Acta Psychologica 177 (2017) 1–9

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Quantifying a threat: Evidence of a numeric processing bias

Karina A. Hamamouche[a,*,1], Laura Niemi[b,1], Sara Cordes[a]

[a] Boston College, Department of Psychology, 140 Commonwealth Ave, 300 McGuinn Hall, Chestnut Hill, MA 02467, USA
[b] Harvard University, Department of Psychology, 33 Kirkland Street, William James Hall, Cambridge, MA 02138, USA

ARTICLE INFO

Keywords:
Number processing
Numerical cognition
Threat estimation
Numerical discrimination

ABSTRACT

Humans prioritize the processing of threats over neutral stimuli; thus, not surprisingly, the presence of threats has been shown to alter performance on both perceptual and cognitive tasks. Yet whether the quantification process is disrupted in the presence of threat is unknown. In three experiments, we examined numerical estimation and discrimination abilities in adults in the context of threatening (spiders) and non-threatening (e.g., flowers) stimuli. Results of the numerical estimation task (Experiment 1) showed that participants underestimated the number of threatening relative to neutral stimuli. Additionally, numerical discrimination data reveal that participants' abilities to discriminate between the number of entities in two arrays were worsened when the arrays consisted of threatening entities versus neutral entities (Experiment 2). However, discrimination abilities were *enhanced* when threatening content was presented immediately before neutral dot arrays (Experiment 3). Together, these studies suggest that threats impact our processing of visual numerosity via changes in attention to numerical stimuli, and that the nature of the threat (intrinsic or extrinsic to the stimulus) is vital in determining the direction of this impact. Intrinsic threat content in stimuli impedes its own quantification; yet threat that is extrinsic to the sets to be enumerated enhances numerical processing for subsequently presented neutral stimuli.

A lightning-fast mosquito slap or a quick jump out of the way of a barking dog's jaws represent the outcome of universal and advantageous information-processing biases that enable humans to quickly attend to threats in the environment (LoBue, Rakison, & DeLoache, 2010; Öhman & Mineka, 2001). Threat-processing biases have been observed at multiple levels of processing (from initial orientation to later elaboration or avoidance), in numerous tasks manipulating attentional focus, and with stimuli ranging in threat-relevance (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, M. H., 2007; Ouimet, Gawronski, & Dozois, 2009; Vuilleumier, 2005). Outside of the psychology laboratory, however, threats may come in swarms, mobs, armies, and other groups that must be evaluated and compared using quantitative processing. Whether and how threat content may affect our ability to extract numerosity has not been studied.

Processing numerosity is basic to moment-to-moment experiencing of the world. The ability to track quantities and perform rudimentary numerical operations has been observed across species (e.g., Cantlon & Brannon, 2007; Cordes, King, & Gallistel, 2007) and as early as infancy (e.g., McCrink & Wynn, 2009; Xu & Spelke, 2000). Numerical tracking has been proposed to facilitate the most fundamental survival needs, from procuring enough food to assessing the risk of a competing group (e.g., review: Gallistel, 1990). In particular, the representation of numerical magnitude is crucial for the quick, rough quantifications necessary for action planning across species, and appears to be foundational to the development of more advanced mathematical skills (e.g., Brannon & Merritt, 2011; Halberda, Mazzocco, & Feigenson, 2008; Hyde, Khanum, & Spelke, 2014; Libertus, Feigenson, & Halberda, 2011; Park & Brannon, 2013). Prior work has revealed some signatures of non-symbolic numerical tracking. For example, our ability to approximate visual number is less precise relative to the symbolic numeric processing system (i.e., the use of Arabic numerals or verbalized count numbers representing exact numbers; Feigenson, Dehaene, & Spekle, 2004); discrimination between sets of entities is enhanced as the numerical ratio between the sets increases (i.e., adherence to Weber's Law; Jordan & Brannon, 2006); and people tend to underestimate when converting non-symbolic quantities to symbolic quantities (Crollen, Castronovo, & Seron, 2011). Yet whether and how humans' everyday numerical magnitude judgments interact with co-occurring affective processes, as in the case of quantifying threats, has been unexplored.

A large extant literature, corroborated by everyday experience, describes the attention-grabbing nature of threatening stimuli. Both

* Corresponding author.
E-mail addresses: hamamouc@bc.edu (K.A. Hamamouche), lauraniemi@fas.harvard.edu (L. Niemi), cordess@bc.edu (S. Cordes).
[1] K. Hamamouche and L. Niemi contributed equally to this work.

http://dx.doi.org/10.1016/j.actpsy.2017.04.001
Received 10 June 2015; Received in revised form 15 November 2016; Accepted 6 April 2017

adults and children are quicker and more accurate in detecting threatening stimuli (of both a social and physical nature) amongst neutral stimuli (e.g., LoBue, 2010; Öhman & Mineka, 2001). However, the strong attentional draw of threats leads to difficulties disengaging from threatening stimuli, such that the detection and/or processing of neutral stimuli may be impaired in the context of threat (Koster, Crombez, Verschuere, & De Houwer, 2004; Williams, Mathews, & MacLeod, 1996). For example, task performance may be hindered in the presence of threatening or emotional content when the task requires shifting attention *away* from the threat and deploying higher cognitive processes (e.g., Cohen, Henik, & Mor, 2011). In contrast, when threats are presented just prior to, and not concurrent with, task-relevant stimuli, these threatening primes have been shown to increase visual contrast sensitivity for subsequently presented neutral stimuli. Therefore, threatening primes facilitate, rather than compete with, the visual processing required for the subsequent contrast perception task (Phelps, Ling, & Carrasco, 2006; Vuilleumier, 2005). Together, results indicate task performance may be impaired when the task requires the participant to *overcome* the attentional capture of threats, yet, task performance may be enhanced when a task *leverages* the attentional capture of threats.

Prior work has examined the effects of emotional stimuli on approximate numerical processing using numerical bisection tasks in which participants judge whether the number of items in an array of dots is "more similar" to a learned small or large standard (Baker, Rodzon, & Jordan, 2013; Lewis, Zax, & Cordes, in press; Young & Cordes, 2013). Baker et al. (2013), for example, asked participants to decide if a briefly presented array of angry, happy, or neutral faces were more similar to a small or large standard value. Results revealed that the number of emotional, relative to neutral, face stimuli were underestimated (Baker et al., 2013), suggesting that entities with intrinsic threatening content may be underestimated relative to neutral stimuli; that is, *if* naturalistic threats function analogously to emotional face stimuli. Yet, because the numerical estimates involved in bisection tasks are rather ambiguous (instructions do not specify whether "similarity" should be judged via numerical differences, ratios, or some other criterion), it is not clear whether underestimation observed in the bisection tasks used in these prior studies necessarily constitutes *impairment* (see Young & Cordes, 2013). Thus, in Experiment 1, we first explore whether underestimation biases observed in the presence of emotional stimuli are also observed in the context of biological threats (i.e., spiders). Importantly, we use a straightforward estimation task, in which participants provide an explicit symbolic estimate of the number of items presented, to begin to address the open question of whether observed underestimation biases reflect impaired, or enhanced, numerical processing.

