, which ensured a fixed distance of 67 cm to the screen and the eye-tracking camera. SR Research's Eyelink 1000 eye-tracking hardware and associated software were used to record the participant's eye movements and pupil area. Visual stimuli were presented on a monitor (screen resolution 1280 × 1024 pixels, display size 34.5 × 26 cm) that was not gamma-corrected (γ = 2.6). It displayed black as 2.38 cd/m^2, white as 168.55 cd/m^2. and the background to fixation cross and images as 13.09 cd/m^2. These images were preceded by a fixation cross (4.7 by 4.6 degrees of visual angle, 18 cd/m^2) presented for 2 s; to create a baseline period. They were then presented at a size of 11.76 by 8.32 degrees of visual angle and remained on screen for 9 s. Auditory stimuli were presented through speakers with volume kept at a fixed level across participants. These sounds were also preceded by the 2 s fixation cross, which then remained on screen for the duration. But, as the sounds were all 6 s in length, they were followed by 3 s of silence.

After each stimulus presentation, participants were given instructions to rate their emotional state during the stimulus they were just exposed to. They then used a number pad to rate each stimulus on how strongly it elicited the five selected emotional dimensions (how happy, sad, angry, fearful, and disgusted they felt) on a 1–9 scale (1 being not at all, 9 being very much). The emotions to be rated were also presented in a random order after each stimulus presentation.

Each participant saw all 18 sounds and 36 images (18 contrast-standardised and 18 scrambled controls) with sounds and images grouped into blocks for presentation by stimulus type, with presentation of these blocks counterbalanced across participants. Within the images block, stimuli were further sub-grouped into scrambled and unscrambled blocks, with the scrambled block always presented before the unscrambled. The aim was to prevent unscrambled images enhancing content recognition in the scrambled images, based on low-level properties such as colour, which could cause an unintended emotional reaction. Within all stimulus blocks (scrambled, unscrambled, and sound blocks), all stimuli were presented in a fully randomised order. Each block began with two practice trials, so the participants were confident with the procedure, and was book-ended by two additional 6-s presentations of a central fixation cross used to measure eye-tracking precision (RMS=0.07 degrees of visual angle).

2.6. Data preparation

All pupil data were recorded and analyzed in Eyelink pupil area size units; the typical pupil area is 100–10,000 units, with a precision of one unit (SR Research, 2010). Throughout all trials, an average of 4.2 % (images) and 4.3 % (sounds) of samples were missing, with only 0.54 % (images) and 0.46 % of trials missing over 50 % of data. The median number of saccades in trials with images was 9.1 (SD = 7.2), with an average amplitude of 2.1 (SD = 1.5) degrees of visual angle. For sound stimuli, the average number of saccades was lower: 4.6 (SD = 4.9), with an average amplitude of 2.6 (SD = 2.1) degrees of visual angle. Note that this was computed over the whole trial and reflects an average of less than 1 saccade per second (images) or per 2 s (sounds).

For each trial where a stimulus (sound or image) was presented, pupil size during blinks (and saccades, if present) was interpolated using cubic splines. Median pupil size was then computed over a baseline period of 2 s prior to stimulus onset and was then subtracted from the signal across the trial (2 s of baseline and 6 or 9 s of the stimulus presentation period). This procedure is in line with recommendations on pupillometry data preprocessing (Mathôt et al., 2018), and similar baseline corrections of the data are common practice in pupillometry (e.g., Hupé et al., 2009; Laeng & Sulutvedt, 2014; Partala & Surakka, 2003).

2.7. Data analysis

To explore the relationships between pupil size and the five emotions measured, the data were modelled using linear mixed-effects models, fitted in Python (v. 3.10.12) using statsmodels (v. 0.14.1). Ratings and pupil data were standardized across individuals and assessments before being fed into each model. We modelled sounds and images separately as images had different low-level properties, such as luminosity and contrast, which may affect pupil size (Barbur et al., 1992; Kimura & Young, 1995; Watson & Yellott, 2012).

To address possible confounds stemming from both between and within subject variation, as highlighted in previous work (Wang & Maxwell, 2015), we used the emotion rating to calculate two types of predictor which were simultaneously entered into the model: (1) a participant-level average (i.e., the participant's mean rating across all stimuli analysed), capturing between-subject differences in emotion perception, and (2) a trial-level deviation (i.e., the difference between a participant's rating on a given trial and their own average), capturing within-subject fluctuations in emotion ratings. Therefore, both their mean disgust, anger, sadness, fear, and happiness ratings overall as well as the deviance from those ratings per stimuli were used as simultaneous fixed effects. Each model also included participant number as random effect, which allowed us to account for natural variation in pupil size between participants. For image stimuli, there are also additional analyses which can be found in the supplementary materials which contain an interaction term for the scrambled images, testing the effect of emotion ratings on the difference in pupil size between the original and the scrambled version of each image. Finally, we also directly compared the strength of regression effect sizes by taking the difference between standardised coefficients and dividing this by the pooled standard error of those coefficients to create a z-score (Clogg et al., 1995).

In addition to running the above models on the average pupil size during stimulus presentation, for the sound stimuli, we also applied the same model on down sampled (to 10 Hz) pupil size signal from 1 s before (i.e. during the baseline period) until 3 s beyond the end of stimulus presentation. This time series analysis splits the total 10 s of each trial into 100 sequential 100 ms time segments where pupil size at each segment was predicted by the disgust, anger, fear, happiness, and sadness ratings given at the end of the trial period. These analyses are conducted on the assumption that there might be meaningful progressions in pupillary reaction throughout stimulus presentation depending on the emotion felt. For example, in previous studies, disgust and fear appear to affect vision approximately 1–1.5 s into a trial (Anwyl-Irvine et al., 2022; Armstrong et al., 2022; Dalmaijer et al., 2021; Woronko et al., 2023). It should also be noted that while images were presented for the full 9 s, sounds were played for 6 s followed by 3 s of silence. As noted in previous research, sound content is unlike image stimuli in that it varies over the presentation period and is not always fully identifiable until the whole sound has been played (Hammond et al., 2024; Hoogerbrugge et al., 2022). There is also potential interest of the continued emotional impact after stimulus presentation, so we will include an analysis of this 3 s period of silence in these analyses. Furthermore, as described in the procedure, the emotion ratings were taken only once at the end of the presentation period, so the final pupil size segments are the nearest to the recorded ratings of emotional responses. It is possible that the emotions felt would have varied during stimulus presentation, but it was not practical to record these measurements alongside pupil size. Finally, as segmenting in this manner concerns a rather large number of tests that are not independent, we opted to offer two extreme options to correct for multiple comparisons: uncorrected ($\alpha = 0.05$) and Bonferroni-corrected ($\alpha = 0.05/100=5e-4$) thresholding of p values. These analyses, therefore, allow us to track the time course of pupil size changes for different emotion ratings (we also included similar analyses on scrambled and unscrambled images, which can be found in the Supplementary Materials).

Data and scripts can be found on https://osf.io/pv5b2.

