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The Impact of Emotion on Numerical Estimation: A Developmental Perspective

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Abstract

Recent literature has revealed underestimation effects in numerical judgments when adult participants are presented with emotional stimuli (as opposed to neutral; Baker, Rodzon, & Jordan, 2013; Young & Cordes, 2013). Whether these numerical biases emerge early in development however, or instead reflect overt, learned responses to emotional stimuli across development is unclear. Moreover, reported links between numerical acuity and mathematics achievement (e.g., Halberda, Mozzacco & Feigenson, 2008) point to the importance of exploring how numerical approximation abilities in childhood may be influenced in real-world affective contexts. In the present study, children (ages 6-10) and adults were presented with happy and neutral facial stimuli in the context of a numerical bisection task. Results reveal that children, like adults, underestimate number following emotional (i.e., happy) faces (relative to neutral). However, children's, but not adult's, responses were also significantly more precise following emotional stimuli. In a second experiment, adult judgments revealed a similar increase in precision following emotional stimuli when numerical discriminations were more challenging (involving larger sets). Together, results are the first to reveal children, like adults, underestimate number in the context of emotional stimuli and this underestimation bias is accompanied with enhanced response precision.

Keywords: *Affective Processing; Numerical Estimates; Numerical Cognition; Emotion*

The Impact of Emotion on Numerical Estimation: A Developmental Perspective

Numerical judgments are a regular part of daily life. One uses numerical information during the most ordinary of decisions from choosing the plate with the greater number of delicious cookies to picking a house in a neighborhood with a lowest crime rate. However, numerical judgments are rarely made in an emotional vacuum. In the real world, numerical processing is subject to moment-to-moment fluctuations in affective states, yet little is known about the impact emotion may have on numerical estimates across development. Recent investigations have recently uncovered robust patterns of numerical underestimation following emotional stimuli in adults (Baker, Rodzon, & Jordan, 2013; Hamamouche, Niemi, & Cordes, submitted; Young & Cordes, 2013), however no work has explored the developmental origin of these biases. It is unclear whether the observed underestimation reflects a top-down, motivated response to emotional stimuli learned over the course of development (e.g., an attempt by adults to minimize the impact of affective stimuli), or instead whether this bias represents an automatic, natural response to emotional stimuli that arises early in development. The answer to this open question could also address broader theories regarding the format of number representation.

Moreover, current data are unable to speak to whether a numerical underestimation bias due to emotional stimuli reflects impaired, or improved, numerical processing. Given the demonstrated link between numerical abilities and math achievement (both in terms of numerical accuracy and numerical precision: Bonny & Lourenco, 2013; Castronovo & Göbel, 2012; Halberda et al., 2008; Mundy & Gilmore, 2009), if emotional stimuli promote numerical abilities, developmental investigations into understanding the intersection of emotion and numerical cognition in young math learners may be relevant for early mathematics education. In the current study, we perform the first developmental investigation into the impact of emotional stimuli on numerical judgments in school-aged children (ages 6-10) and adults.

Background: Prior research with adults has revealed that the presence of emotional stimuli results in the underestimation of number (relative to the presence of neutral stimuli; Baker et al., 2013; Hamamouche et al., submitted; Young and Cordes, 2013). For example, when trained to discriminate between a small numerical standard (4 dots) and a large numerical standard (16 dots) in a bisection task, adults are more likely to judge intermediate set sizes (e.g., 8 dots) as subjectively “similar” to the small standard following the presentation of an emotional face (happy and angry) relative to following a neutral control face (Young & Cordes, 2013). The smaller relative quantity judgments following emotional stimuli indicate a numerical underestimation bias in adults.

Notably, the numerical underestimation bias starkly contrasts the well-documented pattern of temporal dilation, or overestimation of time, following emotional (e.g., happy, angry) stimuli. Across a number of studies, both children and adults have been found to *overestimate* temporal durations in the context of emotional stimuli (Angrilli, Cherubini, Pavese, & Manfredini, 1997; Bar-Haim, Kerem, Lamy, & Zakay, 2010; Droit-Volet, Brunot, & Niedenthal, 2004; Effron, Niedenthal, Gil & Droit-Volet, 2006; Young & Cordes, 2013). For example, in Young and Cordes (2013), the same adults who underestimated number in the presence of emotional faces were found to overestimate temporal durations following angry faces in a parallel task. In a related study on time perception, Effron et al., (2006) reported an overestimation of time for happy and angry emotion trials (relative to neutral). Moreover, this temporal dilation following emotional stimuli has been demonstrated in children as young as 3 years of age (Gil & Droit-Volet, 2011; Gil, Niedenthal & Droit-Volet, 2007), suggesting that this may reflect an automatic, bottom-up process.

The strong dissociation between numerical underestimation and temporal overestimation following identical emotional stimuli is noteworthy in that it has provided a serious challenge to a prominent theory in the field positing that the cognitive systems responsible for representing time, number, and other quantities are inseparable, and are thus processed within a common generalized magnitude system (Cantlon, Platt, & Brannon, 2009; Meck & Church, 1983; Newcombe, 2014; Walsh, 2003). Evidence of common behavioral signatures across development (see Feigenson, 2007 for review), overlapping neural activation (Walsh, 2003; Hubbard, Piazza, Pinel, Dehaene, 2005), cross-dimensional transfer (deHevia & Spelke, 2010; Lourenco & Longo, 2010; Meck, Church, & Gibbon, 1985) and cross-dimensional interference (Droit-Volet, Clement, Fayol, 2003) have all been provided in support of the common magnitude account.

