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Abstract

Prominent theories suggest that time and number are represented by a common magnitude system. However, distinct patterns of temporal and numerical processing occur in the presence of emotional stimuli, calling into question theories of a common magnitude system, while also unveiling questions regarding the mechanisms underlying these temporal and numerical biases. We tested whether numerical processing, like temporal processing, may be impacted by increased arousal levels, yet have a higher threshold level in order to impact estimates. If so, then induced arousal may reverse the typical pattern of numerical underestimation in the presence of emotions. Adults (N = 85) participated in either a stress-induction or a control version of the task. Then, participants completed a numerical bisection task in the presence and absence of emotional content. Increasing arousal had no impact on numerical processing, except in the presence of happy faces, providing further evidence for distinct processing mechanisms.

Keywords: quantity processing; numerical cognition; temporal processing; emotion; stress

Introduction

Temporal and numerical processing is vital for our everyday interactions. How many seconds will it take to cross the street? How many slices of pizza are needed to serve a family dinner? These basic quantitative processes are posited to form the foundations of mathematical thought and have been shown to predict math achievement (Halberda, Mazzocco, & Feigenson, 2008), highlighting the importance of understanding basic quantitative processing.

Prominent theories suggest that the processing of time, number, and space are a part of a common magnitude system (Walsh, 2003; Cantlon, Platt, & Brannon, 2009). Evidence in support of this theory demonstrates analogous performance on timing and counting tasks in both rats and humans (Meck & Church, 1983), and comparable parietal cortex activity during temporal and numerical processing (Walsh, 2003). Further, children suffering from genetic disorders that are known to impact numerical processing (e.g., Turner Syndrome) also experience spatial and temporal deficits, suggesting an overlap among systems involved in quantity processing (Silbert, Wolff, & Lilienthal, 1977).

While many controlled laboratory studies have investigated quantitative processing, this work has largely ignored the fact that temporal and numerical processing in the real world rarely occurs in an emotional vacuum. Some work investigating how emotional stimuli impact numerical and temporal processing has led to distinct theories regarding how these quantities are processed (Droit-Volet & Meck, 2007; Young & Cordes, 2013). The bulk of this work has focused on performance during a bisection task in which participants judge whether a target duration or a target numerosity is more similar to a short/small standard or long/large standard. For example, participants may be presented an array of 7 dots and asked to judge whether it is more similar to the learned standards of 4 dots (small) or 16 dots (large). Bisection task data have been used to assess biases in estimates by measuring the value at which participants are indifferent between the two standards (Point of Subjective Equality or PSE; the point at which 50% of responses are long/large).

Prior studies have revealed that both children and adults exhibit patterns of temporal overestimation (i.e., lower PSEs) in the presence of emotional stimuli (Droit-Volet, 2003; Droit-Volet & Meck, 2007), yet identical emotional content leads to underestimation (i.e., higher PSEs) of numerical values (Baker, Rodzon, & Jordan, 2013; Young & Cordes, 2013). These distinct patterns of temporal and numerical processing in the presence of emotion present a challenge to a common magnitude theory while also posing new questions about the specific mechanisms (i.e., attention, arousal) underlying the processing of different quantities. The current study seeks to explore these mechanisms, specifically arousal, on numerical processing in the context of emotional stimuli.

Temporal overestimation in the presence of emotion has been linked to increased arousal (e.g., Angrilli, Cherubini, Pavese, Manfredini, 1997; Droit-Volet & Meck, 2007; Droit-Volet & Wearden, 2001; Gil & Droit-Volet, 2012;

Ortega & Lopez, 2008). Evidence for this is derived from the fact that temporal dilation under emotion tracks with arousal ratings of emotional stimuli, with the most arousing emotional stimuli resulting in the greatest degree of overestimation (Young & Cordes, 2013). Moreover, increased arousal in neutral tasks has been linked to temporal overestimation. For example, the rapid presentation of a stream of stimuli, thought to elicit increased arousal, has been found to result in the overestimation of the presentation of a simultaneous target during timing tasks (e.g., Ortega & Lopez, 2008). Relatedly, filled intervals (i.e., the consistent presentation of a stimulus throughout the duration to be timed) are estimated to last longer than empty intervals (i.e., intervals demarcated by two distinct stimuli), likely due to increased arousal (see Wearden, Norton, Martin, & Montford-Bebb, 2007). Thus, because increased arousal has been linked to temporal dilation and because temporal dilation under emotional circumstances is greatest in response to the most emotionally arousing stimuli, it is posited that arousal is the source of the temporal overestimation observed under emotional circumstances.