3. Results

We computed correlations for all the raw emotional ratings given for sounds and images separately, which can be seen in Table 1. The purpose of this was to correlate the ratings across all stimuli prior to their use in the mixed effects models. It was expected that there would be some correlation between the negative emotions, but that they should not be very highly correlated (>.80). A very high correlation would suggest difficulty differentiating between the emotions, where rating one highly would be associated with a similarly high rating in the other. All negative emotions were significantly moderately or strongly positively correlated, although not to a problematic extent (all $r < .80$). As expected, the negative correlation between happiness ratings with all negative emotion ratings, suggested that when a participant rated a stimulus as causing happiness, they were less likely to also rate it as eliciting a negative emotion, but the moderate correlation strengths also suggest mixed valence emotional responses did occur.

As the above table focused on ratings across stimuli, to illustrate the strength of emotional response to each stimulus separately, we used violin and box plots (Figs. 1 and 2). Visual inspection shows both that the emotions elicited varied both within and between stimuli. Anger, disgust, happiness, sadness, and fear had a median above the midpoint of the scale for at least one stimulus for both sounds and images. The only stimuli which did not strongly elicit at least one emotion were those stimuli intentionally chosen to be emotionally neutral (IADS identifier 723, IADS identifier 132, IADS identifier 262, IAPS identifier 7161, IAPS identifier 7705, IAPS identifier 7006).

In Fig. 1, for the images, the largest pupil sizes were associated with many of the more violent negative images with a mixed negative emotional response including a slit throat (3071), baby with a facial tumor (3170), beaten naked woman (3191), man being thrown into fire (9428), and a mutilated face (3000). However, the neutral image of a pole (7161) was also associated with larger median pupil size compared to most other stimuli. The lowest pupil sizes were associated with

Table 1
Pearson correlation matrix for all study 1 emotion ratings across the stimuli.

Stimuli	Variable	1	2	3	4
Images	1 Disgust	1			
	2 Anger	.66***	1		
	3 Fear	.56***	.53***	1	
	4 Happy	−.46***	−.34***	−.33***	1
	5 Sad	.65***	.75***	.54***	−.39***
Sounds	1 Disgust	1			
	2 Anger	.56***	1		
	3 Fear	.33***	.44***	1	
	4 Happy	−.32***	−.30***	−.24***	1
	5 Sad	.45***	.65***	.55***	−.26***

*p < .05, ** p < .01, ***p < .001. n = 1755 responses to images, n = 1755 responses to sounds.

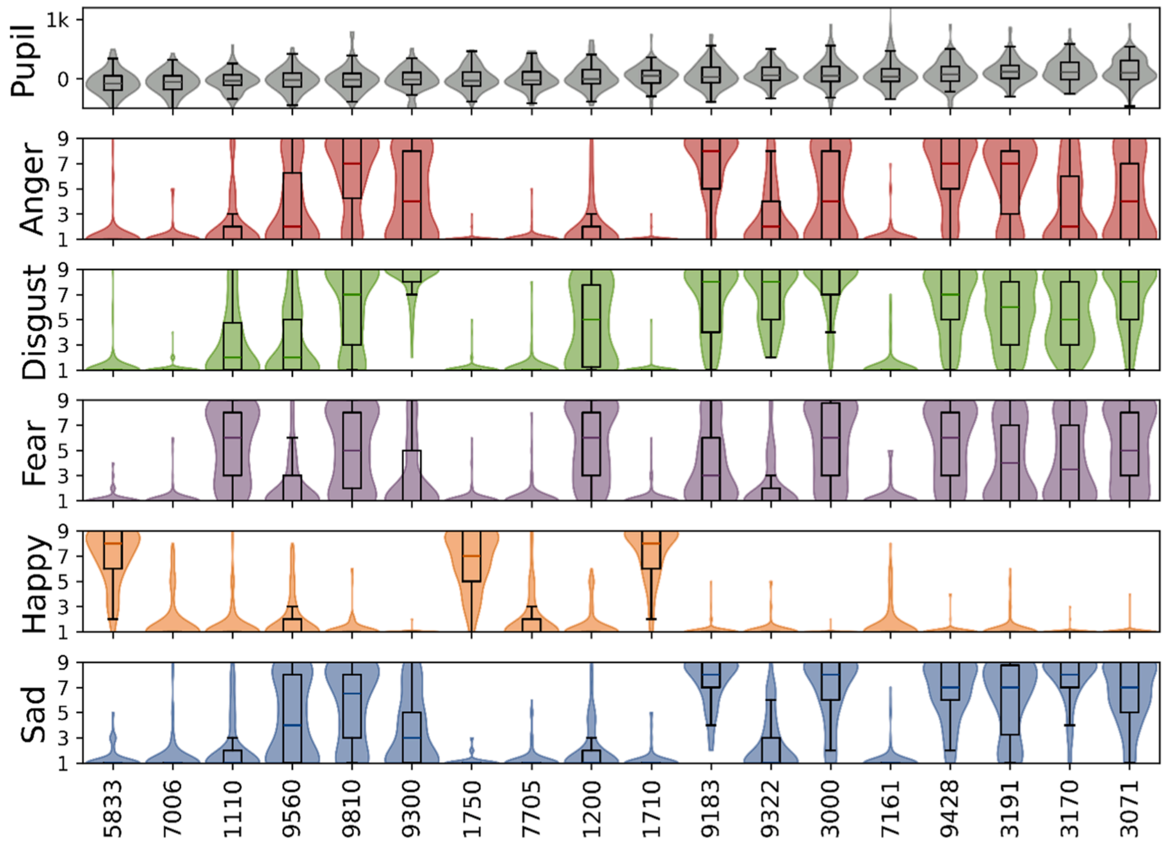

Fig. 1. Box plots of medians and interquartile ranges overlaying violin plots of pupil size change and emotional ratings for each image stimulus. The numbers labelling each facet refer to the IAPS identifier. Stimuli are ordered by median (over participants) average pupil change (in arbitrary units, the mean taken from the trial duration) compared to baseline. This Fig. Shows that some stimuli were rated unidimensionally (e.g. 5833 as mostly happy and 9322 as mostly disgusting), whereas others inspired different mixtures of emotion ratings.

images of a beach (5833), an empty plate (7006), and a snake (1110). Many of the images with the lowest median pupil sizes were also responded to with mixed negative emotions: a bird in oil (9560), the KKK (9810), and a dirty toilet (9300).

In Fig. 2, the sounds associated with the largest pupil sizes also appeared to be the violent, negative sounds which appeared to elicit a range of negative emotions: a scream (275), a baby being hit by a man (278), and a woman being beaten by a man (290). There were also larger pupils in response to the mostly disgusting sounds of vomit (255), and a belch (702). The positive sound of rock music (815) also seemed to have larger pupil sizes in response. The smallest median pupil sizes were associated with chickens clucking (132), a yawn (262), a radio tuning (723), a crowd laughing (226), coughing (242), and car horns (420).

Model 1: Images. In the first model, when controlling for other emotions, main effects indicated that, on the trials where participants reported higher disgust and/or higher sadness than their participant-level average, they had larger pupil sizes, indicating sympathetic activation (see Table 2). None of the participant-level predictors were associated with pupil size changes. Direct comparisons between sadness and disgust suggest that trial-level disgust and trial-level sadness did not have significantly different effect sizes [z = -0.63, p = .530], suggesting similar effects on pupil dilation.

