Do the Seconds Turn into Hours?
Relationships between Sustained Pupil Dilation in Response to Emotional Information and Self-reported Rumination

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Abstract

This study examined relationships between self-reported rumination and sustained pupil dilation, an index of cognitive and emotional processing, in response to emotional information in depressed and never-depressed individuals. Pupil dilation was measured during tasks that required alternating emotional and non-emotional processing. Depressed individuals displayed more sustained pupil dilation in response to stimuli on emotional processing tasks than non-depressed individuals. Such sustained pupil dilation among depressed individuals was particularly apparent in response to negative and personally relevant emotional information. Multiple self-report measures of rumination were moderately correlated with sustained pupil dilation to negative personally relevant information. Results are consistent with the idea that sustained emotional processing of briefly presented stimuli may be associated with the propensity for depressive rumination.

Introduction

Depressed individuals frequently report experiencing rumination, involving repetitive intrusive recollection or re-consideration of negative emotional thoughts or events. Rumination may occur minutes, hours, or even days after the thought or event occurs. Rumination has been associated with more intense and prolonged sad mood (e.g., Nolen-Hoeksema, 1991), vulnerability to, and maintenance of clinical depression (Just & Alloy, 1997), and meta-cognitive aspects of depression (Papageorgiou & Wells, 1999). A parallel literature suggests that depressed individuals tend to engage in elaborative processing of negative information in the seconds following its perception (e.g., MacLeod & Mathews, 1991; Williams & Oaksford, 1992). These disturbances of emotional processing have been hypothesized to result in information processing biases commonly observed in depression such as preferential memory for negative information (e.g., Williams & Oaksford, 1992), and have been implicated in the onset and maintenance of depressive episodes (e.g., Beck, 1967; Ingram, 1984, 1990; Ingram, Miranda, & Segal, 1998; MacLeod & Matthews, 1991; Teadsale, 1988). Although such sustained elaborative emotional information processing has been theoretically linked to rumination (e.g., Ingram, 1984; Wells,

2000), few experiments have been conducted to examine the extent to which these constructs are empirically linked. Therefore, the current study was designed to assess relationships between self-reported rumination and sustained processing of emotional information in clinically depressed and never-depressed individuals.

Linking information processing disruptions to rumination is important for a number of reasons. First, such research could suggest the phenomena share cognitive and brain mechanisms, allowing research to be combined from these literatures. Moreover associating of emotional information processing disruptions with rumination would lend an often-neglected clinical perspective to the information processing literature. Finally, many definitions of rumination have been considered (e.g., Ingram, 1984; Martin & Tesser, 1989; Nolen-Hoeksema, 1991; Philippot & Rime, 1998). It is unclear whether these definitions refer to a single construct and self-report measures created to reflect these theories differ considerably. For example, self-report measures of rumination have nominally assessed thinking about depressive symptoms (Nolen-Hoeksema, Morrow, & Fredrickson 1993), intrusiveness of thoughts about a distressing event (Horowitz, Wilner, & Alvarez, 1979), metacognitive dimensions associated with depressive rumination (Papageorgiou & Wells, 1999), the degree of distress associated with thoughts about recent negative events (Luminet, Rime, & Wagner, submitted), and thinking about what can be done to change one's situation in regard to negative events (Fritz, 1999). An objectively measured correlate of rumination, such as a physiological index of sustained processing, could help to better understand relationships between these constructs.

We assessed sustained information processing by measuring pupil dilation in response to briefly presented emotional stimuli. Many studies have demonstrated pupil dilation to be a reliable correlate of cognitive load, as the pupil dilates more under conditions of higher attentional allocation, memory use, or interpretation of more difficult material (see Beatty 1982a or Steinhauer & Hakerem, 1992, for reviews). Pupil dilation persists if the demand is sustained (e.g., Beatty, 1982b). As individuals are asked to remember larger numbers of digits, for example, pupil dilation increases proportionally (e.g., Kahneman & Beatty, 1966; Granholm et al., 1996). The pupil has also been shown to dilate in response to emotional information (e.g., Janisse, 1974) and is inervated by brain areas associated with both cognitive and emotional processing (e.g., Szabadi & Bradshaw, 1996). Recently, depressed individuals were shown to display greater sustained pupil dilation than never-depressed individuals in the seconds following stimuli on emotional information processing tasks (Siegle, Granholm, Ingram, & Matt, 2001). Sustained pupil dilation was not present on a non-emotional (cued reaction-time) task, suggesting that the phenomenon could reflect emotional processing. While that study did not find a relationship between sustained pupil dilation and a measure of rumination independent of depressive severity, the measure was highly correlated with depressive severity and indexed only one aspect of depressive rumination (concentration on symptoms). Multiple measures of rumination were therefore examined in the current study.

A second question of interest was whether sustained pupil dilation, observed during a distracting task subsequent to the presentation of emotional stimuli was also related to self-reported rumination. Answers to this question could increase the clinical relevance of sustained processing as an index of rumination; it could be used to understand the degree to which rumination impairs or interferes with everyday tasks.