More recently, however, it has been proposed that temporal, numerical, and other quantities may be represented via a common magnitude system early in development, and over time, neural specialization and formal instruction may result in the dissociation of temporal and numerical processing (Newcombe, 2014; Walsh, 2003). Indeed, across numerical, spatial, and temporal domains infants in the first year of life show a similar pattern of discriminating changes in stimulus presentation (see Feigenson, 2007, for a review) and will spontaneously map quantities across dimensions (e.g., map number to durations; Lourenco & Longo, 2010). In contrast, behavioral measures in adults are indicative of distinct systems (Agrillo, Ranpura & Butterworth, 2010; Dormal, Grade, Marmont and Pesenti, 2012). For example, Agrillo, et al., (2010) found no interactions between temporal and numerical information in the context of a conflict task and noted distinct patterns of responding across temporal and numerical estimates lending support to differentiated systems of processing. Similarly, recent studies demonstrating emotional stimuli yield distinctly different estimation biases on temporal and numerical judgments in adults are also inconsistent with the existence of a shared magnitude system in adulthood (Baker et al., 2013; Young & Cordes, 2013). Yet, whether a similar behavioral dissociation is present earlier in development, when a common magnitude system may be at play, is unclear. Though studies have established young children, like their adult counterparts, overestimate durations in the context of emotional stimuli (Gil et al., 2007), it remains to be seen if numerical underestimation biases are also present early in development. It may be the case that children's numerical processing is impacted in a similar manner as temporal processing under emotion, such that children may overestimate durations and number when presented with emotional stimuli. With development, temporal and numeric processing may become increasingly dissociated, and as such, emotional stimuli may only differentially impact temporal and numeric processing in adulthood.

The Current Study: How emotional stimuli impact numerical estimates over the course of development remains to be described. Do children, like adults, underestimate number in the context of emotional stimuli? What are the developmental precursors to adult patterns of numerical distortion in the presence of emotion? Can these biases be employed to impact educational practices? An emerging corpus of data reveals that early numerical abilities, including both nonverbal, approximate abilities (such as the ability to rapidly discriminate between two sets based on number) and exact, verbal counting abilities, are strongly predictive of math achievement in the classroom (Duncan et al., 2007; Geary, 2011; Halberda et al., 2008; Libertus, Feigenson, Halberda, 2011). Moreover, other work reveals emotional stimuli have been shown to enhance attentional processing in distinct tasks (Ohman, Flykt, Esteves, 2001; LoBue 2010). If emotional stimuli functions to heighten attention to numerical information, then results may highlight a strategy to target and improve early numerical abilities.

In the current study, we tested 6-10 year old children's and adult's numerical judgments under the influence of emotional stimuli (happy faces) relative to neutral. Using a numerical bisection task (modeled after Young & Cordes, 2013), we find that children, like adults, underestimate number in the context of emotional stimuli. Importantly, the ambiguous nature of the instructions of the bisection task ("is this array 'more similar' to the small or large one?") make it impossible to ascertain what "accurate" responding may be on this task. As such, it is impossible to evaluate whether this underestimation observed in bisection data reflects improved or impaired numerical abilities under emotion. However, our developmental data provide the first glimpse to address the direction of this observed numerical bias. Unlike those of adults, children's numerical judgments become significantly more precise following emotional stimuli, suggesting that emotional stimuli may be beneficial to numerical processing by heightening attention to number. In our second experiment, we investigate the source of this developmental difference by demonstrating that adult responses also become increasingly precise in the presence of emotional stimuli when numerical judgments involved are more challenging. Together, results from both experiments inform our understanding of how affective stimuli in the world impact our ability to attend to number across development, providing evidence to speak to cognitive theories of number representation while also pointing to methods to facilitate numerical processing in young math learners.

Experiment 1

In Experiment 1, children ages 6-10 and adults completed a bisection paradigm in which they were initially trained to discriminate between a small numerical standard (4 dots) and a large numerical standard (16 dots). Following training, participants were presented with intermediate numeric values (e.g., 7 dots) and were asked to indicate whether the array was more similar to the small or large standard. Importantly, on every trial, either an emotional (happy) face or a neutral (control) face was presented just prior to the dot array, allowing for the assessment of numerical biases under the influence of emotion.

Method

Participants: Sixty children (ages 6-10)[1], divided into two age groups: Young Children (6-7 year olds; N=29, M_{age}=7 years, 1 month; 15 females) and Older Children (8-10 year olds;

[1] This age range was chosen as it approximately matches those used in many other developmental studies using the bisection task to explore timing and numerical abilities in childhood (e.g., Droit-Volet, Clement, & Fayol, 2007; Droit-Volet & Rattat, 2007; Gil & Droit-Volet, 2011). Importantly, our data analysis plan (modeled after Droit-Volet, Brunot, & Niedenthal, 2004) required that we include a minimum of 84 test trials (2 emotions x 7 durations x 6

N=31, M_{age}=9 years, 4 months; 14 females), and 50 adults (M_{age}=22 years; Age range: 18-45 years old, 40 females), participated in Experiment 1. An additional 14 children (4 for failing to complete the task, and 10 for inaccurate responding (performing below 70% correct on at least one of the anchor values for either the happy or neutral stimuli, preventing a reasonable interpretation of results of linear regressions of their data)) and 1 adult (failure to complete the task) were excluded from analyses.

Child participants were recruited via a developmental database of children born in the Boston area, as well as from the Boston Children's Museum and local after-school programs. Parental consent and child assent were obtained for all child participants before the study was conducted. Children received a sticker and small toy as compensation. Adult participants included undergraduate students and others from the campus community (i.e., staff, visitors) who received course credit or a small gift for participating.

Stimuli and Apparatus: Dot arrays consisted of 4, 5, 6, 8, 10, 13, or 16 homogeneously-sized black dots. In half of the trials, the cumulative surface area of the dots in each array was held constant at 48.18 cm^2 across all set sizes. Thus, the size of individual dots negatively correlated with set size. In the other half of trials, the individual dot sizes were all held constant at 5.73 cm^2 each, such that the cumulative area was positively correlated with set size. There were 6 different arrays (each a different dot configuration) of each number (7) x area control (2) combination, which were randomly presented by the REALBasic program. A fixation probe was included consisting of a black cross centered on the screen.

Emotional stimuli consisted of happy and neutral adult faces from Young and Cordes (2013) taken from the NimStim set (Tottenham et al., 2009). These stimuli were pre-rated by

data points each) in our task. As such, we chose to test this age range as it matched that of previous studies and was the youngest age at which we expected child participants to be able to successfully complete the task.

independent coders, and the stimuli were chosen based upon common intensity, attractiveness, arousal, and valence ratings (refer to Young & Cordes, 2013). Each face was 12.5 x 16.8 cm.