On the other hand, arousal is not thought to be the source of the observed numerical underestimation. Instead, because numerical underestimation is found in the context of any emotional stimulus, Young & Cordes (2013) proposed that heightened attentional focusing drives numerical underestimation in the context of emotion. According to this view, the social salience of emotional content serves to heighten attention. Whether this heightened attention to the social stimulus results in numerical underestimation via simultaneous heightened attention to numerical stimuli (and thus, improved numerical processing), or instead, via distracted attention away from the numerical stimulus (and thus impaired numerical processing), has yet to be determined.

Emotional content results in some degree of arousal during temporal and numerical processing; however, it is unclear why the same emotional stimuli may lead to temporal *over*estimation but numerical *under*estimation. One possibility is that numerical processing has a higher threshold than temporal processing in order for arousal to impact estimates, such that a higher level of arousal is necessary to influence numerical estimates. If so, an overall heightened level of arousal, as created by a stress induction task (e.g., Kirschbaum, Pirke, & Hellhammer, 1993), may elicit a pattern of numerical *over*estimation mirroring that of temporal tasks. Relatedly, arousal levels may be slower to rise in response to arousing stimuli, such that it takes time for emotional stimuli to result in threshold levels of arousal. Given that temporal processing is sequential (occurs over a period of time), whereas numerical processing of arrays (as in previous studies) is simultaneous (requires the simultaneous apprehension of several items within a brief presentation period), arousing stimuli may only appear to impact temporal processing because temporal stimuli require more time to process, giving time for arousal levels to rise. If so, then heightening arousal levels via stress induction prior to the numerical task, thus providing time for arousal levels to rise prior to the start of the numerical task may allow for a true assessment of the impact of arousal on numerical processing.

In the current study, we investigated the effects of induced arousal on a numerical task in the presence and absence of emotional stimuli. Arousal was manipulated prior to the numerical task, therefore eliminating concerns regarding the speed of rising arousal levels. Moreover, to our knowledge, no work has investigated the impact of induced arousal on basic numerical processing, making this investigation worthwhile in its own right. While a plethora of evidence suggests that stress in the form of math anxiety can be detrimental for performance on symbolic math tasks (e.g., Meece, Wigfield, Eccles, 1990), it is unclear what role arousal plays in our most primitive sense of number. Lastly, while studies have investigated the impact of emotion on numerical processing, no work has explored factors contributing to individual differences in these emotional biases. That is, are emotions more likely to impact individuals who already have a less precise representation of number? Or, alternatively, is it that all adults, regardless of numerical precision, are similarly vulnerable to the impact of emotional content?

Methods

Participants

Eighty-five undergraduate students (range: 18-25, M_{age} = 19.17, males = 13) participated in this study for course credit. Seven students completed the study, but were excluded from analyses for not following the instructions (n=3), below chance performance on the standard values of the bisection task (n=2), producing PSEs that were more than 3 standard deviations below the group average (n=1), or computer error (n=1), leaving a final sample of seventy-eight. Participants were randomly assigned to two conditions with a final distribution of Stress Induction (N=40, M_{age}=19.02, males = 7) and Control (N=38, M_{age}= 19.00, males = 5).

Stimuli

Stress task A modified version of the Trier Social Stress Test (TSST) was used (Kirschbaum et al., 1993).