To answer these questions, depressed and never-depressed individuals completed multiple tasks in which trials alternately required emotional and non-emotional processing while their pupil dilation was measured. We predicted that depressed individuals would show more

persistent pupil dilation during the emotion-processing trials and into the beginning of subsequent non-emotional processing trials. Reflecting the idea that rumination is often considered to be relevant to negative and personally relevant information, it was expected that sustained processing would be greatest for these types of information. We further hypothesized that sustained pupil dilation, at least in response to negative personally relevant information, would be related to self-reported rumination, as would sustained pupil-dilation during nonemotional-processing trials subsequent to the presentation of negative information. Analysis thus involved two steps: 1) confirming the presence of sustained processing in depressed individuals (i.e., replicating Siegle et al's 2001 result) and 2) examining relationships between sustained processing and self-reported rumination.

Method

Participants.

Participants included 14 patients (6 Male, 9 Caucasian, ages 24-47, $M(SD)_{age}$=38.8 (9.6)) diagnosed with unipolar major depression using DSM-IV criteria (APA, 1994) and 15 never depressed controls (7 Male, 8 Caucasian, ages 25-47, $M(SD)_{age}$=36 (7.4)). Patients were recruited through the University of Pittsburgh's Mental Health Interventions Research Center (MHIRC). Eleven depressed participants were diagnosed using the Structured Clinical Interview for DSM-IV Diagnosis (SCID; First, Spitzer, Gibbon, & Williams, 1997) and three were diagnosed clinically. Depressed participants reported previously having had from one to more than 10 previous episodes of depression, Md=3 episodes, and having been depressed for between 7 weeks and 10 years in their current episode, Md=50 weeks. Control participants endorsed no symptoms of depression, and had no current or historical Axis I disorder using the SCID interview. Participants had normal corrected vision (20/30 using a hand-held eye chart) in their measured eye. Participants described no health problems thought to interfere with performance, alcohol abuse or psychoactive drug abuse within the past six months. Five depressed participants were unmedicated and the rest were on a variety of medications (primarily SSRI's); no patients were prescribed tricyclics or Nefazadone. Participants with a previous history of psychosis or manic episodes were excluded.

Apparatus.

Stimuli were displayed in white on a black computer screen. Participants sat approximately 65.5 cm from the bottom of the stimulus. Stimuli were lowercase letters approximately 1.59 cm high, subtending 1.4 degrees of visual angle. Reaction times were recorded using a game pad capable of reading reaction times with millisecond resolution. It was modified to contain three buttons, arranged in a triangle, so that respondents' fingers were nearly equidistant from each possible response. To account for differential response latencies to different buttons, the mapping of game-pad buttons to responses was counterbalanced across participants.

Pupil dilation was recorded using methods previously described and tested (e.g., Steinhauer, Condray, & Kasparek, 2000) at the VA Pittsburgh Healthcare System. In brief, data were collected using an ISCAN RK406 pupillometer. The pupillometer consisted of a video camera and infrared light source that were pointed at a participant's eye, and a device that tracked the location and size of the pupil using these tools. Pupil size was recorded at 60Hz (every 16.7ms) and passed digitally from the pupillometer to a computer that stored the acquired data along with signals marking the beginning of trials, the end of fixation, stimulus onset time, and reaction time. The pupillometer's resolution for a typical participant was better than 0.025 mm pupil diameter. Data collection was managed using EEGSYS (Hartwell, 1995).

Target Stimulus Materials.

For an emotion-identification task, 10 positive, 10 negative, and 10 neutral words balanced for normed affect, word frequency, and word length were chosen using a computer program (Siegle 1994) designed to create affective word lists from the Affective Norms for English Words (ANEW; Bradley & Lang, 1986) corpus. To obtain personally relevant stimuli, participants were instructed to generate "10 personally relevant negative words that best represent what you think about when you are upset, down, or depressed," as well as "10 personally relevant positive words that best represent what you think about when you are happy or in a good mood," and "10 personally relevant neutral (i.e., not positive or negative) words that best represent what you think about when you are neither very happy nor very upset, down, or depressed," all between three and 11 letters long, as in Siegle et al (2001).

Procedure.

One appointment was scheduled with participants after their initial clinical interview. Participants were told about the experiment, signed consent forms and generated a list of personally relevant words. They then rated the personal relevance of all of the words they would see in the experiment to equate the normed and personally relevant lists for novelty. Participants received a brief vision test, and completed information processing measures followed by questionnaire measures. Testing occurred in a moderately lit room (.56 foot-candles illuminence) in which the experimenter was not present. Time of day was not controlled for. Participants completed a Sternberg memory task (Sternberg, 1969) followed by two emotion processing tasks (valence identification of words and personal relevance rating of sentences), and a control cued-reaction-time task. The order of the sentence rating and valence identification tasks were counterbalanced across participants.

Tasks.

The delayed match to sample, or “Sternberg memory” task was used as a non-emotional processing task. The task was chosen because there is a wealth of behavioral and psychophysiological data on it, because it takes a few seconds to complete a trial in which stimuli are continuously presented allowing detection of residual activity from the previous trial, and is easy enough that depressed individuals would not get frustrated by the task. Participants viewed a fixation mask (row of X’s with vertical prongs over the center) for one second followed by three random two-digit numbers, followed by a mask (row of X’s) for one second each. A target two-digit number appeared for the following nine seconds. Participants were instructed to push a button for “Yes” if the target was in the previously presented set and another button for “No” if it was not. The order of these buttons was counterbalanced across participants.