While a straightforward estimation task allows for a direct assessment of the valence of this numerical bias, it also introduces the potential for individual motivations to play a role in responding. Although underestimation biases observed during an estimation task are likely driven by differential attention allocation in the context of threat or not, it is also possible that these biases are driven by an attempt to lessen the extent of the threat. That is, individuals may generate lower estimates of the number of spiders they see because they actually perceive fewer spiders, but also possibly because of wishful thinking, such that estimating fewer spiders may also psychologically lessen the degree of threat that the spiders pose (e.g., Koudenburg, Postmes, & Gordijn, 2011; Niemi, Woodbridge, Young, & Cordes, in preparation). Thus, it is critical to assess the impact of threatening content on numerical processing using a task in which responding may not conceivably be driven by intrinsic motivations to avoid the threat. In Experiments 2 and 3, we report a novel investigation of the impact of threatening content on numerical discrimination, in which participants are asked to judge the relative numerosity of two arrays of threatening, or two arrays of neutral, stimuli. Importantly, because responding on this task requires the selection of one of two arrays, the threatening content should not motivate participants to select one array over the other. Thus, numerical discrimination tasks are the ideal test for investigating perceptual differences in numerical processing that may arise in the presence of threatening content.

Previous work has shown that accuracy in numerical discrimination tasks is impaired in individuals with high math anxiety, indicating vulnerability of basic numerical processing to anxiety-producing conditions (Maloney, Ansari, & Fugelsang, 2011; Maloney, Risko, Ansari, & Fugelsang, 2010). However, no work has explored whether effects of anxiety on numerical processing are driven by an elevated anxiety level brought on by the thought of completing a numerical task (i.e., anxiety brought on before the task even begins – prior to presentation of the numerical stimuli) or instead by the intrinsic threatening nature of the stimuli (i.e., anxiety evoked by the numerical stimuli itself). In light of work indicating impaired visual attention when stimuli have intrinsic threatening content (e.g. Koster et al., 2004; Williams et al., 1996), yet enhanced visual attention immediately after the presentation of threatening content (e.g., Phelps et al., 2006; Vuilleumier, 2005), it is likely that the timing of the presentation of threatening content may be an important factor in determining the impact of the threat. Moreover, substantial research has linked numerical discrimination abilities to formal mathematical achievement (Halberda et al., 2008; Libertus et al., 2011; Mazzocco, Feigenson, & Halberda, 2011), thus making it critical to understand if threatening content may be leveraged to *enhance* performance on these tasks. Thus, the current study investigates how the timing of presentation of threatening content may alter numerical discrimination abilities. In particular, we explore both numerical discrimination of entities with intrinsic threat content (Experiment 2), and numerical discrimination of sets of neutral entities presented *after* exposure to threat content (Experiment 3).

1. Overview of the current study

In Experiment 1, we test the effects of intrinsic threat content on numerical estimation in a simple task that pits threatening (spiders) against neutral (perceptually matched flowers and other natural objects) stimuli and allows for calculation of the precise deviation of participant's estimates from actual amounts shown. In Experiment 2, we test the effects of intrinsic threat content on numerical discrimination in a task that involves comparing two arrays of threatening stimuli or two arrays of neutral stimuli. Finally, in Experiment 3, we again test the effects of the presence of threatening and neutral stimuli on numerical discrimination. Importantly, in Experiment 3, the arrays of dots to be discriminated were presented immediately following the presentation of a threatening or neutral stimulus granting us the ability to determine how threat content, which is not intrinsic to the items being discriminated, impacts numerical discrimination.

2. Experiment 1

In Experiment 1, participants completed a numerical estimation task in which they estimated the number of threatening (e.g., spiders) or neutral (e.g., flowers) stimuli.

2.1. Method

2.1.1. Participants

Participants were 27 adults (6 males, 21 females: $M_{\text{age}} = 20.69$, range 18–37) who received course credit or a small gift for participation.

2.1.2. Stimuli

Stimuli consisted of arrays of either neutral items (4 kinds: leaves, twigs, and two flower-shapes) or threatening items (4 kinds of spiders).

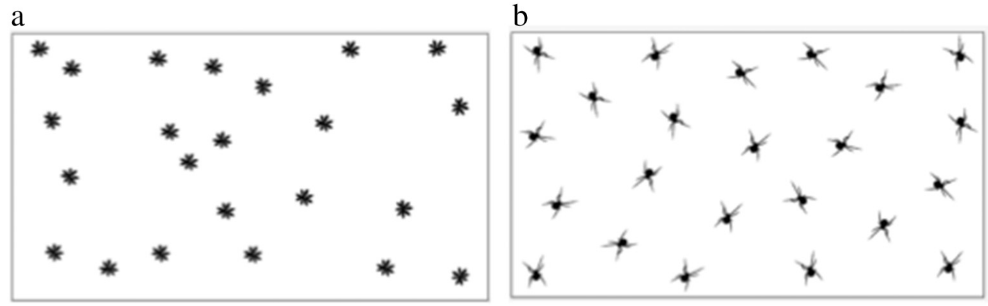

Fig. 1. Examples of stimuli in numerical estimation task. (a) 23 neutral objects. Other neutral arrays included leaves, twigs, and flowers that similarly had multiple curves and/or vertices along the outer contour; (b) 23 threat objects. Other threatening arrays contained spiders with slightly different shapes.

All displays were homogeneous in item type (Fig. 1). The number of items in each array was chosen randomly from one of seven logarithmically-spaced values: 11, 13, 16, 19, 23, 28, 34. All stimuli were black on a white background, and the area of each item was equated across all stimuli. Because the spider shapes had multiple legs, care was taken to ensure neutral stimuli also had multiple parts within each individual item, for example, many petals on the flowers, many leaves on the twig, and many points on the leaf. Items in each array were arranged in a pseudorandom, naturalistic manner, with the limitation that the minimum inter-item distance (the distance between each item and the item closest to it) be at least 13 mm (modeled after He, Zhang, Zhou, & Chen, 2009). There was no significant difference in average inter-item distance (range: 28.00 mm–59.85 mm; M_{Threat} = 45.21 mm vs. $M_{Neutral}$ = 46.73 mm, $p > 0.17$), average cumulative surface area (range: 2800.91–7197.29 mm^2, M_{Threat} = 4050.28 mm^2 vs. $M_{Neutral}$ = 4238.46 mm^2; $p > 0.32$), average convex hull (range: 79,067.79–222,323.48mm^2; M_{Threat} = 117,322.92mm^2, $M_{Neutral}$ = 114,939.28mm^2, $p > 0.60$), or density (area/convex hull as in Gebuis & Reynvoet, 2012; M_{Threat} = 0.035 vs. $M_{Neutral}$ = 0.037, $p > 0.23$), controlling for set size, of the neutral and threatening displays.