Stimulus timing and presentation, as well as subject response recording were controlled by a REALBasic program presented on a 19” ConnectPro Touch 7300 LCD Monitor with a 17” display controlled by a MacBook laptop computer.

Procedure:

Importantly, our numerical bisection task was identical to that of Young & Cordes (2013) with the exception of two major differences to accommodate younger subjects: (1) facial and numerical stimuli were presented for 750 ms. (in Young & Cordes, stimuli were presented for 400 ms each) and (2) only happy and neutral faces were presented in the current task (Young & Cordes included angry faces as well). We chose to present stimuli for slightly longer than previous studies to make it easier for our younger participants to stay engaged in the task, while also making sure the presentation was not long enough to allow for verbal counting. Only happy and neutral stimuli were presented in order to reduce the duration of the entire task for our younger participants. In Young and Cordes (2013), the presence of happy and angry faces both resulted in an underestimation of number with the strongest effects for the presence of happy faces. Therefore to adjust the task from Young & Cordes (2013) for children, only happy and neutral stimuli were included.

The present experiment consisted of 3 phases (pre-training, training, and test). In pre-training, participants were exposed to the small (4) and big (16) anchor arrays for 750 ms each in alternation. When shown arrays containing 4 dots, the experimenter said “This is small”, and when shown 16-dot arrays, the experimenter said “This is big”. Small and big anchors were presented for each area control stimuli type. Importantly, the number of dots in the arrays was never specified for the participant, and participants were not allowed to count the arrays.

In training, participants were then presented with 4 different arrays of either 4 or 16 dots for each area control (order of presentation randomized) and asked to indicate on the touchscreen whether the array was small or big by pressing the “small” or “big” button on the touchscreen display. Prior to presentation of the dot array a fixation probe appeared. The computer provided feedback regarding whether their answers were correct or incorrect during practice trials. Participants were required to respond correctly on 8 consecutive practice trials in order to advance to the test phase (adapted from Droit-Volet et al., 2003).

The test phase consisted of 84 trials. On each trial, participants first saw a fixation cross, followed by either a happy or neutral facial stimuli (for 750 ms) centered in the middle of a white screen. Immediately following, they saw an array containing 4, 5, 6, 8, 10, 13, or 16 dots for 750 ms. Both the facial stimuli and dot arrays presented on each trial were randomly chosen across trials. After presentation of the dot arrays, participants were asked to indicate whether the presented array was more similar to the small (4) or big (16) learned standard by pressing the “small” or “big” button. Participants were told that they would see faces before the dot arrays in test but to continue to judge the number of dots in the dot arrays as more similar to the small or big standards as they had done during training (see Figure 1).

Data Analyses: As in Young & Cordes (2013) and in Gil et al., (2007), linear regressions were performed relating the probability of a “big” response as a function of number of items in the array for trials preceded by neutral faces and again for trials preceded by happy faces for each individual participant. From these regressions, we determined two parameters:

(1) Point of Subjective Equality (PSE; Indifference Point): The set size at which the probability of a big response was 50% (a measure of the subjective midpoint between the two anchor values). The PSE is inversely related to numerical estimates, such that higher PSEs indicate a rightward shift of the curve and thus a lower tendency to indicate the presented arrays were more similar to the “big” anchor (and a greater tendency to indicate arrays were more similar to the “small” anchor), reflecting lower estimates. Thus, as in Young & Cordes (2013), numerical underestimation under the influence of emotional stimuli would be demonstrated by a higher PSE on happy trials relative to neutral. The PSE is not an indicator of accuracy and it is widely accepted that there is no correct answer in the bisection task (i.e., a PSE closer to the arithmetic mean is not necessarily better than one closer to the geometric mean). Rather, the PSE can speak to the overestimation or underestimation of numerical estimates. The direction of numerical estimation is particularly relevant for addressing the validity of a possible shared mechanism for processing time and number. Previous work on temporal judgments has revealed emotional stimuli result in a lower PSE. Our study explores whether numerical judgments reveal a parallel pattern to that of timing (consistent with ATOM), or an opposite pattern of a higher PSE (consistent with adult data and with a dissociation between time and number).

(2) Difference Limen (DL): Half of the distance between the set sizes corresponding to a 75% probability of a big response and a 25% probability of a big response (a measure of response variability). The DL is a measure of numerical precision, such that a smaller DL reflects more precise responding. Differences in the DL between the neutral face and the happy face condition can speak to whether or not there is greater precision (as indicated by a lower DL) as a function of emotion. Importantly, greater precision in numerical judgements suggests enhanced numerical processing.

Results

PSE estimates obtained from linear regressions of the data were subjected to a mixed-measures ANOVA examining the between-subject factor of Age Group (3; Younger Children, Older Children, Adults) and the within-subject factor of Emotion (2; Neutral, Happy). Results revealed a main effect of Emotion, $F(1, 107)=8.58$, $p=0.004$, $\eta_p^2=.074$, such that the PSE for happy trials was significantly higher than the PSE for neutral trials, $M_{Happy}=8.50$ ($SE=.109$), $M_{Neutral}=8.31$ ($SE=.120$), reflecting an underestimation bias (Figure 2). Importantly, no other main effects or interactions were found, p's>0.3; revealing that an identical pattern of underestimation following emotional stimuli was found across the age range.