Bisection task A bisection task (similar to the task used by Droit-Volet et al., 2004; Young & Cordes, 2013) was implemented. Numerical stimuli were composed of arrays of dots. The standard small value had a magnitude of 4; the standard large value had a magnitude of 16. Intermediate values corresponded to the magnitudes 5, 6, 8, 10, and 13. The numerical arrays consisted of black dots displayed on a white background. Surface area of each individual item was identical in half of the trials (*M* = 1147.14). In the other half of trials, cumulative surface area was held constant across trials regardless of set size (*M* = 1385.86). The bisection task was computerized; stimulus presentation was controlled and responses were recorded by a REALBasic program.

Emotional Faces The face stimuli were identical to those used by Young & Cordes (2013). The face stimuli (happy, neutral, and angry) were selected from the NimStim set (Tottenham et al., 2009). The set of faces were standardized on intensity, attractiveness, arousal, and valence so that each image was a clear representation of a specific emotion.

Procedure

Participants were randomly assigned to the Stress or Control condition. Those in the Stress condition sat next to an experimenter who asked them to count backwards by 13 beginning with the number 10,099 (e.g., 10,099, 10,086, 10,073…). Participants were told their performance would be assessed and if a mistake was made, the experimenter would stop them and make them start over from 10,099. Answers were given orally so that the experimenter could keep track of performance. In the Control condition, the experimenter gave similar instructions, except participants were allowed to use a pencil and paper to write their answers down, were told that their performance would not be assessed, and the experimenter left the room while the participant completed the task. After five minutes, participants were stopped and began the bisection task.

Next, participants were seated in front of the computer and familiarized with arrays of dots that were labeled as the "Small" (4) and "Large" (16) standards. Participants were given 12 practice trials in which, they were presented with dot arrays representing either standard value and were asked to indicate whether it was small or large. Dot arrays were presented for 500 ms. Adults selected their response by pressing either [a] for smaller or ['] for larger on the keyboard. Feedback was provided for practice trials only. Following practice, adults participated in 42 baseline test trials that were identical to practice except dot arrays of representing the five intermediate sizes were intermixed among standard trials (6 trials per 7 set sizes). Participants were asked to indicate whether each array was "more similar to the small or large standard". Following baseline, participants had emotion test trials that were identical to the baseline trials expect that a face appeared for 750 ms prior to each dot array presentation. Faces depicted either happy, angry, or neutral emotions. During the emotion test trials, all set sizes (2 standard values and 5 intermediate values) were presented 18 times each, 6 times per emotion, for a total of 126 trials. Emotion trials were presented in a random order, with trials involving the three emotions intermixed throughout. Adults received feedback on the practice trials, but did not receive feedback on any of the test trials.

Data Analyses

Following past work (Droit-Volet et al., 2004; Young & Cordes, 2013), each participant's PSE was calculated for the baseline trials and each of the three emotions separately as a measure of accuracy. PSEs were computed by determining the equation of the line relating the proportion of trials the participant indicated the array was more similar to the large standard and the size of the dot array, and using that to compute the set size corresponding to a 0.5 proportion of large responses. Moreover, each participant's difference limen (DL; the value half way between the set sizes corresponding to a 75% probability of a large response and a 25% probability of a large response) was also calculated as a measure of precision in responding, with higher DLs corresponding to lower precision in responding.

Results

Baseline Performance (no faces)

First, we analyzed performance on the baseline trials to determine whether increased arousal (due to the stress induction) altered numerical processing in the absence of emotional stimuli. Analyses revealed no differences in the PSE or DL of participants across conditions during the baseline trials (PSE: $t(76) = .610$ $p = .544$; DL: $t(76) = -.283$ $p = .778$) revealing that heightened arousal did not result in biases or altered precision in numerical judgments.

Emotion Test Trials - PSE

We conducted a 2 (Condition: Stress, No Stress) x 3 (Emotion: Neutral, Happy, Angry) repeated measures ANOVA on PSEs obtained from the emotion test trials. Analyses revealed a main effect of emotion, $F(2, 152) = 9.767$, $p < .001$ and a significant condition x emotion interaction on PSE, $F(2, 152) = 3.830$, $p < .024$. There was no main effect of condition, $F(1, 76) = .120$, $p = .730$. In order to investigate the interaction further, we looked at the differences across emotions in each of the two conditions separately.