2.1.3. Procedure

Each participant completed the numeric estimation task individually in a sound-attenuated testing room, with stimuli presentation and response (and response time) recording controlled by a RealBasic program on a Mac mini computer with a 22″ monitor. During the task, participants were given four practice trials in randomized order. The sequence of each practice trial was as follows: (1) the word "Ready" appeared in the center of the screen for 1000 ms; (2) one of four practice stimulus arrays (randomly-arranged ovals [10 or 40], circles [13], or eight-pointed starbursts [52]) was presented for 600 ms; (3) a visual mask consisting of overlapping black and white diagonal lines appeared for 500 ms; and (4) the prompt "How many were there?" appeared and remained onscreen until participants entered their estimate of the number of items using the computer keyboard and then clicked on the "Next" button.

Test trials were identical to practice trials except stimulus arrays lasted 550 ms and consisted of either neutral or threatening items. An equal number of neutral and threatening arrays were randomly intermixed throughout test. Each of the 8 different stimuli (4 neutral, 4 threatening) was presented 14 times each (twice for each numerosity) for a total of 112 trials.

2.1.4. Data analysis

Responses more than 3 standard deviations above or below each participant's mean response time or response for that set size were excluded from analyses. To avoid endpoint anchoring effects, only estimates for the five intermediate set sizes (13, 16, 19, 23, 28) were analyzed.[2]

2.2. Results and discussion

The results of a repeated-measures ANOVA examining effects of Threatening content (threat and neutral) and Set size (13, 16, 19, 23, 28) on mean estimates indicated that participants increased their estimates as the number of items increased (main effect of set size: $F(4, 104) = 265.894$, $p < 0.000$, $\eta_p^2 = 0.911$), suggesting that they were engaged in the task and attending to number. Participants made fairly accurate estimates (M = 19.59) relative to the actual mean number of stimuli (M = 19.8; $t(24) = -0.368$, $p = 0.716$). Importantly, as hypothesized, there was a main effect of condition in which participants underestimated the number of threatening stimuli relative to the number of neutral stimuli ($M_{Neutral}$ = 19.881, $SD_{Neutral}$ = 3.04; M_{Threat} = 19.307, SD_{Threat} = 2.87; $F(1,26) = 7.834$, $p = 0.01$, $\eta_p^2 = 0.232$; Fig. 2).[3] There was no interaction between Condition and Set Size ($p > 0.05$) indicating a similar condition effect across array sizes, suggesting that adults underestimated the number of threatening stimuli compared to non-threatening stimuli across all set sizes.

This experiment directly tested quantification of arrays of threatening and neutral stimuli, providing evidence of a general propensity towards underestimation of the number of threatening stimuli by adults. These findings align well with those of experiments involving numerical estimation in the context of emotional stimuli (Baker et al., 2013; Lewis et al., in press; Young & Cordes, 2013), revealing that natural biological threats, such as spiders, may bias numerical estimates in a similar manner to that of emotional stimuli.

What can account for the underestimation observed in the context of threat? There are two potential explanations of this pattern of results. On the one hand, threatening stimuli may have captured attention, causing participants to fixate for longer periods on each individual stimulus. If so, then they may have been unable to visually scan the entire array during the brief (550 ms) presentation, resulting in a failure to track all items in the array leading to lower estimates of the number of items presented. Prior work revealing adults are slower to direct their attention away from threatening stimuli (Koster et al., 2004) provide support for this bottom-up account of the numerical biases observed. Alternatively, participants may have reported fewer threatening stimuli in an attempt to down-regulate negative affect resulting from the

[2] A similar pattern of results emerged when endpoints are included in the analysis. Threatening stimuli (M=19.88, SD=2.84) were underestimated relative to neutral stimuli (M=20.32, SD=3.20), $p < 0.05$.

[3] Data from a prior experiment involving a similar estimation task also revealed a significant underestimation of threatening compared to neutral stimuli ($p < 0.05$; see Appendix A). The stimuli used in this prior experiment, however, inadvertently confounded continuous extent variables (i.e., density, inter-item distance, or cumulative area) with set size.

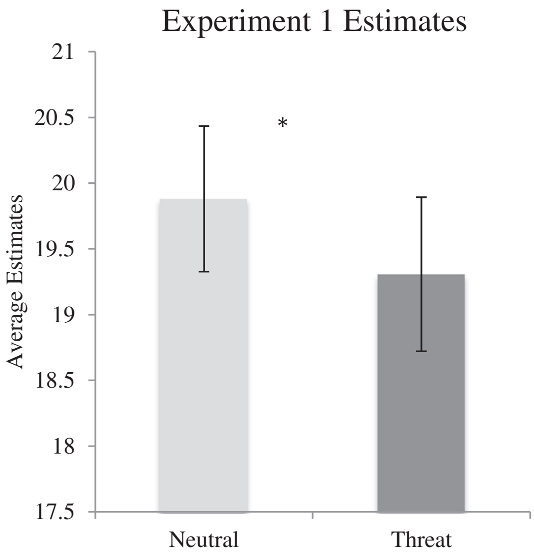

Fig. 2. Disruption of numerical magnitude judgments by threat. The graph illustrates underestimation of threatening stimuli relative to neutral stimuli in Experiment 1. Error bars indicate SEM. * $p < 0.05$.

threatening stimuli, indicative of motivated numerical processing. Work in the realm of political psychology has revealed adults systematically underestimate the number of individuals voting for their *non-preferred* candidate when presented with a hypothetical scenario in which the non-preferred candidate is ahead in the polls (thus posing a threat; Niemi et al., in preparation; see also Koudenburg et al., 2011). If the threat posed by the spiders in our task made participants uncomfortable, then the numerical underestimation observed could have been an attempt to downplay the magnitude of the threat and the discomfort that accompanied the threat, a result of top-down, motivated processing.

Experiment 2 serves to examine the effect of intrinsic threat content on numerical discrimination and also shed light on the plausibility that "bottom-up" effects of attention may impact numerical processing. We presented adults with a numerical discrimination task involving threatening and non-threatening stimuli. In this task, participants briefly viewed a pair of arrays containing different amounts of spiders or neutral stimuli and were asked to indicate which side had a greater number of items. Within each trial, participants compared quantities of only threatening or neutral stimuli, thus, no effect on emotional discomfort would be expected from selecting one side or the other, thereby reducing potential impacts of motivated processing. However, if threatening stimuli serve to capture attention thereby resulting in a failure to enumerate all items in the array, then numerical discrimination of threatening stimuli should be impaired. Finding that participants are impaired in basic numerical discrimination of threatening stimuli would suggest that the impact of threatening information on basic numerical magnitude representation has broader implications for quantification and, possibly mathematical processing and learning generally.