Further analyses were conducted including the scrambled images as well as time series analyses and can be found in the Supplementary Materials. These show the fixed effect of trial-level emotion rating on pupil size for only scrambled images (Table S4 and Fig. S2) and the interaction between image scrambling and trial-level emotional rating when both are included in the same analysis (Table S5 and Fig. S3). In all analyses, the most consistent finding is the association between trial-level disgust and pupil dilation for the unscrambled images. However, it should be noted that images remain imperfect stimuli to probe emotional effects on pupil size due to their inherent and complex visual effects on pupil size.

Model 2: Sounds. For the second model, when controlling for the other emotions, main effects indicated that when participants reported higher disgust, fear, sadness, and/or happiness than their participant-level average they had significantly larger average pupil size. There were no significant effects for the participant-level predictors. Full results of this model can be found in Table 3. Further analyses directly comparing effect sizes suggest that trial-level disgust was a statistically significantly stronger predictor than trial-level happiness [$z = 2.90$, $p < .001$]; but not trial-level fear [$z = 1.68$, $p = .093$] or trial-level sadness [$z = 1.47$, $p = .140$]. This suggests that the trial-level negative emotions were associated with a similarly strong pupil dilation response when taking the whole trial into account.

Time Series Models: Sounds. When applied at each 100-millisecond sample (Fig. 3), linear mixed-effects analyses showed a strong positive relationship between the trial-level deviations in disgust ratings of the stimuli and increased pupil size from 1.4 (uncorrected) or 1.6 s (Bonferroni-corrected), until 8.6 s. As sounds finished at 6 s, this suggests those sounds with higher disgust ratings were associated with increases in pupil size even after stimulus offset (an effect that could be investigated further in future research). Higher trial-level sadness was positively associated with pupil size from 0.5 until 7.8 s (uncorrected), but only from 3.3 to 3.7 when correcting for multiple comparisons. Trial-level fear was not associated with pupil size until later in the trials: from 5.0 until 8.5 s when correcting for multiple comparisons (again, with the influence of fear continuing after the stimulus offset). Trial-level happiness was not associated with pupil size increases when correcting for multiple comparisons. Taken together, this suggests a

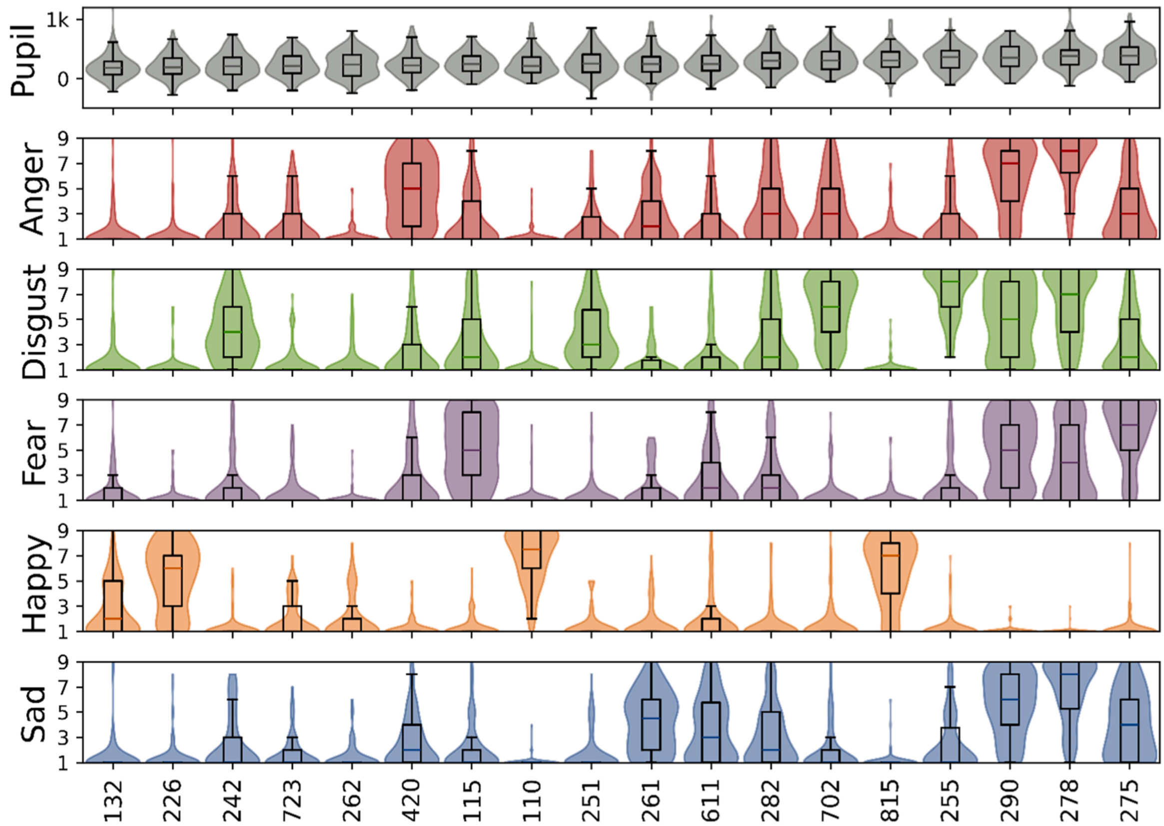

Fig. 2. Box plots of medians and interquartile ranges overlaying violin plots of pupil size differences and emotional ratings for each sound stimulus. The numbers labelling each facet refer to the IADS identifier. Stimuli are ordered by median (over participants) average (over trial duration) pupil change (in arbitrary unit) compared to baseline. This Fig. Shows that some stimuli were rated unidimensionally (e.g. 815 as mostly happy and 255 as mostly disgusting), whereas others inspired different mixtures of emotion ratings.

Table 2
Linear mixed model for study 1 emotion ratings by participants of images as predictors of mean pupil size.

						95 % Confidence Interval	
		β	SE	z	p	Lower Bound	Upper Bound
	(Intercept)	0.418	0.058	7.156	< .001	0.303	0.532
Participant-Level Average	Anger	−0.221	0.114	−1.938	.053	−0.455	0.003
	Disgust	−0.109	0.105	−1.031	.302	−0.315	0.098
	Fear	0.180	0.097	1.854	.064	−0.010	0.369
	Happy	0.038	0.066	0.580	.562	−0.090	0.166
	Sad	0.153	0.122	1.255	.210	−0.086	0.393
Trial-Level Deviation	Anger	−0.024	0.029	−0.834	.404	−0.080	0.032
	Disgust	**0.086**	**0.027**	**3.217**	**.001**	**0.034**	**0.138**
	Fear	0.026	0.023	1.152	.249	−0.018	0.070
	Happy	0.011	0.021	0.496	.620	−0.031	0.052
	Sad	**0.111**	**0.029**	**3.851**	**< .001**	**0.054**	**0.167**

Note. Statistical significance of predictors ($p < .05$) highlighted in bold.

stronger, more consistent pupillary reaction for trial-level disgust compared to the other negative emotions.

4. Discussion

In Study 1, for images, when the other emotions were held constant, trial-level disgust and trial-level sadness significantly predicted pupil dilation. As such, the higher the participant rated their disgust or sadness, the larger their average pupil size was during stimulus presentation when controlling for general emotional reactivity. For the sound stimuli, again, trial-level disgust and trial-level sadness emerged as significant predictors of increases in pupil sizes, when controlling for general emotional reactivity. However, in this case, trial-level fear and trial-level happiness also predicted significant increases. The time series analyses showed early peaks and a mostly consistent, significant association with trial-level disgust. There were less consistent associations with trial-level fear and trial-level sadness, with fear being associated with a very late pupillary response and sadness a very brief pupillary response. High ratings in disgust especially were associated with progress throughout the trial and peaks late in stimulus presentation.