Control Condition In line with prior findings (Young & Cordes, 2013), there was a main effect of emotion on PSE in the Control condition, $F(2, 74) = 9.039$, $p < .001$. The PSEs corresponding to trials involving happy faces ($M = 8.433$, $SD = 0.94$) and angry faces ($M = 8.332$, $SD = 0.90$) were both significantly higher relative to neutral faces ($M = 8.052$, $SD = 1.10$, p's $< .01$), consistent with a pattern of underestimation under emotional circumstances. Performance did not differ between angry and happy faces ($p > .23$). This finding replicates prior research revealing numerical underestimation in the context of both angry and happy faces relative to neutral faces (Young & Cordes, 2013).

Stress Condition There was also a main effect of emotion on numerical judgments in the Stress condition, $F(2, 78) = 4.542$, $p < .014$, however a different pattern emerged. Angry faces ($M = 8.36$, $SD = 0.84$) were significantly underestimated relative to happy faces ($M = 8.155$, $SD = 0.81$) and neutral faces ($M = 8.09$, $SD = .906$; $p's < .03$). There was no significant difference between happy and neutral faces ($p > .5$).

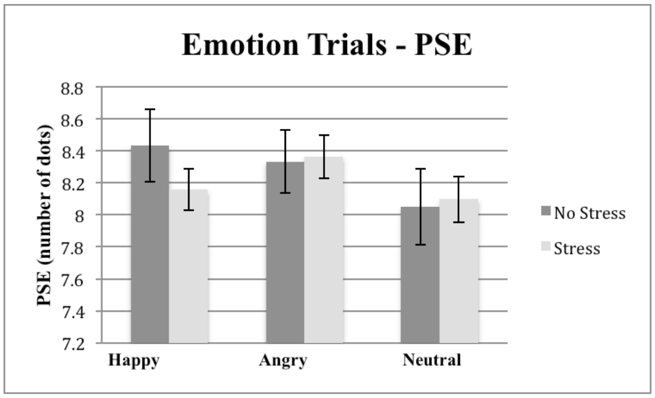

Figure 1. PSE as a function of emotion across conditions.

Emotion Test Trials – DL

We ran a 2 (Condition: Stress, Control) x 3 (Emotion: Neutral, Happy, Angry) repeated measures ANOVA on the DLs obtained on emotion test trials. Analyses revealed a main effect of emotion on DL, $F(2, 152) = 7.765$, $p < .001$, but no main effect of condition $F(1, 76) = .117$, $p = .733$, nor a condition x emotion interaction, $F(2, 152) = 1.722$, $p = .182$. Overall, results revealed increased precision in numerical judgments following presentation of emotional faces ($M_{Happy} = 2.679$, $SD_{Happy} = .265$; $M_{Angry} = 2.647$, $SD_{Angry} = .238$) relative to neutral faces ($M = 2.736$, $SD = .336$, p's $< .04$). There was no significant difference between angry and happy faces ($p = .103$).

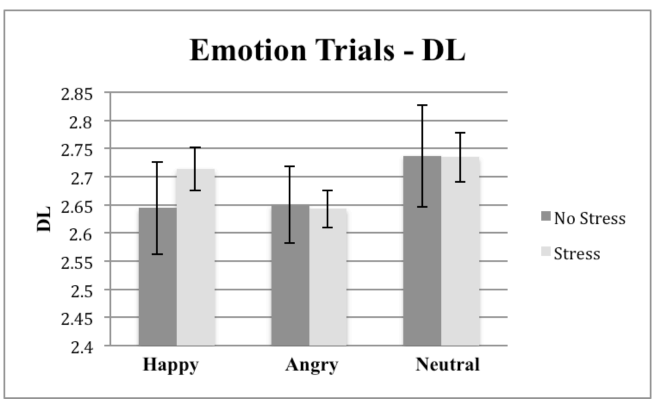

Figure 2. DL as a function of emotion for both conditions.