3. Experiment 2

Experiment 1 revealed the impact of threat on numerical estimation; however, the impact of threatening content on discrimination is unknown. In Experiment 2, participants completed a numerical discrimination task in which they compared the relative sizes of sets of threatening and neutral stimuli.

3.1. Method

3.1.1. Participants

Participants were 22 undergraduate students (8 males, 14 females: $M_{age} = 20.9$, range 19 to 25) who received course credit or cash compensation for participation. One participant was excluded due to program error.

3.1.2. Stimuli

All discrimination task arrays were black on a white rectangular background (922 × 1040 pixels; see Fig. 3). All array pairs were presented side-by-side and were homogeneous in item type and size. The number of items in each array varied from 5 to 16, such that the ratio of the smaller set size to the larger set size in each pair of arrays was chosen from one of four ratios: 0.750, 0.833, 0.857, 0.875. The side of the larger array was counterbalanced across trials. When controlling for the surface area, the size of the individual items displayed in both arrays was identical in half of the trials (range: 24.66–38.06 cm^2); and in the other half, cumulative surface area was held constant across the two arrays in each trial (range: 166.74–611.15 cm^2; area controls were modeled after Halberda et al., 2008).

3.1.3. Procedure[4]

Participants initially completed 4 practice trials in which they were familiarized with the procedure. Two arrays of neutral objects (dots, ovals, starbursts) were displayed side-by-side simultaneously for 500 ms. After this brief presentation, a prompt: "Which side had more?" appeared and remained onscreen until participants made a selection (left arrow key for the array on the left-side, right arrow key for the array on the right-side). After the participants made a keypress, the program advanced to the next trial. Test trials were identical to practice trials except the objects were replaced with spiders in the threatening trials, or flowers/leaves in the non-threatening trials. Again, an equal number of neutral and threatening trials were randomly presented throughout test. Each Condition (threat, neutral) × Item Type (4 different types) × Ratio (4) combination was presented 4 times each, for a total of 128 test trials.

3.2. Results and discussion

A repeated-measures ANOVA examining effects of the two conditions (threat and neutral) on accuracy for each of the tested ratios (0.750, 0.833, 0.857, 0.875) first indicated that, as predicted by Weber's Law (e.g., Jordan & Brannon, 2006), accuracy improved as the ratios became easier (e.g., when the numerical distance between the paired arrays was greatest; $F(3, 63) = 16.182$, $p < 0.000$, $\eta_p^2 = 0.435$). Crucially, there was a main effect of condition in which participants' accuracy was lower for threatening stimuli relative to neutral stimuli (Neutral proportion correct: $M = 0.839$, $SD = 0.07$; Threat proportion correct: $M = 0.793$, $SD = 0.063$; $F(1, 21) = 13.401$, $p = 0.001$, $\eta_p^2 = 0.390$). There was no interaction between Condition and Ratio ($p > 0.50$) indicating a similar effect of condition on accuracy across ratios.

Lastly, we explored whether threatening content resulted in differential impacts on performance as a function of how surface area was controlled. Previous research has found adults perform better on trials

[4] An anxiety survey was administered before the numerical tasks for half the participants, and after the tasks for the other half of participants. No effect of the survey order on task performance and no relationship between the survey and task results were observed; therefore, we do not discuss the survey further. All participants also completed a numerical estimation task (identical to Experiment 1) prior to the discrimination task. Results of this estimation task matched those of Experiment 1 (threatening stimuli were underestimated relative to neutral, $p < 0.05$); however, it was discovered that the average inter-item distances were not matched across threatening and neutral arrays. Given that greater overlap (i.e., smaller inter-item distances) has been shown to result in numerical underestimation (He et al., 2009), these data are not reported here.

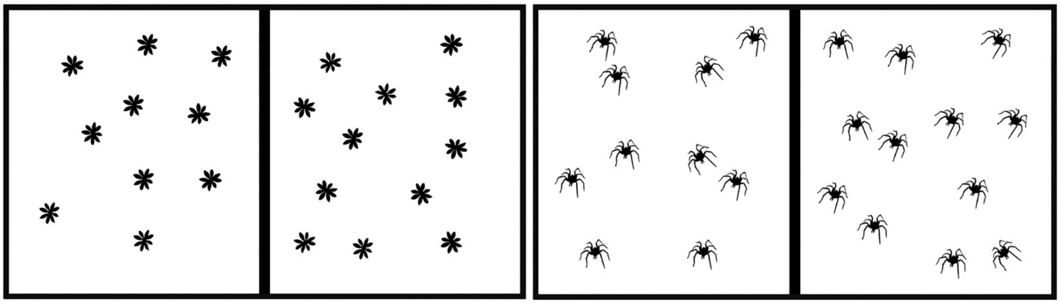

Fig. 3. Examples of stimuli in numerical discrimination task. Left panel represents a pair of arrays as shown in a non-threatening trial; right panel represents a pair of arrays as shown in a threatening trial.

in which cumulative area correlates with number (such that the more numerous array also has the largest cumulative surface area; i.e., congruent trials) than on those trials in which cumulative area of the arrays is held constant (such that the more numerous array contains smaller individual items, i.e., incongruent trials; e.g., DeWind & Brannon, 2012). Moreover, evidence suggests that performance on incongruent trials is more malleable to training. Thus, we ran a Congruency × Threat repeated measures ANOVA to explore the impact of Congruency.[5] Importantly, although main effects of Congruency, $F(1,21) = 13.401, p < 0.001$, and Threat, $F(1, 21) = 57.009, p < 0.001$ were found, there was no interaction between Threat and Congruency ($p > 0.116$), suggesting that threat impacted all trials similarly regardless of the trial type.

In sum, results of Experiment 2 reveal that adults perform worse when discriminating between different sizes of arrays of threatening stimuli compared to neutral stimuli (Fig. 4a). These results are unlikely to be accounted for by motivated numerical processing because the selection of one array or the other should not have had any impact on discomfort levels experienced by the participants. However, results are consistent with a bottom-up, attentional capture account of numerical processing under threat; such that threatening stimuli may have captured attention, slowing down visual scanning, thus resulting in a failure to enumerate all items in the array. That is, threatening stimuli may have inhibited complete numerical processing of the stimuli, resulting in faulty numerical discrimination abilities. As such, results of Experiment 2 suggest it is likely that the underestimation observed in Experiment 1 may have at least been partially mediated by bottom-up, attentional processes.