Like previous findings, we found an emotional pupillary response in response to emotionally engaging images and sounds (Babiker et al., 2015; Bradley et al., 2008; Partala & Surakka, 2003). However, when controlling for other emotion ratings, unlike previous research, these findings did not show that all negative affect or both negative and positive affect were consistently associated with pupil dilation (Babiker et al., 2015; Bradley et al., 2008; Partala & Surakka, 2003). Specifically, while most negative emotions were associated with pupil dilation at the

Table 3
Linear mixed model for study 1 emotion ratings by participants of sounds as predictors of mean pupil size.

		β	SE	z	p	95 % Confidence Interval	
						Lower Bound	Upper Bound
	(Intercept)	0.001	0.078	0.017	.986	-0.151	0.154
Participant-Level Average	Anger	0.166	0.126	1.317	.188	−0.081	0.412
	Disgust	−0.246	0.133	−1.851	.064	−0.507	0.015
	Fear	0.062	0.123	0.502	.615	−0.179	0.303
	Happy	−0.036	0.086	−0.418	.676	−0.204	0.132
	Sad	0.052	0.145	0.362	.718	−0.232	0.337
Trial-Level Deviation	Anger	0.019	0.021	0.896	.370	−0.023	0.061
	Disgust	**0.111**	**0.018**	**6.028**	**< .001**	**0.075**	**0.147**
	Fear	**0.068**	**0.018**	**3.782**	**< .001**	**0.033**	**0.103**
	Happy	**0.038**	**0.017**	**2.201**	**.028**	**0.004**	**0.072**
	Sad	**0.070**	**0.021**	**3.324**	**.001**	**0.029**	**0.111**

Note. Statistical significance of predictors ($p < .05$) highlighted in bold.

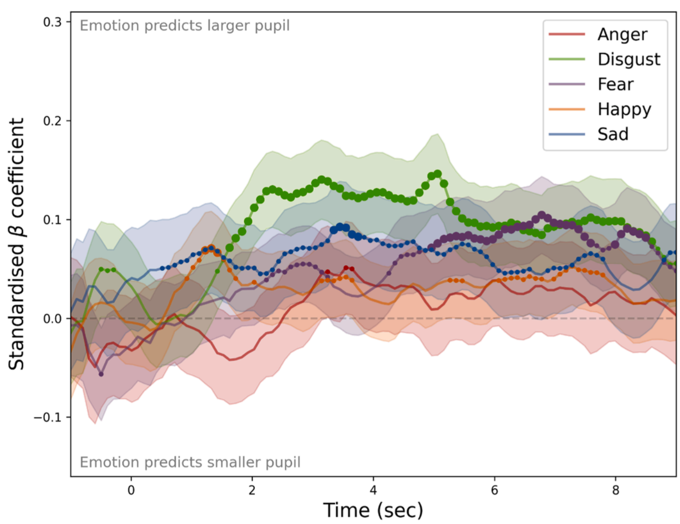

Fig. 3. The association between trial-level deviations in self-reported emotion ratings (anger, disgust, fear, happiness, sadness) and pupil size for sounds. One second of baseline is included prior to stimulus onset at t = 0 s. Solid lines reflect the standardised coefficient from a linear mixed-effects analysis at each 100-ms sample, and shaded areas reflect its 95 % confidence interval. Dots along line segments reflect statistical significance at an uncorrected level ($p < 0.05$), and thicker dots reflect statistical significance at a Bonferroni-corrected level ($p < 5e-4$). Positive coefficient values indicate that emotion ratings were associated with a relative increase in pupil size compared to baseline, and negative values a relative decrease.

trial level, interestingly, anger was not. This somewhat distinguishes anger from other negative emotions which have similar valence (Barrett, 2006a, 2006b, 2013, 2017; Lindquist, 2013). It also distinguishes disgust from anger when both are considered high arousal emotions (Barrett, 2006a, 2006b, 2013, 2017; Lindquist, 2013).

5. Study 2

Results from Study 1 suggest higher disgust and sadness ratings to emotional stimuli have a stronger relationship with pupil dilation compared to other emotions. We also found relationships with happiness and fear, which were also associated with increases in pupil size, but less consistently. In a follow-up study, we sought to confirm whether Study 1's findings replicate by further exploring whether trial-level disgust, fear, happiness, sadness, and anger predict pupil dilation and addressing potential methodological confounds. Specifically, as we cannot rule out the previous findings being specific to the stimuli in Study 1, we repeated the study using longer, novel stimuli not drawn from research databases. We also focused on only auditory stimuli to eliminate the potential impact associated with low-level properties of images which affect pupil sizes (such as luminosity and contrast) while any impact of eye-movements on pupil size data is reduced as participants only need to attend to a presented cross in the center of the screen rather than an image. Based on the results of Study 1, we hypothesize that higher ratings of disgust and sadness more so than other emotions will predict significantly larger pupil sizes at the trial level.

6. Methods

6.1. Participants

Based on the same parameters from the power analysis for Study 1, the desired sample size is 94. To meet this, data were collected from 102 participants, an additional 8 participants were recruited to allow potential attrition or missing data during data cleaning. The participants were recruited via the University of Essex's participant pool. Of these 102 participants; 75 reported they were female, 26 male, and one preferred not to specify. Ages ranged from 18 and 29 years ($M = 20.13$, $SD = 2.15$; one participant preferred not to specify their age). All participants reported English language skills and should, therefore, understand the content of all stimuli which, in this study, included some short conversations in English. Data was collected between November 2017 and March 2018.

6.2. Ethics

This study was reviewed by the University of Essex Science and Health Ethics Sub-committee and was approved under the ethics code McC1701.

6.3. Materials

For the stimuli used in Study 2, we selected 24 audio recordings which we describe below (see Table 4). Of these, broadly, 16 were negative in valence, 5 were positive, and 3 were neutral and appeared to elicit the range of emotions investigated in this study. These stimuli were sourced from YouTube by the researcher in 2017 and using the same methodology as Study 1, were rated on the same emotions investigated in Study 1 (see Supplemental Materials for further detail about the methods and analysis of this survey). These sounds were all 30 s audio clips from user generated YouTube videos as well as from films and TV shows.

6.4. Procedure

Before the study began, each participant signed a paper consent form containing information about the upcoming experiment. Stimuli were presented using headphones with the volume kept at a constant level

Table 4
Descriptions of Stimuli used for Study 2.