Individual Differences

Lastly, we explored whether individual differences in precision in the underlying representation of number relates to the magnitude of numerical bias observed in the presence of emotional stimuli. Is it the case that individuals with lower numerical acuity (as assessed via performance on baseline trials) may be more vulnerable to numerical biases in the presence of emotional stimuli? In order to test this question, we computed a measure of numerical bias by subtracting each participant's average PSE across the emotion trials (average of PSE_{Happy} and PSE_{Angry}) and subtracting this from their $PSE_{Neutral}$. Importantly, these analyses only pertain to participants in the Control condition. This measure represents the degree to which participants' underestimated number following emotional stimuli compared to neutral stimuli. Each participant's Baseline DL was used as a measure of numerical acuity in the underlying representation. If those individuals with less precise numerical representations were more prone to numerical biases, we would expect a positive correlation between the participant's Baseline DL and this numerical bias measure. A marginal correlation between $DL_{Baseline}$ and this measure of numerical bias ($r = .298$, $p = .074$) was obtained, suggesting that the magnitude of numerical bias observed under emotional circumstances may be partially predicted by the precision in an individual's underlying representation in number.

Discussion

Prominent theories posit a common magnitude system for representing temporal and numerical magnitudes (Cantlon et al., 2009; Meck & Church, 1983; Walsh, 2003). If this is the case, then temporal and numerical processing should reveal similar biases under identical circumstances. Yet, work reveals that identical emotional stimuli impact temporal and numerical processing in distinct fashions (Young & Cordes, 2013). Given that the pattern of temporal overestimation tracks with the level of arousal of the emotional stimuli (i.e., angry, but not happy, emotional stimuli result in overestimation of durations), it has been posited that increased arousal underlies the observed temporal biases (Droit-Volet & Meck, 2007; Gil & Droit-Volet, 2012). Conversely, given that numerical underestimation is observed in the presence of both arousing (angry) and less arousing (happy) emotional stimuli, it has been hypothesized that changes in attention modulate the numerical underestimation observed (Young & Cordes, 2013). These distinct patterns, however, could potentially be explained by different arousal thresholds for numerical and temporal processing and/or by a delayed arousal response.

In the present study, we examined how induced stress (i.e., increased arousal) impacted subsequent numerical judgments, both in the presence and absence of emotional stimuli. By heightening arousal prior to participation in the numerical task, we were able to assure altered arousal levels in participants at the time of numerical judgments. Moreover, by presenting arousing emotional stimuli (angry faces) following a stress induction task, we maximized arousal in participants prior to engagement in the numerical task to increase the likelihood that any arousal threshold was met. As such, results of this study can speak to how increased arousal impacts numerical processing, providing a true test of the common magnitude system. That is, by maximizing arousal in participants prior to participation in a numerical task, we are able to explore whether numerical biases mimic those found in temporal processing. Yet results did not reveal this to be the case.

Results of our baseline trials revealed that heightened arousal (as induced in our stress task) did not disrupt basic numerical processing as we had predicted. In fact, results revealed no significant differences between the Stress and Control conditions for baseline responding, suggesting that induced stress did not alter numerical processing in the absence of emotional stimuli.

Importantly, responding during emotional trials in the Control condition mimicked that of previous studies, again revealing a pattern of underestimation following the presentation of either happy or angry emotional stimuli relative to neutral stimuli. Thus, again, in the absence of heightened arousal, participants underestimate number in the presence of emotional stimuli.

However, a different pattern of underestimation following emotional stimuli emerged among those in the Stress condition. Those in the Stress condition only underestimated angry faces compared to neutral faces, with responding on happy trials mirroring that found on neutral trials. These findings are significant for two reasons. First, despite no differences in numerical processing in baseline, findings of a distinct pattern of results across condition make it clear that our stress induction task was effective. Results revealed that induced stress led to a differential pattern of numerical judgments in participants across conditions. Thus, a failure to find baseline differences suggests that induced arousal does not have a strong impact on numerical processing in the absence of emotional stimuli. Second, despite heightened arousal, participants in the Stress condition did not respond with a pattern of overestimation of numerical stimuli, as might have been predicted by a common magnitude system. That is, induced arousal prior to presentation of the numerical task failed to result in numerical biases mimicking those found in temporal tasks, providing strong support against a common magnitude system. Instead, results in the Stress condition revealed a similar (though not identical) pattern of underestimation in the presence of emotional stimuli. However, importantly, in contrast to the Control condition, underestimation was only observed following the presentation of angry faces, not happy ones.