In the other tasks, trials alternated between task-relevant trials and Sternberg memory trials. Before Sternberg trials the cue “Did you see it” was displayed for one second. For the valence identification task, 60 positive, negative, and neutral words described previously were presented. The cue “What’s the emotion” was displayed for one second followed by a two-second fixation mask. The mask was replaced by the target word for 150 ms followed by a mask (row of X’s) for nine seconds. Participants were instructed to name the emotionality of each word by pushing buttons for “Positive”, “Negative”, or “Neutral” as quickly and accurately as they could after the word appeared. Labels for these responses were on a card in the participant’s field of view. In the emotional sentence-rating task, the same procedure was used except that instead of viewing a word followed by a mask, participants viewed 30 positive and 30 negative sentences from the Automatic Thoughts Questionnaire (Hollon & Kendall, 1980) for nine seconds. Participants were asked to push buttons reflecting whether the sentences were not personally relevant, somewhat relevant, or personally relevant. The order of the yes and no buttons were the same as for the

Sternberg trials. The cued reaction-time task was the same as the valence identification task except that instead of a word, a row of "a"'s between three and five letters long was displayed. Participants were instructed to push the middle button as quickly as possible after the stimulus.

Measures of Mood and Rumination.

To assess depressive severity at the time of testing, the Beck Depression Inventory (BDI; Beck, 1967) was administered. The BDI has been validated as a measure of depressive severity in control and adult depressed populations (Beck et al, 1988) and was used rather than the newer BDI-II, since the BDI was the measure most frequently employed in other studies of the relationship between rumination and depressive severity.

A packet of self-report measures was administered that has been shown to measure different and somewhat independent aspects of rumination, as well as to have different relationships to depressive severity in a university sample (Siegle, submitted). Measures with acceptable internal consistency from Siegle's (submitted) study included the Response Styles Questionnaire (RSQ; a 71 item inventory containing a 22 item rumination subscale (RSQ-RUM) assessing the frequency of thoughts about one's symptoms of depression; Nolen-Hoeksema et al, 1993), a multi-dimensional rumination questionnaire (MRQ; 27 item questionnaire with a scale reflecting concentration three aspects of a past serious and distressing event including emotions (MRQ-EMOTS; 11 items), instrumental or constructive methods for coping with the event (MRQ-INST; 6 items), and searching for meaning in the event (MRQ-SRCH; 5 items); Fritz, 1999), Revised Impact of Event Scale (R-IES; a 15 item inventory with a 7 item scale that measures the intrusiveness of thoughts; Horowitz, Wilner, & Alvarez, 1979), the Thought Control Questionnaire (TCQ; a 30 item inventory that assesses how people cope with intrusive thoughts, containing a 6 item reappraisal (TCQ-REAP) scale representing reconceptualization of negative thoughts, a 6 item worry scale (TCQ-WORRY), and a 6 item self-punishment scale (TCQ-PUN); Wells & Davies, 1994) and the Emotion Control Questionnaire (ECQ; a 56 personality inventory with a factor analytically weighted scale measuring a tendency to rehearse thoughts (ECQ-REH), Roger & Najarian, 1989). In addition, two recent-event-related measures were given to assess the degree to which, in the week prior to the exam, individuals found themselves engaging in rumination-like behaviors on a negative event (RNE; Luminet, Rime, & Wagner, submitted) and negative thought (RNT; Papageorgiou & Wells, 1999). These latter measures reflected a number of dimensions of rumination; they were factor-analyzed by Siegle (submitted), yielding general rumination factors that were used in analysis (labeled RNE-GEN; RNT-GEN).

Data Selection, Cleaning, and Reduction

Selection of Stimuli for Analysis. Valence identification and sentence rating trials with reaction times below 150 ms were discarded as outliers, because previous results suggest that reaction times in this range indicate that a response was made without regard for the stimulus (Matthews & Southall, 1991). Analysis was restricted to words for which the normed or generated valence was consistent with the participant's ratings on a word-rating task given at the end of the experiment. This technique was used to be sure that participants interpreted words as belonging to the categories in which they were analyzed (e.g., to be sure that words analyzed as "positive" were really considered positive by the participant). These procedures resulted in the elimination of M(SD)=15.46(7)% of trials per subject on the valence-identification task.

Calculation of Pupil Dilation Indices. Data were cleaned using methodology previously described by Granholm (e.g., Granholm et al, 1996). Blinks were identified as large changes in pupil dilation occurring too rapidly to signify actual dilation or contraction. Trials comprised of over 50% blinks were removed from consideration. Linear interpolations replaced blinks

throughout the data set. Data were smoothed using a ten point weighted average filter. Then, linear trends in pupil dilation calculated over blocks of 20 trials were removed from pupil dilation data to eliminate effects of slow drift in pupil diameter that were not related to trial characteristics. Pupil diameter, measured as the average dilation over the one second preceding the onset of the stimulus, was subtracted from pupil diameter after stimulus onset to produce pupil dilation difference score indices.