An Age Group (3) x Emotion (2) mixed-measures ANOVA was then conducted on the Difference Limen (DL) estimates. A main effect of Age Group was obtained, $F(2, 107)=5.76$, $p=0.004$, $\eta_p^2=.097$, revealing that responses became more precise (lower DL) with age, $M_{Younger}=2.90$ ($SE=.065$), $M_{Older}=2.78$ ($SE=.063$), $M_{Adults}=2.63$ ($SE=.049$). Additionally, a main effect of Emotion was found, $F(1, 107)=15.33$, $p=0.000$, $\eta_p^2=.125$, revealing that responses became significantly more precise following happy faces, $M_{Happy}=2.71$ ($SE=.035$), relative to neutral faces, $M_{Neutral}=2.82$ ($SE=.039$). This main effect, however, was qualified by an Age Group x Emotion interaction, $F(2, 107)=5.33$, $p=0.006$, $\eta_p^2=.091$, revealing a different response pattern in precision across development. Whereas both Younger and Older Children made more precise numerical judgments following emotional stimuli, Younger Children: $M_{Happy}=2.80$ (SE=.066), $M_{Neutral}=2.99$ (SE=.074), $t(28)=2.85$, $p=0.008$, *Cohen's d*=0.416; Older Children: $M_{Happy}=2.70$ (SE=.063), $M_{Neutral}=2.85$ (SE=.071), $t(30)=2.87$, $p=0.007$, *Cohen's d*= 0.350, the precision of adult judgments was unaffected by emotional stimuli, M_{Happy}=2.63 (SE=.045), $M_{Neutral}$ =2.62 (SE=.035), $t(49)=0.25$, $p>0.8$, *Cohen's d*= 0.028, (Figure 3).

Moreover, additional analyses on data from neutral trials confirmed that child responses were significantly more variable than adult responses following, as demonstrated by a difference in the DL: $F(2, 109)= 8.467$, $p=0.000$, $\eta_p^2=.137$, Younger Children vs. Adult: $p=0.00$, Older Children vs. Adult: $p=0.041$, Younger Children vs. Older: $p>.5$ (using the Bonferonni adjustment for multiple comparisons). In contrast, child and adult responses were equally precise following emotional stimuli, $F(2, 109)= 2.178$, $p>0.1$, $\eta_p^2=.039$; all *p*'s>0.1. Thus, not only did emotional stimuli increase response precision in child participants, the presence of emotional faces caused children to respond with a level of precision comparable to that of adults.

Lastly, correlational analyses confirmed that the observed underestimation biases and increased precision following emotional stimuli were concomitant, such that the magnitude of underestimation observed (as measured by $PSE_{Happy} – PSE_{Neutral}$) was correlated with the magnitude of change in response precision (as measured by $DL_{Happy} - DL_{Neutral}$) in children, Younger Children: $r(27)= -0.553$, $p=0.002$, Older Children: $r(29)=-0.526$, $p=.002$, but only marginally in adults $r(50)=-0.266$, $p=.062$. That is, the amount by which emotion impacted bias in numerical judgments (as measured by the PSE) correlated with the amount by which emotion impacted precision in numerical judgments (as measured by the DL).

Discussion

Results from Experiment 1 reveal that children, like their adult counterparts, underestimate number in the context of emotional stimuli relative to neutral stimuli. Across the age range, a pattern of underestimation (higher PSE) following the presentation of happy faces was found, and this did not vary as a function of age. Thus, our data both replicate and extend previous findings with adults (Baker et al., 2013; Young & Cordes, 2013) to indicate that in early and middle childhood, emotional stimuli provoke a significant underestimation of number. Together, findings suggest that demonstrated numerical biases under emotional influences likely reflect automatic, bottom-up processes that are present early in development. Moreover, coupled with findings from other developmental studies revealing temporal overestimation following emotional stimuli in children (Gil et al., 2007), data provide further support to suggest that temporal and numeric processing are not subserved by a common magnitude system.

Unfortunately, as in previous studies, the ambiguous nature of changes in the PSE in numerical bisection task data limits our ability to conclude whether this numerical bias reflects more or less accurate numerical judgments. Participants were asked to judge whether numerical values were more "similar" to the small or big anchor. Given that similarity judgments were entirely subjective, such that each participant could have been determined "similarity" as minimizing either the *arithmetic* difference or the *ratio* between the numerical value and the two anchors (or via some other undefined criterion), it is impossible to gauge whether lower numerical estimates reflects a decrease or increase in accuracy. Thus, as in previous studies, the pattern of numerical underestimation observed does not speak to how emotional stimuli impact accuracy.

Importantly, however, changes in precision observed among children in our sample provide the first evidence to indicate that these numerical biases may reflect improved numerical processing, at least in childhood. Whereas the variability of adult responses in emotional trials was identical to that of neutral trials, both Younger and Older Children alike demonstrated a significant increase in precision in their responses (as demonstrated by a smaller DL) following emotional stimuli. Moreover, this increased precision was so dramatic that it resulted in child participants, as young as 6 years of age, making numerical judgments with the same level of precision as that observed in adult participants. Moreover, correlations observed between numerical underestimation biases and changes in precision suggest that changes in the PSE and DL go hand-in-hand. Together, these results suggest that the numerical biases observed under emotional circumstances likely reflect overall improved numerical processing, both in children and adults.

Questions are raised, however, by the distinct developmental pattern observed. Why is it that children's responses became significantly less variable under emotional circumstances, whereas the precision of adult responses was unaffected? One possibility is that these developmental differences reflect differences in how emotional information is processed across development. That is, children may find emotional stimuli relatively more salient than adults, thus resulting in a greater impact on subsequent numerical tasks.

Alternatively, these developmental differences may reflect differences in the underlying precision of number representation across development. It has been well-documented that adult numerical abilities are significantly more precise than that of young children (i.e., neutral trials of the current study; Gil et al., 2007; Halberda & Feigenson, 2008). Moreover, the specific numerical values presented in the current study (4-16), though chosen to match that of previous work (Young & Cordes, 2013), did include at least one or two set sizes which are hypothesized to fall within the range of numerical values that adults are able to apprehend without counting (i.e., subitize up to 4 or 5 items; e.g., Trick & Pylyshyn, 1994). This high numerical precision in adulthood, coupled with the inclusion of small numerical values that were easily estimated, may have resulted in ceiling levels of precision. Thus, emotional stimuli may not have affected precision in adult responding because adults were already responding as precisely as possible. Because children's numerical estimation abilities are far less precise than that of adults, the precision of their estimates was still subject to improvement following emotional stimuli.