Results of Experiment 2 are consistent with other work revealing poorer performance on cognitive tasks when the task-relevant stimuli are emotionally-laden (Williams et al., 1996). However, studies have revealed enhanced performance on perceptual tasks when primed with threatening stimuli (Phelps et al., 2006; Vuilleumier, 2005), such that the subsequent task does not compete with the effects of the threat (Phelps et al., 2006; Vuilleumier, 2005). If so, numerical processing may be similarly enhanced in the context of a threatening stimulus so long as the numerical task does not compete with the effects of the threat. In Experiment 3, we examine whether a threatening prime may benefit a subsequent numerical discrimination task in order to provide a holistic account of the impact of threatening stimuli on numerical processing.

4. Experiment 3

In Experiments 1 and 2, threatening stimuli resulted in underestimation and impaired numerical discrimination. In both cases, however, threat was intrinsic to the numerical stimuli, making it likely that the attentional capture created by the threatening stimuli competed with task demands, resulting in impaired numerical processing. It is unclear, however, how threatening stimuli may interact with enumeration processes when this competition is removed. In Experiment 3, participants were again presented with a numerical discrimination task; however this time, threat was not inherent in the numerical stimuli. Instead, participants were primed with a threatening stimulus just prior to the numerical discrimination task, thus eliminating competition between the threat and task demands and allowing an exploration for how threats may impact numerical discrimination when threats are not inherent to the numerical stimuli. Because the timing of presentation of stimuli was distinct from that of Experiment 2, we chose to model the numerical discrimination task in Experiment 3 directly from prior research involving approximate numerical discrimination tasks (Halberda et al., 2008).

4.1. Method

4.1.1. Participants

Participants were 24 undergraduate psychology students (10 males, 14 females: $M_{age} = 19.13$, range 18–23) who received course credit or cash compensation for participation. Additional participants were excluded for experimenter error (n = 3) and for performing at chance levels (n = 3; responding correctly on fewer than 40 of 64 trials (62.5%) as determined by Binomial statistics).

4.1.2. Stimuli

Numerical arrays consisted of a randomly intermixed collection of heterogeneously-sized blue and yellow dots shown on a black screen (modeled after Halberda et al., 2008). The number of dots in each individual array (blue or yellow) varied from 5 to 16, such that the ratio between the number of dots in each pair of arrays was chosen from one of four ratios: 0.750, 0.833, 0.857, 0.875. The color of the more numerous array was counterbalanced across trials. As in Experiment 2, the average size of the dots in each array was held constant in half of the trials, and in the other half of trials, the cumulative areas of the two arrays were equated. Within each array, the individual dots varied in size by ± 33% (modeled after Libertus et al., 2011). All threatening and neutral stimuli were black and centered on a white background, subtending 16° of visual angle vertically and horizontally.

4.1.3. Procedure

Participants first performed 10 practice trials in which they were presented with an intermixed array of blue and yellow dots for 500 ms and were asked to indicate the color of the more numerous array. Participants responded by pressing either the left arrow key (to indicate yellow) or the right arrow key (to indicate blue). The two arrow keys on the keyboard were labeled to ensure participants remembered the appropriate keys to press. Once a key press occurred, the program advanced to the next trial.

Following practice, test trials began in which participants were briefly shown either a threatening (spider) or neutral (e.g., flower) stimulus (for 500 ms) just prior to the presentation of the intermixed dot arrays (500 ms). Participants were again asked to indicate the color

[5] Ratio was not included in the analysis as it did not interact with threat.

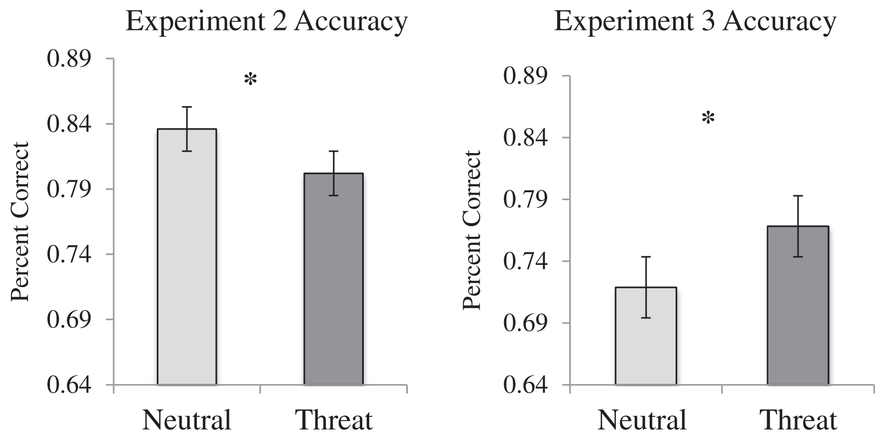

Fig. 4. a: Accuracy when participants are asked to discriminate between the numerosity of two arrays of either threatening or neutral stimuli (Experiment 2). b: Accuracy when participants are asked to discriminate arrays of dots immediately after seeing either threatening or neutral stimuli (Experiment 3). Error bars indicate SEM. * $p < 0.05$.

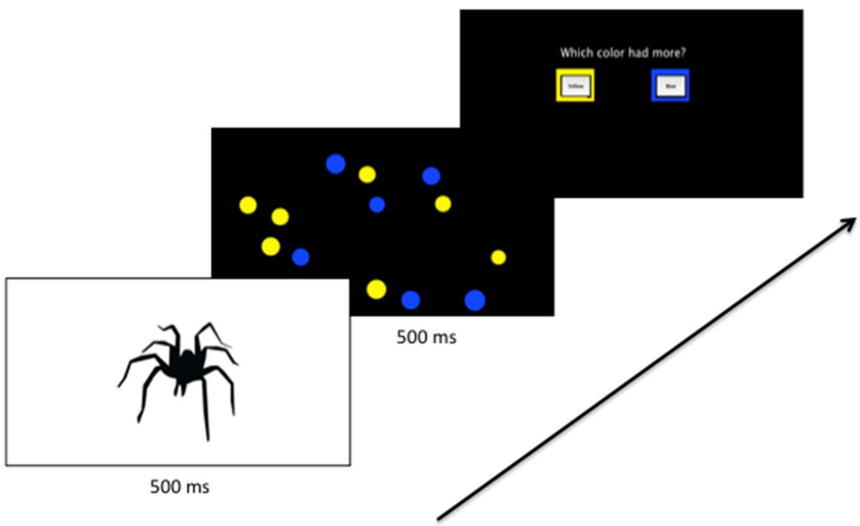

Fig. 5. Example of a single threatening trial of the numerical discrimination task in Experiment 3. Neutral trials were identical except instead of a presenting an image of a spider, participants viewed a neutral stimulus (e.g., flower, twig) prior to the numerical array. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the more numerous array (Fig. 5). There were a total of 64 test trials such that the combination of each Condition (2; neutral, threat) × Item Type (4) × Ratio (4) was presented 2 times each.