Analytic Strategy. Within and between-group contrasts on pupil dilation were examined at each point along pupil dilation waveforms. Following Guthrie and Buchwald's (1991) strategy, regions of the waveforms were considered significantly different when over 1.36 seconds of consecutive tests[1] were statistically significant at $p<.1$. This strategy uses consecutive points on a waveform as replications to control for type 1 error at $p=.05$ for all tests along a given waveform. This technique was adopted to allow quantification of the duration of significant differences in waveforms between groups; techniques involving aggregation of values throughout the waveform would not have allowed such estimates, and would be confounded by the magnitude of differences between waveforms at each point. Effects involving valence (e.g., differential response to negative v. neutral stimuli) were examined using hierarchical regressions on responses to negative words in which responses to neutral words were entered on the first step and incremental variance due to group was tested. This type of analysis is more powerful than a standard MANOVA contrast since it does not rely on difference variances, which can be unreliable. Family-wise alpha for planned pairwise contrasts was controlled at 0.05 using a Bonferroni correction.

Results

Two groups of analyses were performed. The first group examined the extent to which Siegle et al's (2001) basic result, that depressed individuals displayed sustained pupil dilation in comparison to controls, was replicated. The second group of analyses examined relationships between sustained pupil dilation and self-report measures of rumination. The groups differed marginally significantly in age, $t(27)=1.7$, $p=.06$, Difference (D)=6.3 years, but not on gender, $t(27)=-1.0$, $p=.30$, D=18%, or education $t(27)=1.0$, $p=.30$, D=.67 years. As expected, the depressed group scored as significantly more dysphoric on the BDI than the control group, depressed M(SD)=21(9.3), control M(SD)=2.3(1.8), $t(27)=-7.4$, $p<.0005$, D=18 points.

Decision times

Average reaction times and relevant pupil dilation indices for each condition are shown in Table 1. Multivariate split-plot ANOVAs on decision time using valence and personal relevance as factors yielded no significant main effects or interactions with group, though there was a significant personal-relevance by valence interaction, $F(2,23)=8.75$, $p=.001$, driven largely by quick reactions to personally relevant positive words and slow reactions to personally relevant negative words, $F(1,24)=17.5$, $p<.0005$, $\eta^2=.42$. On subsequent Sternberg trials there were no statistically significant effects. A planned contrast revealed that depressed individuals were marginally slower to respond to Sternberg trials on the valence identification task following personally relevant negative than normed positive words, compared to controls, $F(1,24)=4.6$, $p=.04$, $\eta^2=.16$, D=-173ms. On the sentence ordering test, there was a significant valence x group

[1] A significant sequence length of 1.36 seconds corresponded to 17 points in the data downsampled to 12.5 hz. This estimate was derived from Buchwald & Guthrie's (1991) table 1, assuming there were between 5 and 10 relevant components of the pupil dilation waveform (based on Siegle et al's (2001) data) which yielded an estimated autocorrelation of waveform residuals of .87-.92. Downsampling to 12.5Hz yielded approximately 150 points in each of the valence identification and Sternberg segments of trials.

interaction, F(1,26)=4.25, p=.049, η^2=.14. Depressed individuals reacted 200ms more quickly to negative than positive sentences, t(13)=2.84, p=.014, whereas there was no valence difference for controls, t(13)= .65, p=.52, difference (D)=2ms. No main effects or interactions were observed for subsequent Sternberg trials. On the cued reaction time task there were no significant group differences on the task or subsequent Sternberg trials.

Insert Table 1 about here

Test of differences in pupil dilation between groups

Average pupil dilation waveforms for relevant trial types for the valence identification, sentence rating, and cued reaction time tasks are shown in Figure 1, along with regions of significant differences between waveforms. There were no group differences in baseline pupil diameter, $M_{depressed}$ =4.9mm , $M_{control}$ = 5.1mm, t(27)=.58, p=.28.

Insert Figure 1 about here

Did depressed individuals display sustained pupil dilation on the emotional processing tasks relative to controls? As shown in Figure 1, depressed individuals displayed significantly greater pupil dilation than controls from 5.1 to 10.0 seconds after the presentation of all stimuli on the valence identification task, t(27)=2.1, p=0.02, D=0.08mm, d=0.78, and from 4.1 to 12.9 seconds after stimulus onset on the sentence rating task, t(26)=2.53, p=0.01, D=0.12mm, d=0.96.

Were effects of sustained pupil dilation absent for the cued reaction time task (consistent with identifying sustained pupil dilation with emotion-processing)? Depressed individuals did not display increased sustained processing relative to controls during the cued reaction time task.

Was sustained pupil dilation especially large for negative and personally relevant words in depressed individuals? On the valence identification task, depressed individuals displayed greater sustained processing in response to personally relevant negative than normed neutral words relative to controls throughout the window from 5.1 to 6.3 seconds after stimulus onset on the valence identification task, ΔR^2= 0.11, FΔ (1,26)=5.65, p=0.03. This contrast was driven by two main effects: depressed individuals displayed greater dilation to negative than neutral words from 4.5-6.2 seconds, ΔR^2=0.10, FΔ(1,26)=5.12, p=0.03, and from 8.0-10.0 seconds, ΔR^2=0.11, FΔ(1,26)=5.9, p=0.02 after stimulus onset relative to controls. They also displayed greater dilation to personally relevant than normed words from 4.9-6.3 seconds after stimuli relative to controls, ΔR^2= 0.18, FΔ (1,26)=14.2, p<0.005, and 8.3-9.2 seconds, ΔR^2= 0.11, FΔ (1,26)=5.01, p=.03. Depressed individuals also displayed marginally significantly higher dilation to negative than positive words relative to controls from 4.8 to 6.1 seconds following stimuli ΔR^2= 0.11, FΔ (1,26)=4.0, p=.06. Depressed individuals did not display greater dilation to negative than positive information for 17 consecutive points during the emotional sentence rating task either relative to themselves or in comparison to controls.