Identifier	Description
#4	The sound of a baby laughing hysterically with his father laughing back while he rips paper.
#6	A multi-tone cycling car alarm sequence which progresses through different sirens, whooping noises, and beeps at different speeds and tones.
#9	A recording of a peaceful evening with predominately crickets chirping but also bird calls.
#11	The sound of squirting, liquid diarrhea hitting a toilet seat with flatulence.
#12	The sound of aggressive dog barking with panting, progressing to alternating barking and growling.
#14	An alarm clock which progresses from less frequent steady beeps to urgent, frequent, steady higher pitched beeps.
#16	A scene from the series the Fresh Prince of Bel Air (1994, Season 4 Episode 24) where a man talks angrily about how he would be a better father than his own, followed by him asking "why don't he want me, man?" and crying.
#17	A scene from the film Goodwill Hunting (1997) which begins with the client swearing at his therapist as he reassures him his trauma is not his fault ("it's not your fault"), most of the clip is the client crying loudly with some music in the background.
#18	A repeated, high-pitched meow from a young kitten.
#19	Two women intensely laughing together, one with wheezing laughter which makes the other laugh more.
#20	The buzzing sound of a mosquito flying closer and further away on repeat.
#22	A scene from the film Paranormal Activity (2007) where a couple call out for each other while both are screaming and there is a sound of dragging, then 10 ss of eerie almost silence before a paranormal growl and a slam.
#23	The sound of a young puppy crying and whining repeatedly followed with some distressed barks, finishing on some more whining.
#24	The sound of a cat purring. It begins with quiet purring gradually getting louder with a meow at 18 s followed by more purring.
#25	A scene from the horror film REC (2007) with a man and woman briefly speaking in hushed voices and crying in Spanish, then panting, a paranormal roar, followed by a loud, distorted shriek from the woman.
#29	The sound of a ship at sea with water splashing, the wood of the boat creaking, and seagulls calling.
#30	The steady sound of a Grandfather Clock ticking getting gradually louder.
#31	The sound of a tiger growling and roaring quietly at first, finishing on some louder roars and huffs as the clip progresses.
#32	The sound of vomit hitting a toilet bowl with a belch and then some coughing, finishing with some gagging and coughing with some more vomit hitting the bowl.
#33	The steady sound of white noise getting louder as the clip progresses.
#34	The sound of a whoopee cushion repeatedly being pressed, that could also sound like flatulence. Varied in length of press with some pauses.
#35	A lone adult woman sobbing, graduating to a louder, wailing cry as the clip progresses.
#36	A woman eating soup noodles. There is a wet sound of her slurping the noodles as well as loud, open-mouthed wet chewing.
#39	An argument from the UK series Airline (1999, Season 2, Episode 5) where an angry man argues with a customer service agent in Luton airport. This includes bleeped swearing and the man angrily repeating "why not" as the customer service agent repeats that there are no seats.

during each session. Participants were asked to direct their visual attention to a fixation cross, present for each trial during stimulus presentation, located in the center of the computer screen in front of them (screen resolution 1280 ×1024 pixels). As in Study 1, participants' head motion was restricted using an SR Research head support to ensure a fixed distance to the screen and the eye-tracking camera. SR Research's Eyelink 1000 eye-tracking hardware and associated software were used to record the participant's pupil size.

Each participant was then presented with the 24 audio stimuli in a fully randomized order. Some of the stimuli in this case are narrative sections taken from films or TV shows, where English skills would have helped to understand the emotional content, such as the scene from the Fresh Prince and the Airline argument. Thus, prior to the experiment starting, each participant confirmed they had the required English language skills to complete the study. We also included sounds that were not narrative, such as predominately screaming noises taken from films (REC 1 and Paranormal Activity) as well as noises such as eating, the ocean, or purring. We ensured all participants were confident in English to understand the content and elicit an emotional response. Participants were directed to focus visually on the fixation cross while listening. Each session began with two practice trials, so the participants were familiar with the procedure. Before each stimulus was presented, there were two seconds of silence followed by the audio which was 30 s in length. As with Study 1, after each stimulus was presented, participants were asked to rate the stimulus for each of the five target emotions—disgust, anger, fear, sadness, and happiness—presented in a random order on a 1–9 scale (1 being not at all, 9 being very much) using a numeric keypad.

The experiment started with a 9-point calibration followed by a 9-point validation. As before, the experiment was book-ended by a 6-s presentation of a central fixation cross. Data collected during this was used to compute gaze-tracking precision (RMS=0.1 degrees of visual angle).

6.5. Data preparation

As in Study 1, the pupil data were quantified using the Eyelink area measurement units (typical pupil size between 100 and 10,000 units). The data were cleaned in the same way as Study 1. Throughout all trials, an average of 6.3 % of samples were missing, with only 1.1 % of trials missing over 50 % of data. The average number of saccades was 10.2 (SD = 10.5), with an average amplitude of 2.2 (SD = 1.8) degrees of visual angle. Note that this was computed over the whole trial and reflects an average of less than 1 saccade per 3 s.

6.6. Data analysis

The analysis strategy was identical to Study 1: in linear mixed-effects analyses, the participant-level average and trial-level deviations were calculated using the emotional ratings and used as simultaneous fixed effects to predict mean pupil size. Participant number was used as a random effect. For time series analyses, we then also fitted the same models on each of 310 time points from 1 second prior to stimulus onset to stimulus completion (original signal down sampled to 10 Hz). For the time series, we again report statistical significance that is uncorrected (α=0.05) and Bonferroni-corrected (α=0.05/310 =1.61e-4) for multiple comparisons. Data and scripts can be found on https://osf.io/pv5b2.

6.7. Results

As in Study 1, before modelling the full results, we computed correlations between the emotional ratings, as can be seen in Table 5. Again, we wished to investigate whether the negative emotion ratings across the stimuli were too highly correlated (>.80) which would have suggested that the participants did not distinguish between them. All negative emotions were significantly but weakly positively correlated and negatively correlated with happiness. However, again, the weak strength of the negative correlations between happiness and the negative emotions suggests that there were mixed valence emotional responses.

Table 5
Pearson correlation matrix for all Study 2 emotion ratings across the stimuli.

Variable	1	2	3	4
1 Disgust	1			
2 Anger	.45***	1		
3 Fear	.09***	.30***	1	
4 Happy	−.27***	−.29***	−.26***	1
5 Sad	.17***	.39***	.30***	−.28***

*p < .05, ** p < .01, ***p < .001. n = 2405.

As in Study 1, visual inspection of box and whisker plots of the emotion ratings of the individual stimuli (Fig. 4) shows a range of emotions elicited with variance in the strength of responses. All emotions had a median above the midpoint of the scale for at least one stimulus, other than anger, which still had a moderate median of 4 for Alarm Clock (#14), a mosquito (#20), and the Airline argument (#39) sounds.

The largest median pupil sizes were recorded during the diarrhea (#11), vomit (#32), whoopee cushion (#34), woman loudly chewing (#36), baby laughing (#4), cat purring (#24), Paranormal Activity (#22), and Goodwill Hunting (#17) audio. The smallest median pupil sizes were recorded during exposure to the alarm clock (#14), the dog barking (#12), the crickets chirping (#9), the sailing ship (#29), the car alarm (#6), the mosquito (#20), the tiger (#31), and the kitten meowing (#18) audio.

The results of the full linear mixed effects model indicate that, when controlling for other emotions, higher deviations in trial-level ratings of disgust, happiness, and sadness significantly predicted larger pupil size, whereas higher trial-level anger predicted smaller pupil sizes (Table 6). There were, again, no relationships for the participant-level variables. These results somewhat replicate the results for sounds in Study 1, which showed trial-level disgust, happiness, and sadness increased pupil size. Direct comparisons of effect sizes showed trial-level disgust was a statistically significantly stronger predictor than trial-level anger [$z = 10.80$, $p < .001$], trial-level happiness [$z = 5.10$, $p < .001$], and – in this study – also trial-level sadness [$z = 7.21$, $p < .001$].