4.2. Results and discussion

A repeated measures ANOVA examining the effects of Condition (threatening, neutral) and Ratio (0.750, 0.833, 0.857, 0.875) was conducted. Again, analyses revealed that, consistent with Weber's law (e.g., Jordan & Brannon, 2006), accuracy of responding decreased as the ratio between the two set sizes increased, $F(3,69) = 15.148$, $p < 0.000$, $\eta_p^2 = 0.397$. As in Experiment 2, there was also a main effect of condition, $F(1,23) = 4.585$, $p < 0.043$, $\eta_p^2 = 0.166$. In contrast, however, accuracy in the current experiment was significantly *higher* for threatening stimuli ($M = 0.768$, $SD = 0.081$) relative to neutral stimuli ($M = 0.719$, $SD = 0.091$, Fig. 4b). Again, there was no interaction between Condition and Ratio ($p > 0.2$), thus indicating a similar effect of Condition across easy and hard discriminations.

Again, we explored whether the impact of threat varied as a function of area congruency. A Congruency × Threat repeated measures ANOVA revealed a main effect of Threat, $F(1, 23) = 4.585$, $p < 0.043$. However, unlike in Experiment 2, there was no main effect of Congruency, $F(1, 23) = 0.576$, $p > 0.45$. Again, there was no interaction between Threat and Congruency ($p > 0.57$). Thus, as in Experiment 2, we found that threat impacted both trial types in a similar fashion.

The results of Experiment 3 reveal that the presence of a threatening stimulus just prior to a numerical task, and not inherent in the numerical stimuli, resulted in improved numerical discrimination. Consistent with prior work revealing enhanced contrast sensitivity following a threatening prime (Phelps et al., 2006; Vuilleumier, 2005), our data reveal that numerical processing is similarly enhanced when threat is not inherent in the numerical stimuli. Taken together with the results of Experiment 2, these data indicate that the presence of biological threats can either detract attention away from, or heighten attention towards, numerical stimuli depending on whether the threat competes with the task at hand.

5. General discussion

Real-world decisions often rely on the assessment of numerical information in the presence of threat. Thus, understanding how we process number in the presence of threat is vital. Results of three experiments reveal that the presence of threatening content affects numerical processing, but that effects are task-dependent. In Experiment 1, threats were underestimated relative to non-threats. In Experiment 2, numerical discrimination was impaired when the entities to be enumerated had intrinsic threat content. However, results of

Experiment 3 indicated that threatening content *enhanced* subsequent numerical processing, when the entities to be enumerated did not possess inherent threat. Thus, threats do not function in an exclusively detrimental fashion for numerical processing. These results highlight the importance of considering task demands when investigating the affect-cognition interface, and also reveal several specific features of the numerical processing of naturalistic threats.

In Experiment 1, the number of threatening stimuli was underestimated relative to the number of neutral stimuli, however the processes underlying this pattern were unclear. A bottom-up account would suggest that the threatening content heightened the participants' attention towards the threat and thus away from the numerical task at hand, resulting in an automatic, non-conscious process of underestimation. For example, the tendency for threatening stimuli to constrain the attentional spotlight to a particular spatial location (e.g., Van Steenbergen, Band, & Hommel, 2011) may have resulted in fewer items actually perceived at the site at which the participant lingered during the estimation tasks. As such, the attentional capture of threats may have reduced participants' abilities to shift attention between sets, preventing an accurate holistic assessment of the relationship between the sets during the discrimination tasks (e.g., Cohen et al., 2011; Pessoa, 2009). Alternatively, individuals could have made a motivated decision to underestimate the number of stimuli present in order to down-regulate anxiety, in line with the top-down model. If participants simply underestimated spiders relative to flowers because they wished there were fewer spiders present in an attempt to down-regulate associated negative affect, then threatening stimuli should have no impact on numerical discrimination, a task that would not reasonably be expected to have the capacity to regulate affect. Results from the discrimination task in Experiment 2 confirmed that bottom-up processes were impacting the processing of the numerosity of the stimuli. Although results cannot speak to whether top-down processes are also at play in the pattern of underestimation observed in Experiment 1, our data suggest that this pattern is not likely solely a result of motivated cognition.

In contrast, results of Experiment 3 revealed that threatening stimuli enhanced participants' performance on a numerical discrimination task involving neutral stimuli. In this case, threatening stimuli presented prior to the numerical arrays appeared to function as an alert - orienting participants to the numerical discrimination task that immediately followed. This result is consistent with experiments showing that fearful faces enhance visual processing in a subsequent task assessing contrast sensitivity (Phelps et al., 2006), providing more evidence that performance on certain cognitive tasks, including numerical discrimination ones, may benefit from the presence of threatening stimuli, as long as the threat is not intrinsic to the stimuli.

Although this is the first experiment of its kind to explore numerical processing under threat, a large body of literature exists detailing the impact of threat on temporal judgments (Bar-Haim et al., 2007; Gil & Droit-Volet, 2011; Tipples, 2011). These experiments reveal adults and children alike consistently *over*estimate the duration of threatening, relative to neutral, situations (Gil & Droit-Volet, 2011; Tipples, 2011), an effect often attributed to a biologically prepared threat-detection module (Öhman & Mineka, 2001). In contrast, this study joins other work that shows that adults and children tend to *under*estimate number in the presence of emotionally charged stimuli (Lewis et al., in press; Young & Cordes, 2013). In light of prominent theories positing shared cognitive and neurological structures responsible for representing time and number (common magnitude system; Cantlon, Platt, & Brannon, 2009; Walsh, 2003), these contrasting patterns of temporal dilation and numerical underestimation in the context of threat may be surprising. However, these findings contribute to a growing body of literature documenting notable dissociations between temporal and numerical processing (Agrillo, Ranpura, & Butterworth, 2011; Baker et al., 2013; Cappelletti, Freeman, & Cipolotti, 2009; Cappelletti, Freeman, & Cipolotti, 2011; Dormal, Andres, & Pesenti, 2008; Dormal, Seron, & Pesenti, 2006; Odic et al., 2016; Young & Cordes, 2013), suggesting that temporal and numerical information may instead be processed via distinct systems (see Young & Cordes, 2013). Future work should explore these dissociations further by comparing temporal and numerical processing in the context of threat under identical task demands to verify that temporal and numerical processing are impacted in distinct manners under identical circumstances.

Finally, these experiments represent basic research that may serve to increase understanding of the mechanisms of math anxiety in children and adults. Prior work has found impairment in both the speed of numerical estimation and the accuracy of numerical comparisons (discrimination) in individuals with high math anxiety (Maloney et al., 2010; Mazzocco et al., 2011). Here we showed that threat content *intrinsic* to entities was detrimental to discrimination (an ability predictive of math achievement; Halberda et al., 2008; Park & Brannon, 2013), likely due to impeded attention shifting. These results suggest that individuals with high math anxiety may have difficulty disengaging from stimuli, making numerical discrimination more difficult; or, may even have conditioned associations between numerical information (see Maloney et al., 2010) and threat.