Did sustained pupil dilation effects continue into subsequent Sternberg trials? Depressed individuals displayed increased pupil dilation from 12.2 to 14.9 seconds after the beginning of the Sternberg trial on the valence identification task, t(27)=1.87, p=0.04, D=0.07mm, d=0.70, relative to controls. They also displayed greater pupil dilation to negative than neutral words on the valence identification task 10.8-14.8 seconds after the Sternberg trial's onset relative to controls, ΔR^2=0.17, FΔ (1,26)=5.91, p=0.02. On the sentence rating task, depressed individuals showed increased pupil dilation throughout the first 3.8 seconds of the Sternberg trial relative to

controls. Unexpectedly, on the cued reaction-time task, depressed individuals showed increased pupil dilation from 9.4-11.6 seconds after the Sternberg trial's onset, $t(26)=1.87$, $p=0.04$, $D=0.10$mm, $d=0.71$ and from 11.7-14.4 seconds, $t(26)=2.12$, $p=0.02$, $D=0.10$mm, $d=0.80$.

Effects were robust to alternate methods of dividing the sample (e.g., using only clearly dysphoric and non-dysphoric individuals), and cleaning the data (e.g., restricting analyses to just stimuli rated consistent with the normed valence). Group differences in overall sustained dilation on the valence identification task and cued reaction-time task were not significant after age was covaried out, but valence-specific differences and overall effects on the sentence rating task were still significant. Analyses of the valence identification task in which no outlying or inconsistent trials were removed, and in which trials were time-locked to reaction times rather than stimulus onset yielded the same significance and nearly the same effect sizes as were reported.

Relationships among the rumination scales

Before examining relationships between the rumination measures and sustained pupil dilation, the extent to which rumination measures could be combined was examined. The 11 measures had low between-scale internal consistency, Cronbach's alpha=.23 (95% CI = -.28-.67). Exploratory factor analysis of the scale scores yielded two factors with eigan values over 1, one of which passed a Scree test, and explained only 57% of the variance. The second factor explained only 12% of the variance. Thus, consistent with data from a larger sample of undergraduates (Siegle, submitted), initial exploration did not support combining measures.

Relationships between sustained pupil dilation and rumination.

Relationships between sustained pupil dilation and self-report measures were examined to assess relationships between self-reported rumination and sustained pupil dilation and the extent to which these relationships are mediated by depressive severity. Correlations were examined between scores on each administered questionnaire and each point along pupil dilation waveforms. Monte Carlo simulations (following Guthrie & Buchwald, 1991) in which obtained questionnaire responses were correlated with simulated waveforms with the obtained autocorrelation (.93) revealed that restricting significance to chains of correlations 1.76 seconds long was appropriate for testing these relationships at a level of $p=.05$. Because multiple measures of rumination were used, the chances of finding a significant relationship with at least one questionnaire was greatly increased (the probability that any one questionnaire would have a significantly long chain of correlations was .39-.47). To control for type I error, correlations with a single rumination measure were not interpreted as significant. Rather, to interpret results as generalizable (e.g., to a general notion of rumination), interpretation of significance was restricted to cases in which multiple rumination measures simultaneously yielded significant correlations with difference waveforms. Simulations showed that interpreting chains of correlations 1.76 seconds long with at least three rumination measures restricted alpha to .02-.05, and for planned comparisons on the last four seconds of the valence identification task, enforcing at least two measures restricted alpha to .05.

Was rumination related to sustained pupil dilation following negative information?

Correlations of self-reported rumination with differential pupil dilation to negative information were examined throughout valence identification and sentence rating trials as shown in the top panel of Figure 2. In the last four seconds of the valence identification task correlations with the difference in pupil dilation to negative personally relevant and normed neutral words were significant ($p<.1$ for at least 1.6 seconds, as above) for the BDI and four scales (RNE general, MRQ emotion focused , MRQ searching, TCQ punishment). Another 4 scales were correlated for over 1.36 seconds during this time (RSQ rumination, MRQ instrumental, TCQ worry, ECQ

rehearsal). On the sentence rating task there were no significant correlations for 1.6 seconds common to 3 measures though significant correlations with the difference in pupil dilation to negative and positive words came after the onset of the Sternberg task for five scales (RSQ rumination, MRQ emotion focused, instrumental, TCQ punishment, reappraisal subscales).

Insert Figure 2 about here

Was rumination related to overall sustained pupil dilation? Self-reported rumination was less strongly related to overall sustained pupil dilation on any task, as shown in the middle panels of Figure 2. In no case did 3 scales simultaneously display long chains of correlations.

Were relationships between rumination and sustained pupil dilation mediated by depressive severity? Relationships between each measure of rumination and depression are shown to demonstrate considerable variability in Table 2.