In Experiment 2, we explore how numerical precision may have impacted our developmental pattern of results by presenting adult participants with another numerical bisection task involving affective stimuli. In contrast to Experiment 1, however, the set sizes presented were significantly larger (15-60 dots), making it unlikely that adults could accurately estimate the size of the arrays without verbally counting. In doing so, we increased the uncertainty (and thus response variability) of adult numerical judgments, allowing a direct test of the hypothesis that developmental differences in Experiment 1 were driven by differences in numerical acuity. That is, if emotional stimuli impact the acuity of adult judgments when presented with more difficult numerical judgments, then this would suggest that the distinct patterns observed across children and adults in Experiment 1 reflect a difference in baseline numerical acuity levels. Alternatively, if a developmental difference in responses to emotional stimuli drove the pattern of results obtained, the precision of adult judgments should be unaffected by emotional stimuli, even when presented with difficult numerical judgments.

Experiment 2

In Experiment 2, adults completed a numerical bisection paradigm with two emotional faces (happy, neutral) identical to that of Experiment 1 with the exception that the size of the dot arrays was significantly larger (15-60 dots). These particular range of set sizes was chosen so as to maintain a 4-fold difference between anchors while also reducing the likelihood that adults could accurately estimate (without counting) the number of dots presented in each array.

Method

Participants: Forty-eight adults (M_{age}=19.1, Range: 18-22 years; 30 females) participated in a numerical bisection paradigm for course credit. An additional 3 participants were excluded for failing to respond over 70% accuracy on at least one of the anchor values, presumably due to lack of interest in the experiment.

Stimuli: Facial stimuli were the same as those used in Experiment 1, though numerical stimuli were increased as to make the task more challenging for adults. The small anchor array contained 15 dots, and the big anchor array contained 60 dots, and intermediate arrays contained 19, 24, 30, 38, and 48 dots (holding the 1:4 ratio constant between small and large anchors for Experiments 1 and 2, while making the intermediate arrays more challenging to distinguish for adult participants). Again, there were two stimulus sets – one in which the cumulative area of all arrays was held constant at 133.7cm^2 (thus individual dot size negatively correlated with set size), and another in which the size of the individual dots was held constant at 4cm^2 (thus cumulative area positively correlated with set size). Within each stimulus set a total of 42 stimuli were created with six different stimuli created for each of the 7 dot quantities yielding 84 different stimuli overall. Stimulus timing and presentation as well as subject response were controlled by a REALBasic program presented on 13” Macbook laptop computer

Procedure: The procedure of Experiment 2 was identical to Experiment 1. Again, the only difference was the number of dots presented in the numerical arrays.

Data Analyses: As in Experiment 1, individually computed linear regressions of the probability of a “big” response as a function of set size were calculated. The resulting regressions were then used to determine the PSE and DL.

Results

First, analyses were conducted to verify that the adult numerical judgments in Experiment 2 were more difficult than that of Experiment 1. To do so, overall accuracy on only neutral trials involving anchor values (4 & 16 in Experiment 1; 15 & 60 in Experiment 2) was compared across experiments (adult data only). Although the difference was not large, accuracy on these trials was indeed significantly lower when the anchor values involved larger sets, M_{Expt1}=99.4%; M_{Expt2}=98.4%; t(96)=2.28, *p*=0.025, *Cohen's d*=0.462.

Mirroring Experiment 1 and previous findings, adults significantly underestimated the subsequent number of dots that appeared following happy faces, as demonstrated by a significantly higher PSE for happy faces, *M*=32.71, *SE*=.70, compared to neutral faces, *M*=30.76, *SE*=.81; *t*(47)=4.35, *p*<0.001, *Cohen's d*=0.373; Figure 4.

Difference Limen analyses of adult data, on the other hand, did not follow the same pattern as adult data of Experiment 1. Given more difficult numerical judgments, adult participants responded with significantly greater precision following happy faces, *M*=10.29, *SE*= .22, relative to neutral faces, *M*=11.11, *SE*=.22, with analyses revealing a smaller DL following the emotional expressions, *t*(47)=3.38, *p*=0.001, *Cohen's d*=0.542; see Figure 4. Again, the magnitude by which participants underestimated (PSE difference scores) was negatively correlated with the magnitude of precision improvement observed under emotional circumstances (DL difference scores), *r*(46)=-0.365, *p*=0.011, such that the more emotional stimuli influenced the PSE, the more precision was also affected by emotional stimuli.

Discussion

Initial analyses confirmed that increasing the amount of dots from the range of 4-16 in Experiment 1 to a new range of 15-60 in Experiment 2 did make the numerical discriminations involved in the task more difficult, as participants performed less accurately when judging the numerical anchors in Experiment 2 as compared to Experiment 1. Despite the increased challenge, the change in numerical magnitude did not affect the pattern of numerical underestimation observed following happy faces (relative to neutral), replicating Experiment 1. In contrast to adult data of Experiment 1, however, we found response precision (the Difference Limen), to be impacted by the presence of emotional faces, resulting in an increase in acuity following emotional stimuli in adult data. This increase in acuity mimics that found with children in Experiment 1, and suggests that the developmental differences observed in Experiment 1 do not reflect changes in response to emotional stimuli over development, but instead suggest that previous failures to find differences in acuity in the bisection task may be driven by ceiling levels of performance by adults when smaller sets are involved (4-16 dots).

General Discussion

The present study is the first to investigate the impact of emotion on numerical estimates across development. Our findings reveal that children, like adults, underestimate number following the presentation of happy faces. The finding of a consistent pattern of numerical underestimation following emotional stimuli across development provides strong evidence to suggest that these numerical biases have early developmental origins, and likely reflect automatic, bottom-up processes.

In addition, in both children and adults we find that this numerical underestimation following emotional stimuli goes hand-in-hand with an increase in precision when making numerical judgments. That is, both children and adults (in Experiment 2) responded significantly more precisely following the presentation of happy faces (relative to neutral), and the extent to which precision was impacted in an individual tracked with the extent to which number was underestimated.