What can explain this novel pattern of results? Findings are likely accounted for by a difference in how participants in the Stress condition may have perceived the emotions presented. It is possible that induced stress may have resulted in an overall negative interpretation of the face stimuli, causing participants to perceive angry faces as angrier, yet happy faces were perceived as more neutral, thus resulting in underestimation of angry trials, yet similar performance on happy and neutral trials. This finding is in line with work demonstrating that highly anxious individuals may be more likely to attend to threatening content, which may be at the expense of attending to the happy stimuli (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, van IJzendoorn, 2007). Other work has shown that stress increases one's sensitivity to threats, but *reduces* specificity (van Marle, Hermans, Qin, & Fernandez, 2009), thus leading to a failure to differentiate happy from neutral faces. Thus, participants in the Stress condition likely perceived the happy faces as being more similar to the neutral faces, thus minimizing any differences observed between the happy and neutral face trials.

Results are also the first to suggest that numerical underestimation biases in the presence of emotional stimuli may reflect heightened numerical acuity. While it has been hypothesized that the numerical biases observed under emotional circumstances may be the results of impaired numerical processing (Rodzon, Baker, & Jordan, 2011; Young & Cordes, 2013), our findings provide evidence for enhanced numerical performance following emotions. Our data reveal significantly smaller DL (i.e., greater precision) after emotional content is presented. This finding is consistent with the literature investigating children's and adult's numerical judgments in the presence of emotional faces (Lewis, Zax, & Cordes, submitted). Prior work has shown that children's numerical judgments become more precise following the presentation of emotional faces (relative to following neutral faces). Prior work has also shown positive impacts of emotions on subsequent tasks. For example, Phelps, Ling, & Carrasco (2006) reported increased contrast sensitivity, and thus enhanced performance on neutral tasks following emotions. Vuilleumier (2005) found similar effects of enhanced performance when emotions preceded and were not concurrent with the task demands. This study joins others suggesting that emotional or threatening content may benefit numerical processing if the emotional content is not inherent in the stimuli to be enumerated (Hamamouche et al., submitted). The adults in our study were also more precise in their numerical judgments following the presentation of emotional faces likely due to heightened attention brought on by the socially salient stimuli, providing further support for the attention model associated with numerical processing.

While many studies have investigated the impact of emotional faces on temporal and numerical processing (e.g., Baker et al., 2013; Droit-Volet, 2003; Droit-Volet & Meck, 2007; Young & Cordes, 2013), it has been unclear if emotions impact an individual's numerical judgments to the same degree, regardless of one's initial numerical representations. We investigated whether those with less precise numerical representations would be more likely to adjust their numerical judgments in the presence of emotion than those with more precise representations. Our data hinted at a possible relationship between participant's baseline precision on the numerical task and the degree to which they underestimated during the emotion trials, indicating that the underestimation effect seen in the presence of emotion may be related to individual differences in numerical representation. However, this correlation was only marginally significant and thus we cannot make strong claims about the potential of this relationship. Future work should explore whether the magnitude of these numerical biases may also be predicted by individual sensitivities to emotional stimuli and/or social stimuli, more generally.

This study is the first of its kind to investigate the interaction of stress and emotion on numerical processing. Although arousal did not impact numerical processing as predicted, this study joins a growing body of literature providing evidence questioning the plausibility of a common magnitude system (e.g., Agrillo, Ranpura, & Butterworth, 2011; Baker, Rodzon, & Jordan, 2013; Young & Cordes, 2013). Future work should investigate the interaction between stress and emotion on temporal processing, in order to further understand basic quantitative processing in real-world situations.

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