Insert Table 2 about here

Effects of controlling for depression in the relationships between sustained processing and self-reported rumination were examined for intervals that were significant in the first analysis, as shown in the bottom panel of Figure 2. As expected, significant associations of rumination scales that were strongly correlated with BDI scores displayed decreased relationships with pupil dilation to negative versus neutral stimuli when BDI scores were controlled for; two scales still displayed simultaneous correlations of over 1.6 seconds in the last four seconds of the valence identification task (RNE general and TCQ reappraisal), though, four scales (RNE general, MRQ emotion focused and searching, TCQ punishment) still displayed significant sequences of correlations for 1.36 seconds, in the last seconds of the valence identification task and three other scales still displayed half-second sequences of significant correlations in the last four seconds of the valence identification task (RNT emotion focused, MRQ instrumental, TCQ reappraisal), suggesting that these relationships may not have been entirely explained by self-reported depression. On the sentence rating task, all significant sequences of correlations were greatly reduced (becoming nonsignificant) with the exception of two scales representing adaptive aspects of rumination (MRQ instrumental coping and TCQ reappraisal).

Interactions of BDI scores and rumination with sustained processing of negative words were also examined. On the valence identification task, only one scales displayed a significant 1.3 second sequence of semipartial correlations for the interaction term (MRQ instrumental), though four scales displayed significant sequences of semipartial correlations directly following the valence-identification stimuli (2.0-3.8 seconds following stimuli; RSQ rumination, RNE general, TCQ punishment, ECQ rehearsal). Few other correlations were significant. On the sentence rating task there were no significant sequences of correlations with the interaction term.

Discussion

This experiment examined the extent to which sustained cognitive processing, indexed by sustained pupil dilation, in response to emotional information was related to self-reported rumination in depressed and never-depressed individuals. Results replicated an earlier finding that depressed individuals show more sustained pupil dilation on emotional information processing tasks than controls. While sustained dilation in depression was not unique to emotional processing tasks (i.e., it also happened in response to a Sternberg memory task), it was only present on tasks that required a moderate level of cognitive load (i.e., it was not present in response to a cued reaction-time task). Sustained dilation in depressed individuals was

particularly apparent for negative and personally relevant information across multiple tasks involving words and sentences. Multiple self-report measures of rumination were associated with sustained pupil dilation to negative words, but generally, were not strongly related to overall sustained pupil dilation, sustained pupil dilation in response to non-emotional tasks, or sustained pupil dilation to negative sentences. Relationships of rumination to sustained pupil dilation were largely mediated by depressive severity.

Results are consistent with a number of common ideas about depression. First, to the extent that pupil dilation can be used as a proxy for cognitive and emotional processing, sustained processing on the order of seconds after a negative stimulus occurs among the same individuals who experience rumination on a longer time scale. Second, distraction may largely dampen such sustained processing of negative words. Put another way, rumination may be associated with excessive elaboration on negative information, and not with an inability to shut off that process.

Sustained pupil dilation on the Sternberg memory task outside the context of any nominally emotional information processing was observed but not expected, and was not correlated with rumination. Potentially, there are multiple causes for sustained cognitive processing; rumination may be particularly associated with sustained processing of emotional information. Other processes may involved in sustained processing of cognitively engaging but non-emotional material by depressed individuals (consistent with the lack of sustained processing on the cued-reaction-time task). As some depressed participants reported doubt regarding their performance on the task, this result could reflect sustained affective processing regarding the task. Since this result did not survive controlling for age, it could have been confounded with age effects. In either case, more research is necessary to understand this result.

The observation that rumination was weakly related to sustained pupil dilation to negative information on a personal relevance rating task for sentences seconds later than on an emotion rating task with words could have many explanations. A simple explanation is that sentences took longer to be read or encode than words, so it took longer for elaboration on them to begin, and occurred with more variability.

Pupil dilation did not appear similarly related to all self-report measures of rumination-like constructs. From one perspective, this phenomenon could be expected based on the low internal consistency of measures; potentially they do not each reflect rumination. Alternately, because each of these measures has been shown to reliably assess rumination-like constructs in separate studies, heterogeneity among rumination measures may reflect the construct's complexity and multidimensionality (see Siegle, submitted for further discussion of relationships between measures and the construct of rumination). As such, despite low power to interpret results based on each questionnaire separately, a few consistent patterns emerged that warrant further study. Two scales were consistently related to sustained processing of negative information over multiple tasks. Fritz's (1999) MRQ emotion-focused scale and Wells & Davies's (1994) TCQ punishment scale both contained multiple items pertaining to self-criticism. In an information processing experiment in which individuals are made to commit to a large number of decisions over a short period of time, such self-criticism could have been particularly involved in the observed sustained processing. A second pattern is that two scales that nominally measured more adaptive aspects of rumination were the only ones consistently associated with overall sustained processing; the MRQ instrumental coping scale had items like "In the past two weeks, how much have you thought about how to solve any problems that were caused by the event?" and similarly, the TCQ re-appraisal scale had items like "I challenge the thought's validity." If this pattern is replicable, it could indicate an association of valence-independent sustained processing

with adaptive reframing, solution-focused sustained processing, or alternately, meta-cognitive strategies to protect against emotional arousal. Finally, scales commonly employed to examine aspects of repetitive negative thinking, e.g., Horowitz et al's (1979) RIES intrusion scale and Nolen-Hoeksema et al's (1993) RSQ did not display significant correlations with valence-related sustained processing. These results suggest that it may be important to administer alternate measures or multiple self-report measures in assessing relationships of cognitive functioning to rumination.