Consistent with previous work, Experiment 1 revealed numerical underestimation following emotional stimuli in adults and children. As noted previously, because task instructions were intentionally ambiguous and each participant may have defined numerically "similar" in a distinct manner (i.e., via arithmetic difference, ratio, or some other means), it is impossible to ascertain from the PSE alone whether this underestimation reflects improved or impaired numerical processing. That is, there is no *correct* answer when participants are asked whether 8 dots is more "similar" to 4 or 16. In fact, dependent upon the specific task parameters, human adults have been shown to produce data with a PSE near either the geometric mean or the arithmetic mean (or somewhere between the two; Allan & Gibbon, 1991; Droit-Volet & Wearden, 2001; Wearden & Ferrara, 1996; Zélanti & Droit-Volet, 2011). As such, it is impossible to determine what a *correct* answer is on any given trial. Our PSE analyses can only tell us the direction of numerical bias - namely underestimation - observed in the presence of emotional stimuli.

On the other hand, the Difference Limen can tell us about how precisely participants made their judgments. That is, the DL gives us a measure of certainty in participant responses - how consistently they picked a given response - a measure considered as a proxy for numerical acuity (or precision in the underlying representation). For example, individuals with very low numerical acuity (i.e., noisy representations of number) will be less certain in their numerical judgments, and thus likely to make less precise judgments. Interestingly, Experiment 1 analyses revealed that child numerical judgments under emotion became increasingly precise, so much so as to be comparable to that of adult participants. In contrast, the precision of adult judgments was unaffected by the presentation of happy faces. To explore the source of this developmental difference, in Experiment 2 we presented adults with more challenging numerical judgments. When numerical judgments were more challenging (by presenting larger set sizes), making the precision in adult judgments below ceiling levels, we find that adult patterns mimicked that of children such that adults underestimated number and made more precise estimates following emotional stimuli. Therefore differences in the pattern of responding between children and adults in Experiment 1 appears to be a function of increasing numerical acuity across the lifespan. Together, results of both experiments reveal a pattern of numerical underestimation and increased numerical precision following emotional stimuli across development in the context of relatively challenging numerical discriminations.

General Implications: Although many have argued for the existence of a common magnitude system, particularly for time and number (Cantlon et al., 2009; Meck et al., 1985; Meck & Church, 1983; Walsh, 2003), findings of numerical *underestimation* following emotional stimuli have sharply contrasted other evidence of temporal *dilation* following emotional stimuli (Bar-Haim et al., 2010; Droit-Volet & Meck, 2007; Gil et al., 2007; Tipples, 2008). These distinct behavioral patterns across time and number judgments in response to identical emotional stimuli have recently presented a challenge to this account (Baker et al., 2013; Young & Cordes, 2013). Aligning with these findings, developmental data have similarly revealed that children overestimate temporal durations after emotional trials (compared to neutral; Gil & Droit-Volet, 2011; Gil et al., 2007), whereas here we show that children underestimate number following happy faces (compared to neutral). These differences are indicative of non-overlapping developmental trajectories for time and number processing, suggesting that, at least by 6 years of age, temporal and numeric processing do not rely upon a common magnitude system.

Numerical underestimation in the presence of emotional stimuli during early childhood supports the hypothesis that the resulting bias is a function of bottom-up, attentional processing. In support of this hypothesis, previous work has demonstrated that a target is more likely to be detected and at a greater speed under emotional influences (LoBue & DeLoache, 2008; Ohman, 2002; Ohman et al., 2001). Moreover, in addition to the amygdala, bottom-up emotion generation draws on regions of the brain implicated in attentional vigilance (Ochsner et al., 2009). It is possible that the emotional stimuli in the present study orient attention to the numerical stimuli by way of bottom-up processes – namely perceptual and affective autonomic responses. Given that previous studies have found emotional stimuli to impact attention in non-numerical domains, it seems likely that the phenomenon of numerical underestimation observed in our study is the result of a general heightened attention, and not number-specific attentional process. It is an open question, however, whether this purported heightened attention to number may come at the cost of attention to other irrelevant attributes - that is, would participants be less likely to attend to changes in other perceptual features when engaging in our numerical task in the presence of emotional stimuli?

It is worth speculating over the underlying mechanism driving increased bottom-up attention following emotional stimuli. One possibility, is that emotional stimuli induce a change in emotional state. Previous work with adults found that angry and happy facial stimuli led to an overestimation of time (relative to neutral), but only when participants were permitted to spontaneously imitate the emotional facial expressions presented. When imitation was inhibited (i.e., when participants were asked to hold a pen in their mouth), duration estimation following emotional stimuli did not differ from neutral (Effron et al., 2006). Although no work has explored the role of facial imitation in the context of a numerical task, it is likely that similar mechanisms are at play. In the present study, emotional stimuli may have similarly led to a change in emotional state through embodied mechanisms. Future research, however, is needed to determine the extent to which the present findings relate to theories of embodied cognition. Additionally, characteristics of the participant need to be considered. For example, individuals who experience acute emotional responses to numerical tasks in general, such as individuals with high levels of math anxiety, may already underestimate numerosity in the absence of emotional stimuli, leading to a muted impact of emotional stimuli. As such, the presence of math anxiety may mediate how a participant responds to emotional stimuli in the context of a numerical task.

There are two important issues to be considered when discussing these implications, however. First, although we refer to "emotional stimuli", the current findings only apply to happy stimuli. Previous work has found that happy and angry stimuli result in identical patterns of numerical underestimation in adults (Baker et al., 2013; Effron et al., 2006; Young & Cordes, 2013), and thus we have every expectation that angry stimuli would result in an identical pattern of underestimation in children. Given that it is suspected that a general heightening of attention to emotional stimuli is the source of our pattern of numerical underestimation and heightened precision, there is no reason to expect angry faces to produce a distinct pattern of results. However, this is a question for future research. Second, it is impossible to know for certain whether a distinct profile may be found earlier in development. Due to particular task constraints, we chose to test school-aged children (6-10 year olds) in this study. It is possible that the pattern of underestimation observed in these children may be the function of a learned response, yet it is unclear *how* and *why* they would have learned such a response during early childhood. Future research should explore how emotional stimuli may influence numerical abilities earlier in development in order to clarify the developmental origins of these biases.