Time Series Models. When applied at each 100-ms sample (Fig. 5), linear mixed-effects analyses showed a strong positive relationship between trial-level disgust and pupil size from 2.6 s (Bonferroni-corrected), until the end of the trials. It peaked with $\beta = 0.30$ ($p < .001$) at 6.9 s after stimulus onset. Higher deviations in the ratings of happiness at the trial level were positively associated with increased pupil size throughout most of the trials, although more inconsistently after correcting for multiple comparisons. While trial-level sadness was positively but inconsistently associated with pupil size throughout the trials, it does not show an association when correcting for multiple comparisons (with an exception very near the outset). Trial-level anger was negatively associated with pupil size, but more inconsistently after correction for multiple comparisons. Similar to Study 1, trial-level fear was only associated with a very late pupillary response: from 28.0 (Bonferroni-corrected) until the end of the trials.

Finally, as trial-level disgust seems to show the most consistent and strongest relationship with pupil dilation, to allow for the visual inspection of pupil traces across all experiments in relation to disgust, we plotted the change from baseline for each stimulus separately, averaged across all participants. These are presented in Fig. 6, separated for standardised images and sounds in Study 1, and longer sounds in Study 2 (see below for details). Colour intensity indicates the average disgust emotion rating for each stimulus, with darker colours showing higher deviations in trial-level disgust ratings. This again shows higher trial-level disgust associated with early and consistent increases in pupil size across different types and lengths of stimuli.

7. General discussion

Across two studies, with a total of 200 participants, using three different sets and two types of stimuli, the trials with higher self-reported disgust or sadness were most often associated with pupil dilation. However, this effect seemed to be strongest and most consistent for the trial-level deviations of disgust ratings in both whole trial and time series analyses. The disgust pupillary response started around 2 s after stimulus onset and was maintained throughout presentation, which was a pattern not seen as consistently for the other emotions. Disgust was also the strongest effect compared to happiness, fear, and anger in both Study 1 and 2, and stronger than sadness in Study 2. Trial-level deviations in sadness were also associated with increases in pupil size, but

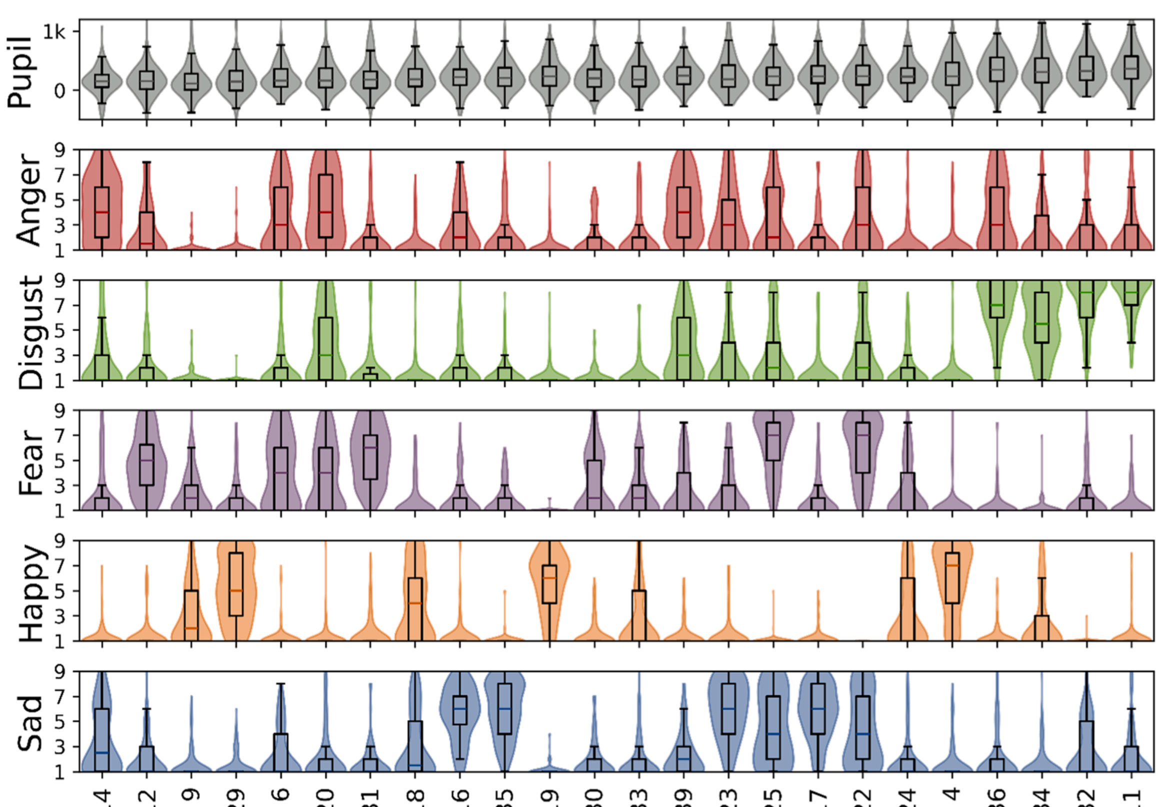

Fig. 4. Box plots of medians and interquartile ranges of pupil size change and emotional ratings for each sound stimulus. Stimulus numbers refer to specific sound clips, the content of which is enumerated in Table 4.

Table 6
Linear Mixed Model for Study 2 Emotion Ratings by Participants of Sounds as Predictors of Mean Pupil Size.

		β	SE	z	p	95 % Confidence Interval Lower Bound	Upper Bound
	(Intercept)	−0.006	0.075	−0.078	.938	−0.152	0.140
Participant-Level Average	Anger	−0.011	0.127	−0.083	.934	−0.260	0.239
	Disgust	−0.174	0.122	−1.424	.154	−0.414	0.065
	Fear	0.138	0.127	1.090	.276	−0.110	0.387
	Happy	0.022	0.086	0.262	.793	−0.146	0.190
	Sad	−0.049	0.154	−0.320	.749	−0.351	0.253
Trial-Level Deviation	**Anger**	**−0.046**	**0.016**	**−2.809**	**.005**	**−0.078**	**−0.014**
	Disgust	**0.198**	**0.016**	**12.652**	**< .001**	**0.167**	**0.229**
	Fear	0.011	0.015	0.728	.467	−0.018	0.040
	Happy	**0.082**	**0.016**	**4.978**	**< .001**	**0.050**	**0.114**
	Sad	**0.041**	**0.015**	**2.720**	**.007**	**0.011**	**0.071**

Note. Significance of predictors ($p < .05$) highlighted in bold.