Other factors further complicate interpretation of the results. Measures of rumination and depressive severity were strongly correlated weakening the ability for individual scales to survive partialing out depressive severity; potentially, measures constructed to explicitly separate out these constructs (e.g., Treynor et al, this issue) may be useful. The 6 year age difference between groups was a potential confound, though it is unclear why results would vary with age. Also, the sample was smaller and not as homogeneous as in Siegle et al's (2001) study; depressed individuals were not all diagnosed by structured interview, were not all unmedicated, and were not excluded for having low BDI scores. Though SSRI's are not expected to affect pupil dilation, and all participants had adequate pupil motility, it is possible that effect sizes were underestimated due to medication effects. Given these concerns, the replication of Siegle et al's (2001) results in this sample was heartening, and the use of a broader sample may have allowed more variation in rumination in the depressed group than in the original study. There is also some ambiguity in interpreting the employed measures. Pupil dilation does not vary only with cognitive and emotional processing; while efforts were made to control for psychophysical characteristics that affect pupil dilation such as light-levels and stimulus luminance, intrasubject variability in variables such as tiredness and pain could have contributed to unexplained inter-individual variability. Interpreting physiological reactions to word-stimuli is also somewhat ambiguous; words-stimuli were employed to provoke associative processes involved in recognizing emotional information. The extent to which these reactions represent how individuals react to emotional information in their every-day environments is unclear; potentially emotional association represents only a small part of general ecological reactions to emotional stimuli. The cued-reaction time task may also not have been an effective test of the specificity of sustained processing to emotion-processing tasks as reactions occurred quickly relative to the other tasks, and may thus not have provoked non-emotion-related sympathetic system activity.

Despite these concerns, this study supports the idea that depressed individuals engage in sustained processing in response to negative information, especially if it is personally relevant. The study also suggests that this sustained processing in the course of seconds after a negative stimulus may be associated with a more pervasive tendency to ruminate for hours or days after an emotional event, as predicted by theoretical and computational models (e.g., Siegle, 1999). Of course, it is difficult to use pupil dilation to say exactly which brain structures or autonomic systems are involved in sustained processing; the pupil is inervated by many potentially relevant brain areas and responds to both sympathetic and parasympathetic nervous system activity (relationships between pupil dilation and other potential physiological correlates of rumination are discussed in Siegle & Thayer, in press). One extension of this research involves relating sustained processing of negative information to underlying brain mechanisms. Initial work by our group (Siegle et al, in press) suggests that when a subset of the same individuals who engaged in the current tasks were assessed using functional magnetic resonance imaging (fMRI), depressed individuals showed sustained amygdala activity in response to negative information; sustained amygdala activity was also associated with self-reported rumination. Thus activity in a

brain area consistently relevant to emotional processing in depression may be particularly associated with sustained pupil dilation.

This research may also have implications for selection for and development of interventions for depression. Sustained pupil dilation has distinct physiological correlates, is easy and inexpensive to measure, and seems to be a useful measure of sustained cognitive and emotional processing. Treatments such as Cognitive Therapy work to change disrupted cognitive styles, e.g., excessive maladaptive elaboration on negative thoughts. As sustained pupil dilation to negative information appears to be sensitive to this cognitive style, it may be a useful predictor of treatment response to cognitive therapy. If sustained processing of negative information can be causally, rather than correlationally, related to rumination, targeting this phenomenon in novel interventions for depression could be also be useful.

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Table 1
Mean harmonic mean decision times for each task in seconds

	normed						personally relevant					
	positive		negative		neutral		positive		negative		neutral	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Valence Identification Task												
Control decision time	1.40	.48	1.45	.53	1.49	.35	1.33	.41	1.50	.53	1.63	.56
Depressed decision time	1.74	.37	1.86	.52	1.80	.44	1.55	.39	1.96	.59	1.88	.54
Control Sternberg decision time	1.17	.31	1.10	.28	1.23	.34	1.19	.30	1.22	.38	1.21	.26
Depressed Sternberg decision time	1.34	.34	1.38	.27	1.45	.38	1.37	.29	1.50	.37	1.37	.30
Sentence Rating Task											**Cued RT Task**	
Control decision time	2.18	.49	2.15	.41							.22	.14
Depressed decision time	2.88	.62	2.60	.39							.31	.19
Control Sternberg decision time	1.13	.27	1.12	.26							.92	.19
Depressed Sternberg decision time	1.36	.33	1.30	.24							1.02	.23

Note: Harmonic means were used based on Ratcliff's (1993) recommendation. To eliminate spurious skew due to outliers while preserving rank-ordering of data, outliers more than 1.5 times the interquartile range from the median harmonic mean on any variable were scaled to the closest obtained value below this cutoff plus the difference between this value and the next closest value as in Siegle et al (2001).

Table 2
Correlations of Beck Depression Inventory scores and self-report measures of rumination

Measure	RSQ RUM	RNT EMOT	RNE GEN	MRQ EMOTS	MRQ INST	MRQ SRCH	RIES INT	TCQ WORRY	TCQ PUN	TCQ REAPP	ECQ REH
r	.773	.492	.798	.651	.370	.458	.495	.632	.723	-.233	-.697
p	.000	.009	.000	.000	.057	.016	.006	.001	.000	.252	.000

Abbreviations for measures are described in the Methods.