6. Conclusions

In conclusion, results reveal that numerical processing was disrupted when participants operated upon entities with intrinsic threat content, yet enhanced when threats were presented prior to a neutral numerical stimuli. Our ability to estimate and track number is essential to action-planning and even success in mathematics (e.g. Park & Brannon, 2013; Spelke, 2011). Thus, continuing to map how emotional information—negative and positive, and ranging in motivational intensity—impacts quantity representations will be important in order to more precisely understand numerical processing in real-world contexts.

Disclosure statement

The authors had no financial interests in the outcome of this project.

Acknowledgements

Funding was provided by an Alfred P. Sloan Foundation fellowship to S.C. We are grateful for the assistance of Sarom Kim and Alison Goldstein for their assistance in programming and data collection. We also thank an anonymous reviewer for their insightful feedback on our manuscript.

Appendix A. Experiment A1

We conducted a prior version of Experiment 1 in which participants completed a numerical estimation task in which they estimated the number of threatening (e.g., spiders) or neutral (e.g., flowers) stimuli. Results also revealed a significant underestimation of the number of threatening items compared to neutral stimuli. However, post-hoc analyses revealed some aspects of the perceptual features of the arrays were unintentionally confounded with threat status of the stimuli, making it unclear whether we could attribute our pattern of results to the presence (or absence) of threatening stimuli. As such, a careful replication, controlling for potential perceptual confounds was conducted and is now included in the main text as Experiment 1. However, because results of Experiment 1 mimic that of our earlier experiment, we include Experiment A1 here in the Appendix.

Method

Participants

Participants were 42 undergraduate psychology students (22 males, 20 females: M_{age} = 19.5, range 18–23) who received course credit or cash compensation for participation.

Stimuli

Stimuli were identical to Experiment 1, except that the number of items in each array was chosen randomly from one of seven logarithmically-spaced values: 10, 13, 17, 23, 30, 40, 52. Arrays did not differ in cumulative surface area (range: 3023.92.84–19,331.22 mm^2, M_{Threat} = 8016.08 mm^2 vs. $M_{Neutral}$ = 8587.80 mm^2; $p > 0.2$). However, as mentioned above, when number was entered as a covariate, arrays did inadvertently differ in the average interitem distance (range: 30.29–86.17 mm, M_{Threat} = 41.31 mm vs. $M_{Neutral}$ = 48.83, $p < 0.001$), the average convex hull (range: 87,418.18–240,639.05mm^2; M_{Threat} = 176,881.76mm^2, $M_{Neutral}$ = 160,065.94mm^2, $p < 0.01$), and (relatedly) in density (area/convex hull as in Gebuis & Reynvoet, 2012; M_{Threat} = 0.043 vs. $M_{Neutral}$ = 0.050, $p < 0.001$). Importantly, however, according to prior research on the impact of perceptual features on numerical estimates (Gebuis & Reynvoet, 2012), it would be predicted that direction of these differences (in convex hull and density) would lead to larger numerical estimates of threatening items in the displays.

Procedure

The procedure for this replication was identical to that of Experiment 1 except that each of the 8 different stimuli (4 neutral, 4 threatening) was presented 7 times each (once for each array size) for a total of 56 trials.

Data analysis

Again, responses more than 3 standard deviations above or below each participant's mean response time or mean response for that set size were excluded from analyses and only estimates for the five intermediate set sizes (13, 17, 23, 30, 40) were analyzed.

Results and discussion

The results of a repeated-measures ANOVA examining effects of Threatening content (threat and neutral) and Set size (13, 17, 23, 30, 40) on mean estimates indicated that participants increased their estimates as the number of stimuli increased (main effect of set size: $F(4, 164) = 384.660$, $p < 0.000$, $\eta_p^2 = 0.904$). Importantly, as in Experiment 1 participants underestimated the number of threatening stimuli relative to the number of neutral stimuli ($M_{Neutral} = 22.14$, $SD_{Neutral} = 4.44$; $M_{Threat} = 21.57$, $SD_{Threat} = 3.94$; $F(1,41) = 4.485$, $p = 0.040$, $\eta_p^2 = 0.099$). As in Experiment 1, there was no interaction between Condition and Set Size ($p > 0.05$) indicating a similar condition effect across array sizes.

As in Experiment 1, threatening stimuli were reliably underestimated relative to neutral stimuli. As noted, the density of the threatening arrays was inadvertently smaller than that of the neutral arrays, and the convex hull was larger in the threatening arrays relative to the neutral arrays. Previous literature has reported that these perceptual variables can influence numerical estimates, such that arrays containing smaller density and/or larger convex hull are estimated as being more numerous (Gebuis & Reynvoet, 2012). Though perceptual variables may possibly have influenced estimates in our task, it should be noted that the stimulus differences are unlikely to account for underestimation of threatening arrays relative to neutral arrays. The differences in perceptual variables (lower density and higher convex hull for threatening arrays relative to neutral) should have biased participants towards *overestimating* the number of threatening items relative to neutral; thus it seems likely that these perceptual differences may have attenuated the magnitude of underestimation observed under threat. In fact, in Experiment 1, when perceptual features were controlled, the threat variable had a notably larger effect size ($\eta_p^2 = 0.232$) than that of Experiment A1 ($\eta_p^2 = 0.099$).