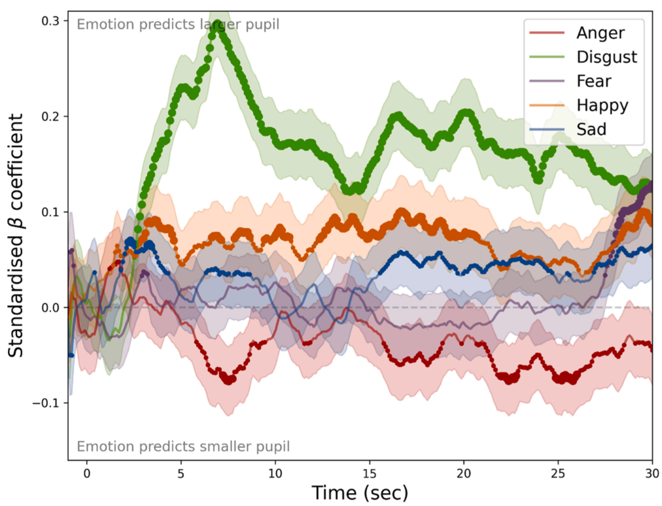

Fig. 5. The association between self-reported emotion rating on five scales (anger, disgust, fear, happiness, sadness) and pupil size for longer (more narrative) audio clips. One second of baseline is included prior to stimulus onset at $t = 0$ s. Solid lines reflect the standardised coefficient from a linear mixed-effects analysis at each 100-ms sample, and shaded areas reflect its 95 % confidence interval. Dots along line segments reflect statistical significance at an uncorrected level ($p < 0.05$), and thicker dots reflect statistical significance at a Bonferroni-corrected level ($p < 1.61e-4$). Positive coefficient values indicate that emotion ratings were associated with a relative increase in pupil size compared to baseline, and negative values a relative decrease.

this was only strong and consistent for the whole trial analyses. Other emotions were less consistent: fear only showed a very late pupil dilation response only for sounds; happiness also was only associated with pupil dilation for sounds; and anger was either unrelated to pupil size or with smaller pupil sizes. As participant-level emotion ratings were not significant predictors of pupil size in any models, this suggests that only trial-level deviations were driving the pupillary reactions, rather than broadly emotionally reactive participants having larger pupil sizes.

Our results show a more nuanced relationship between negative and positive emotions than prior pupillometry studies, which linked general negative and positive affect with pupil dilation (Babiker et al., 2015; Bradley et al., 2008; Partala & Surakka, 2003). Notably, even in these previous studies, the strong negative response may be driven by disgust, as the stimuli are frequently morally disgusting and disease-relevant (*mutilation,* Bradley et al., 2008; *violent imagery*, Henderson et al., 2014; *immoral or pathogenic content,* Al-Shawaf et al., 2016). Beyond disgust, sadness was the negative emotion with the most consistent pupillary association in our analyses, possibly because it is a social emotion closely tied to empathy, making it easier in response to social stimuli such as sounds of humans or animals when they are upset (Al-Shawaf et al., 2016; Cosmides & Tooby, 2000; Tooby & Cosmides, 2008). Additionally, our finding that anger ratings during trials were related to pupil constriction whereas trial-level happiness was associated with pupil dilation aligns with prior research associating smaller pupil sizes more with angry faces and larger pupils with happy faces (Hess, 1975; Kret, 2017). This constriction response is also of potential interest in separating anger and disgust which are often considered challenging to distinguish, with some even claiming disgust is anger's semantic equivalent (Barrett, 2017; Herz & Hinds, 2013; Nabi, 2002). Our findings better fit with recent research finding differences in cardiovascular patterns for disgust and anger (e.g., Konishi et al., 2019; Kreibig, 2010; Rohrmann & Hopp, 2008), rather than earlier studies which only find differences based on arousal and valence (e.g., Barrett, 2006a; Cacioppo et al., 2000). The different patterns of pupil responses broadly suggest that the difference in these emotional labels may go beyond purely descriptive, culturally learned categorization (Barrett, 2013; Lindquist, 2013; Mauss & Robinson, 2009; Stearns et al., 2009).

It also seems that emotions emerged at different points in trial periods and differently depending on the stimuli used. Happiness and sadness were most often significant trial-level predictors when the stimuli were sounds and the whole trial period was analysed. A significant fear response only appeared very late in the trial period which perhaps suggests the whole content of the stimuli must be processed prior to this emotional reaction occurring. A quicker and stronger disgust response compared to fear is also interesting as both disgust and fear have been argued to play a role in avoidance of danger (Al-Shawaf et al., 2016; Cosmides & Tooby, 2000; Tooby & Cosmides, 2008). This suggests that the type of stimuli used (audio or visual) as well as the period analyzed may affect which emotions emerge as significant. However, it seems that the disgust response may be strong enough to emerge no matter the details of the analysis or stimuli.

It is of further interest that the pupil dilation response demonstrated in the present research does not fit with certain prior psychophysiological results. For example, anger is usually associated with sympathetic activity, such as increases in skin conductance levels (Christie & Friedman, 2004; Tsai et al., 2002), increased heart rate, and low heart rate variability (Foster & Webster, 2001; Rainville et al., 2006; Vrana, 1993). The present results suggest that anger is associated with the parasympathetic response of pupil constriction, which suggests anger may not elicit sympathetic activity in every effector organ. This fits with evidence of independent sympathetic and parasympathetic activation in different effector organs (Folkow, 2000). Other emotions, such as disgust, have also been associated with a suite of both sympathetic and parasympathetic activity in different organs (Kreibig, 2010): parasympathetic activity, such as lowered heart rate, high heart rate variability, or both (Christie & Friedman, 2004; Codispoti, Surcinelli, & Baldaro, 2008; de Jong, van Overveld, & Peters, 2011; Konishi, Himichi, & Ohtsubo, 2019; Ottaviani, Mancini, Petrocchi, Medea, &