Lastly, the findings of increased numerical precision following emotional stimuli suggests affective numerical processing may be an important avenue for future research. Precision in numerical judgments has been found to correlate with math achievement across a number of studies in children and adults (Halberda, Mazzoco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Bonny & Lourenco, 2013; Piazza et al., 2010; Mazzocco, Feigenson, & Halberda, 2011), making precision of central importance to educational applications. Although these studies have generally used estimation or discrimination tasks to assess numerical acuity, we chose to use a bisection task in order to allow for direct comparisons to prior work in the domain of emotion and number/time. However, it should be noted that there is considerable overlap in the construct of response precision measured across standard numerical estimation (requiring verbal estimates of the set size of an array), discrimination (determining which of two arrays of dots is larger), and bisection tasks. In line with findings from discrimination tasks (Halberda & Feigenson, 2008), our bisection data reveal an increase in numerical acuity with age (adults produced a lower DL than children) and with task difficulty. Moreover, other work has revealed that precision in responding, relative to the range of values presented (termed the Weber fraction), remains constant across a range of values tested (holding the ratio of numerical values constant) across bisection tasks (e.g., Droit-Volet, Clement, & Fayol, 2007), estimation tasks (e.g., Cordes et al., 2001, 2007), and discrimination tasks (e.g., Halberda & Feigenson, 2008). Thus, strong parallels across these tasks make it likely that our results would be relevant to math achievement, suggesting that emotional stimuli may have the potential to influence math achievement. In fact, a recent study has found preschoolers to count happy faces much more accurately than they count neutral faces (Hamamouche, Taylor, Cordes, 2016), hinting at some of the implications of this work. In light of these findings, research should continue to investigate how emotional stimuli may be used to enhance precision and facilitate numerical understanding in children.

Conclusion: In conclusion, results of the current study both replicate previous studies of affective numerical processing in adults, and extend this work to a younger population. Findings again reveal a systematic pattern of underestimation following happy faces (relative to neutral) while also revealing increased precision in responses consistent with attentional enhancement towards numerical stimuli in the context of emotional stimuli. These developmental data provide strong evidence to suggest that these observed biases reflect automatic, bottom-up processes and add to the growing body of evidence revealing dissociation between temporal and numeric processing in children and adults.

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Figure Captions

Figure 1. Schematic of the Pre-Training, Training and Test phases of the Numerical Bisection task in Experiment 1.

Figure 2. Point of Subjective Equality for each emotion condition across age groups in Experiment 1. Error bars represent standard errors.

Figure 3. Difference Limen for each emotion condition across age groups in Experiment 1. Error bars represent standard errors.

Figure 4. Point of Subjective Equality (top) and Difference Limen (bottom) as a function of emotion condition in Experiment 2. Error bars represent standard errors.