Figure 1:
Median pupil dilation among control and depressed individuals during the tasks. Differences significant at p<.1 are highlighted in light gray and differences significant at p<.05 are highlighted in dark gray. On the X axis, stimulus onset occurred at 0 seconds. The height of significance shaded bars represents their p value, using same scaling labeled on the Y axis. Significantly long sequences of differences were observed for overall pupil dilation on each task, and in response to negative and personally relevant words on the valence identification task. Depressed individuals displayed significantly greater sustained dilation than controls in response to all stimuli on the valence identification, sentence rating tasks, and the Sternberg memory task, as well as to negative and personally relevant words on the valence identification task.

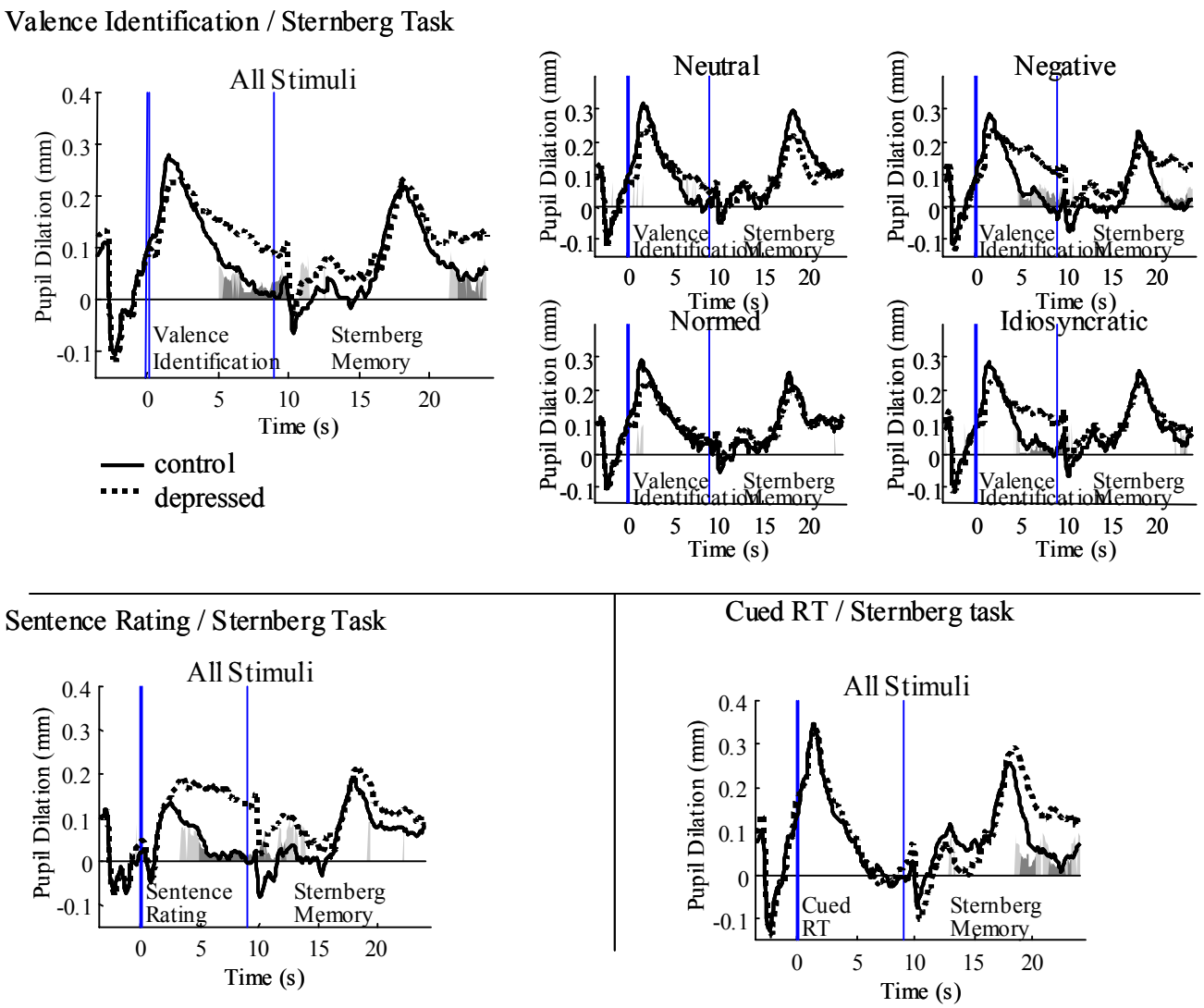

Figure 2:

Correlations of self-report measures of depressive symptomatology and rumination with pupil dilation throughout trials, beginning with stimulus onset (0). The top panel shows correlations with waveforms representing differential processing of negative information. The middle panel shows correlations with all stimuli. The bottom panel shows semi-partial correlations with difference waveforms controlling for BDI score. Successively darker gray shades represent correlations of increasing magnitude (.3, .4, .5). Black lines above correlation bands represent sequences of 1.6 seconds of correlations significant at p<.1. Grey lines above correlation bands represent sequences of .5 seconds of correlations significant at p<.1, which were examined in the last four seconds of the valence identification trials.

As shown in the figure there are dense correlations for waveforms representing differential processing of negative information, and more sparse correlations with overall processing, and differential processing after controlling for depressive severity.