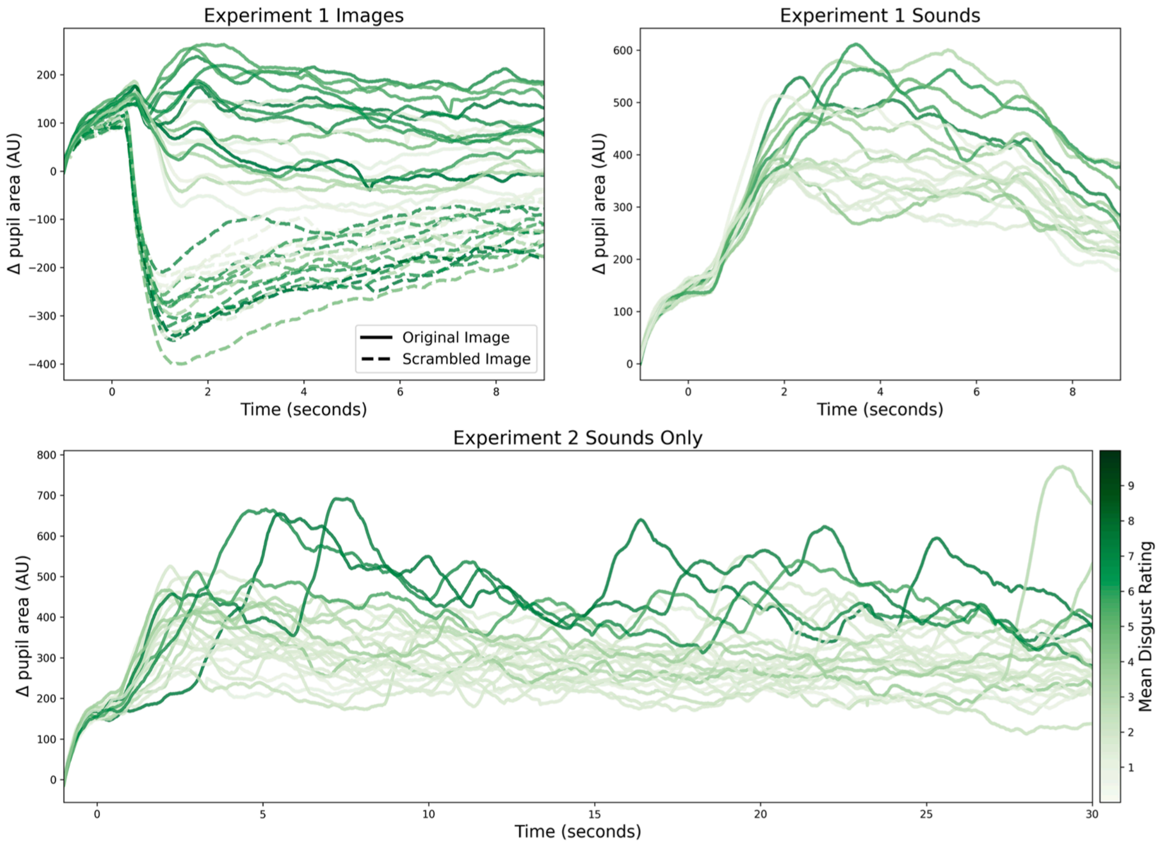

Fig. 6. Pupil change traces for each stimulus. The median pupil area during a baseline period of 2 s has been subtracted from the signal, resulting in the traces visualised here. Each line reflects a different stimulus, with solid lines indicating the original stimuli, and dashed lines (where applicable) their scrambled counterparts. Colour intensity indicates the average trial-level deviation in disgust emotion rating for each stimulus (copied for scrambled stimuli).

Couyoumdjian, 2013; Rohrmann & Hopp, 2008; Shenhav & Mendes, 2014), as well as sympathetic, such as galvanic skin response (Christie & Friedman, 2004; Codispoti, Surcinelli, & Baldaro, 2008; de Jong, van Overveld, & Peters, 2011; Rohrmann & Hopp, 2008; Tsai, Chentsova-Dutton, Freire-Bebeau, & Przymus, 2002). To offer further evidence for this hypothesis it would be ideal to concurrently measure a range of effector organs to ascertain a whole-body reaction which may distinguish emotions further.

8. Limitations and future directions

As a correlational, lab-based study based on a specific set of emotions there are limitations to this study which could be addressed in future research. First, while our evidence does offer preliminary evidence of differences in pupil dilation based on discrete emotional responses (Al-Shawaf et al., 2016; Cosmides & Tooby, 2000; Ekman, 2016; Ekman & Cordaro, 2011; Lench et al., 2011), rather than a general emotional valence and arousal framework (Barrett, 2006a, 2006b, 2013, 2017; Lindquist, 2013), we did not directly ask participants about their emotional arousal or valence. Therefore, future research could directly compare these two approaches in self-reported affective experiences. Second, even using a discrete framework, differences in the function and role of discrete emotions may affect how they emerge in a lab setting. For example, disgust is associated with the behavioral immune system which functions to protect us from disease (Schaller, 2011) and commonly makes false-positive errors: mistaking harmless stimuli for actual disease threats (Ryan et al., 2012). Similarly, sadness is associated with empathy, which can be elicited distantly (Al-Shawaf et al., 2016; Cosmides & Tooby, 2000; Tooby & Cosmides, 2008). Whereas anger is often argued to only be elicited by personally harmful events, with some arguing all other uses of the word are rhetorical (Batson et al., 2007; O'Mara et al., 2011; Sell et al., 2009). Therefore, there is a need for evaluation of emotions evoked by stimuli versus more immediate contexts to understand the relative validity of each. Further experimental research could also be used to strengthen any claims about the relationship between emotions like disgust and pupil dilation.

Our research also showed different emotions emerged depending on the stimuli type used. It could be an important consideration that stimuli such as the IAPS and IADS most effectively elicit disgust and sadness, especially in regard to images, as other methodologies and statistical analyses do not explicitly address this (Babiker et al., 2015; Bradley et al., 2008; Partala & Surakka, 2003). However, the use of non-standardised sounds in Study 2 also introduces noise and variation into the data which may limit the consistency in which they are responded to. This can be seen by the difficulty in finding sounds which elicited anger as strongly as the other emotions as well as relying on both narrative and non-narrative stimuli. Variation should also be considered as it is also possible that the greater variation in anger ratings in Study 2 compared to Study 1 led to anger emerging as significant despite the weaker ratings. Another consideration is the differences found between sounds and images. For example, happiness only appeared as a significant predictor in sounds despite comparable intensity of the self-rated experience with images. Therefore, which emotions emerge as significant may depend on other unmeasured aspects of the stimuli, such as novelty (Wagemans et al., 2019). We were also limited to visual and auditory stimuli, while previous research has found that there are differences in autonomic responses such as skin conductance and systolic blood pressure depending on whether a disgusting stimulus is visual, auditory, haptic, or olfactory (Croy et al., 2013). As such, wider stimuli sets, perhaps also including haptic and olfactory stimuli, should be investigated which also consider additional unmeasured variables such as novelty.

While the focus of this study was on self-reports of participant's own emotional experiences, it should be noted that researchers are often sceptical of the value of self-report, for theoretical or measurement reasons (e.g., Barrett & Westlin, 2021). Even for those who value this approach, it has been noted that self-report contains both the underlying affective experience but also variations and noise associated with the decision-making process, environment, and how the information is requested (Teoh et al., 2023). In this study, we requested emotional ratings at a singular point, after the stimuli presentation has finished, which may impact the emotions reported due to the delay from their emotional reaction to the stimuli. However, there have been efforts to improve and develop self-report measures of emotion (Teoh et al., 2023) as well as consider a more complex structure of discrete emotions (Cowen & Keltner, 2017). Future research could, therefore, consider these more complex approaches to self-report as well as consider additional emotions beyond our limited set.

A final limitation with Study 1 was the difference in presentation period between images and sounds, with the sounds also including 3 s of silence after stimulus presentation. This was not the focus of our study, but the evidence that the disgust and fear response, continue after stimulus presentation suggests it may be valuable to also look at emotional pupillary responses which persist after stimulus presentation in future research. This could also be of particular concern for emotions which appear to have a later pupillary response than disgust, such as fear, which only seemed to impact pupil size very late in stimulus presentation. This means the impact of certain emotions could be missed by focusing only on the trial period. While investigating this further went beyond the scope of the current study, future research could investigate this post-trial period in more depth.

9. Conclusion

These two studies provide evidence using a novel methodology that pupil dilation could be used as a measure of individual emotions rather than only general emotional valence and arousal. We found that emotions of similar valence are associated with different pupillary responses, with disgust being the most prominent emotion associated with pupil dilation when controlling for anger, fear, sadness, and happiness. This suggests some potential different characteristic physiological patterns for similar negative emotions such as anger and disgust, rather than them being semantic equivalents (Herz & Hinds, 2013; Nabi, 2002). Thus, pupillometry offers a potential novel approach to investigating disgust while offering additional findings regarding the question of discreteness in emotions.

CRediT authorship contribution statement

Rick O'Gorman: Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Edwin S. Dalmaijer:** Writing – review & editing, Visualization, Validation, Formal analysis. **Gerulf Rieger:** Writing – review & editing, Supervision, Conceptualization. **Kate McCulloch:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

Generative AI or AI-Assisted Technologies were not used for any part of this manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2025.109044.

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