References

Agrillo, C., Ranpura, A., & Butterworth, B. (2011). Time and numerosity estimation are independent: Behavioral evidence for two different systems using a conflict paradigm. *Journal of Cognitive Neuroscience*, *1*(2), 96–101.
Baker, J., Rodzon, K., & Jordan, K. (2013). The impact of emotion on numerosity estimation. *Frontiers in Psychology*, *4*, 521.
Bar-Haim, Y., Lamy, D., Pergamin, L., Bakermans-Kranenburg, M. J., & van IJzendoorn, M. H. (2007). Threat-related attentional bias in anxious and nonanxious individuals: A meta-analytic study. *Psychological Bulletin*, *133*(1), 1–24.
Brannon, E., & Merritt, D. (2011). Evolutionary foundations of the approximate number system. *Space, time, and number in the brain: Searching for the foundations of mathematical thought* (pp. 207–224).
Cantlon, J. F., & Brannon, E. M. (2007). How much does number matter to a monkey (*macaca mulatta*)? *Journal of Experimental Psychology: Animal Behavior Processes*, *33*(1), 32–41.
Cantlon, J. F., Platt, M. L., & Brannon, E. M. (2009). Beyond the number domain. *Trends in Cognitive Sciences*, *13*(2), 83–91.
Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2009). Dissociations and interactions between time, numerosity and space processing. *Neuropsychologia*, *47*(13), 2732–2748.
Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2011). Numbers and time doubly dissociate. *Neuropsychologia*, *49*(11), 3078–3092.
Cohen, N., Henik, A., & Mor, N. (2011). Can emotion modulate attention? Evidence for reciprocal links in the Attentional Network Test. *Experimental Psychology*, *58*(3), 171–179.
Cordes, S., King, A., & Gallistel, C. (2007). Time left in the mouse. *Behavioral Processes*, *74*, 142–151.
Crollen, V., Castronovo, J., & Seron, X. (2011). Under- and over-estimation: A bi-direction mapping process between symbolic and non-symbolic representations of number. *Experimental Psychology*, *58*(1), 39–49.
DeWind, N. K., & Brannon, E. M. (2012). Malleability of the approximate number system: Effects of feedback and training. *Frontiers in Human Neuroscience*, *6*(68), 1–10.
Dormal, V., Seron, X., & Pesenti, M. (2006). Numerosity-duration interference: A Stroop experiment. *Acta Psychologica*, *121*(2), 109–124.
Dormal, V., Andres, M., & Pesenti, M. (2008). Dissociation of numerosity and duration processing in the left intraparietal sulcus: A transcranial magnetic stimulation study. *Cortex*, *44*, 462–469.
Feigenson, L., Dehaene, S., & Spekle, E. (2004). Core systems of number. *Trends in Cognitive Science*, *8*(7), 307–314.
Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: Bradford Books. MIT Press.
Gebuis, T., & Reynvoet, B. (2012). The role of visual information in numerosity estimation. *PloS One*, *7*(5).
Gil, S., & Droit-Volet, S. (2011). How do emotional facial expressions influence our perception of time? In S. Masmoudi, D. Yan Dai, & A. Naceur (Eds.), *Attention, representation, and human performance: Integration of cognition, emotion, and motivation*. London: Psychology Press, Taylor & Francis.
Halberda, J., Mazzocco, M. M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*, 665–668.
He, L., Zhang, J., Zhou, T., & Chen, L. (2009). Connectedness affects dot numerosity judgment: Implications for configural processing. *Psychonomic Bulletin & Review*, *16*(3), 509–517.
Hyde, D., Khanum, S., & Spelke, E. (2014). Brief non-symbolic, approximate number practice enhances subsequent exact symbolic arithmetic in children. *Cognition*, *131*, 92–107.
Jordan, K. E., & Brannon, E. M. (2006). The multisensory representation of number in infancy. *Proceedings of the National Academy of Sciences*, *103*(9), 3486–3489.
Koster, E. H. W., Crombez, G., Verschuere, B., & De Houwer, J. (2004). Selective attention to threat in the dot probe paradigm: Differentiating vigilance and difficulty to disengage. *Behaviour Research and Therapy*, *42*, 1183–1192.
Koudenburg, N., Postmes, T., & Gordijn, E. H. (2011). If they were to vote, they would vote for us. *Psychological Science*, *22*(12), 1506–1510.
Lewis, E., Zax, A., & Cordes, S. (2017). The effects of emotion on numerical estimation: A developmental perspective. *Quarterly Journal of Experimental Psychology* (in press).
Libertus, Feigenson, & Halberda (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science*, *14*(6), 1–9.
LoBue, V. (2010). And along came a spider: An attentional bias for the detection of spiders in young children and adults. *Journal of Experimental Child Psychology*, *107*, 59–66.
LoBue, V., Rakison, D. H., & DeLoache, J. S. (2010). Threat perception across the life span: Evidence for multiple converging pathways. *Current Directions in Psychological Science*, *19*(6), 375–379.
Maloney, E. A., Risko, E. F., Ansari, D., & Fugelsang, J. (2010). Mathematics anxiety affects counting but not subitizing during visual enumeration. *Cognition*, *114*, 293–297.
Maloney, E. A., Ansari, D., & Fugelsang, J. A. (2011). The effect of mathematics anxiety on the processing of numerical magnitude. *The Quarterly Journal of Experimental Psychology*, *64*(1), 10–16.
Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PloS One*, *6*(9), e23749.
McCrink, K., & Wynn, K. (2009). Operational momentum in large-number addition and subtraction by 9-month-old infants. *Journal of Experimental Child Psychology*, *104*, 400–408.
Niemi, L., Woodbridge, M., Young, L., & Cordes, S. (2017). *Biased mathematical processing*

of political polling statistics. (in preparation).

Odic, D., Lisboa, J., Eisinger, R., Olivera, M., Maiche, A., & Halberda, J. (2016). Approximate number and approximate time discrimination each correlate with school math abilities in young children. *Acta Psychologica*, *163*, 17–26.

Öhman, A., & Mineka, S. (2001). Fear, phobias and preparedness: Toward an evolved module of fear and fear learning. *Psychological Review*, *108*, 483–522.

Ouimet, A. J., Gawronski, B., & Dozois, D. J. A. (2009). Cognitive vulnerability to anxiety: A review and an integrative model. *Clinical Psychology Review*, *29*, 459–470.

Park, J., & Brannon, E. M. (2013). Training the approximate number system improves math proficiency. *Psychological Science*. published online 6 Aug 2013 http://dx.doi.org/10.1177/0956797613482944.

Pessoa, L. (2009). How do emotion and motivation direct executive control? *Trends in Cognitive Science*, *13*, 160–166.

Phelps, E. A., Ling, S., & Carrasco, M. (2006). Emotion facilitates perception and potentiates the perceptual benefits of attention. *Psychological Science*, *17*(4), 292–299.

Spelke, E. S. (2011). Natural number and natural geometry. In E. Brannon, & S. Dehaene (Eds.), *Attention and performance (Vol. 24) space, time and number in the brain: searching for the foundations of mathematical thought* (pp. 287–317). Oxford, United Kingdom: Oxford University Press.

Tipples, J. (2011). When time stands still: Fear-specific modulation of temporal bias due to threat. *Emotion*, *11*(1), 74.

Van Steenbergen, H., Band, G. P. H., & Hommel, B. (2011). Threat but not arousal narrows attention: Evidence from pupil dilation and saccade control. *Frontiers in Psychology*, *2*(281), 1–5.

Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention. *Trends in Cognitive Sciences*, *9*, 585–594.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*(11), 483–488.

Williams, J. M. G., Mathews, A., & MacLeod, C. (1996). The emotional stroop task and psychpathology. *Psychological Bulletin*, *120*(1), 3–24.

Xu, F., & Spelke, E. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*, B1–B11.

Young, L. N., & Cordes, S. (2013). Fewer things, lasting longer: The effects of emotion on quantity judgments. *Psychological Science*, *24*(6), 1057–1059.