Figure 1. Stimuli Presentation

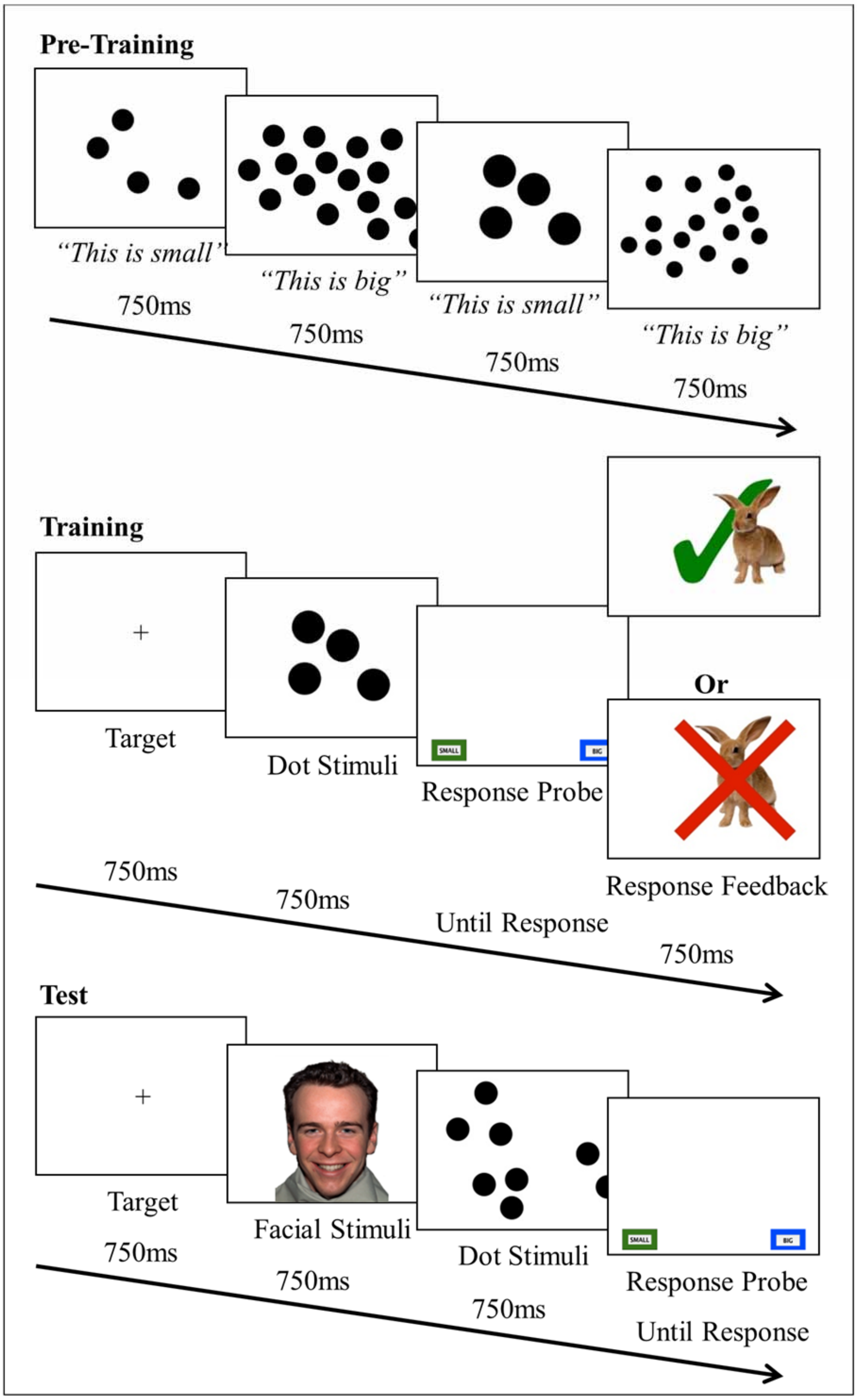

Figure 2. Experiment 1 Point of Subjective Equality

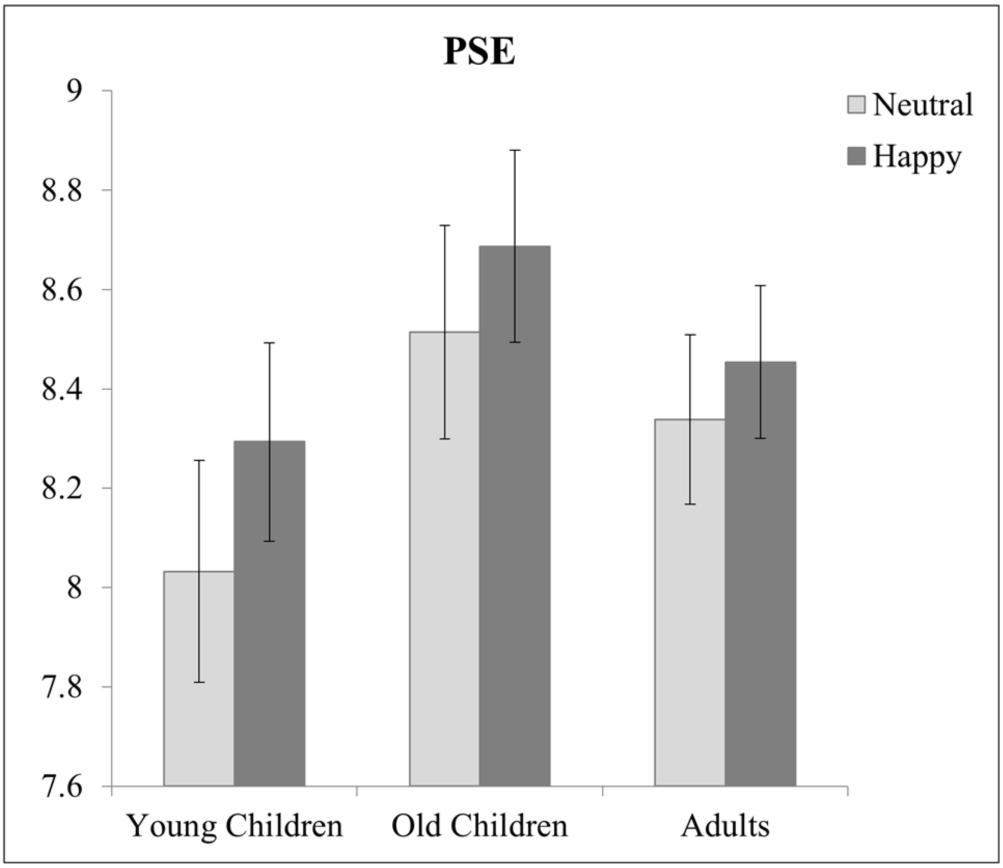

Figure 3. Experiment 1 Difference Limen

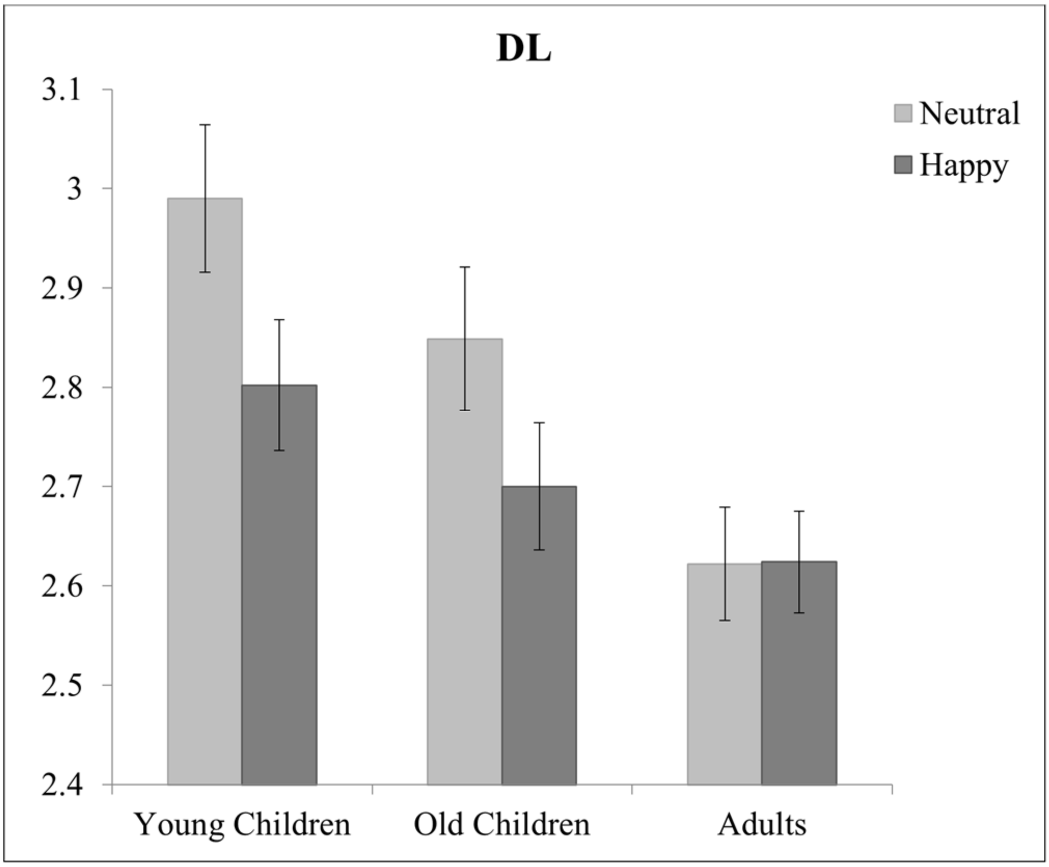

Figure 4. Experiment 2 Point of Subjective Equality and Difference Limen