Burgio *et al. BMC Biology* (2025) 23:305
https://doi.org/10.1186/s12915-025-02417-2

BMC Biology

RESEARCH

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Stronger reliance on visual perceptual history in individuals with higher math anxiety

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Abstract

Background Perception is inferential, relying not only on current sensory input but also on prior knowledge. When sensory input is unreliable, history effects such as central tendency and serial dependence smooth out noise by combining previous and current stimuli. These processes support perceptual continuity but also introduce biases, making the current stimulus appear erroneously similar to the previous one. Despite being observed in many perceptual domains, the mechanisms underlying these dynamic processes remain debated. Although perceptual, cognitive, and developmental factors have been studied, the influence of psychological traits has received little attention. In this study, we compared serial dependence and central tendency effects measured with a visual numerosity task across individuals with different levels of math anxiety.

Results We found that individuals with higher math anxiety exhibited worse numerosity thresholds as well as stronger central tendency and serial dependence effects compared to those with lower math anxiety. Both effects were best explained by differences in participants' sensory thresholds and were unrelated to their visuo-spatial working memory, suggesting they mainly originate from perceptual uncertainty rather than memory span. Math anxiety, as measured by a questionnaire, demonstrated minimal predictive power in explaining history effects once sensory precision was accounted for. Finally, we found no correlation between serial dependence and central tendency effects, suggesting that they may rely on independent mechanisms.

Conclusions Overall, our study indicates that central tendency and serial dependence are distinct perceptual mechanisms, both amplified in individuals with reduced sensory precision linked to specific psychological traits, such as math anxiety.

Keywords Central tendency, Serial dependence, Math anxiety, Numerosity

Background

Our eyes receive constantly changing information, but our brains return the impression of an organized world of discrete objects. Continuity of visual experience is made possible by the inferential nature of perception, which depends on the current sensory input, but also on the perception of previous stimuli [1]. Within the Bayesian framework, perception is the optimal combination of the current sensory stimulus with prior knowledge [2].

At least two perceptual phenomena demonstrate that stimulus history affects our current perception: central tendency and serial dependence. Central tendency is the attraction of current perception towards the average magnitude of the stimulus distribution [3]. This mechanism results in the overestimation of stimuli below the range average and the underestimation of those above it. This phenomenon has been demonstrated for many

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visual features, including size [3], shape [4], hue [5, 6], duration [7, 8], and numerosity [9]. Serial dependence, on the other hand, describes the tendency for the current stimulus to be perceived as similar to the previous stimulus [1, 2, 10]. For example, the numerosity of a dot array is overestimated when the previous stimulus is more numerous than the current one, but underestimated if the previous stimulus is less numerous. As in the case of central tendency, serial dependence has also been demonstrated in several domains of visual perception, from basic visual attributes such as orientation [11–17] and numerosity [9, 18–29], to more complex features such as face identity [30], expression [31], attractiveness [32], and body size [33]. While these phenomena may serve as efficient strategies in ecological contexts characterized by temporal redundancies, central tendency and serial dependence can introduce systematic response errors in experimental settings where each stimulus is "unrelated" to the next.

Despite being widely reported in the literature, the underlying mechanisms determining and influencing history effects are still largely debated. One influential account suggested that both effects increase under high-noise conditions, as strategies to smooth out noise from signals: when sensory representation is less reliable, individuals rely more on past experiences [2, 8, 18]. Supporting this view, previous studies have shown that central tendency and serial dependence effects are related to sensory precision [8, 9]. For instance, Cicchini and colleagues [8] examined temporal reproduction abilities in expert drummers and non-percussionists. Non-percussionists exhibited lower sensory precision compared to drummers and stronger central tendency effects; in contrast, drummers, whose sensory precision was twice as high as that of the other participants, reproduced the duration of visual flashes more accurately. This finding suggested that the drummer's optimal encoding may be linked to their heightened sensory precision. Other studies have found that younger children exhibit lower sensory precision, showing stronger central tendency effects compared to older participants in duration [34] and length reproduction tasks [35].

In the domain of numerosity perception, Anobile and colleagues [9, 36] investigated central tendency and serial dependence effects using a number line task, in which participants placed an array of dots along a numerical scale. The authors modeled participants' responses with a performance-optimizing Bayesian framework incorporating sensory precision into stimulus context. The results showed stronger central tendency when participants performed the number line task together with a concurrent visuo-spatial dual task. They suggested that this effect was due to a reduced precision in the case of divided attention, leading participants to leverage more on priors [36]. Subsequently, the same group demonstrated a direct link between history effects and sensory precision by showing that both central tendency and serial dependence effects can be predicted by the participants' sensory thresholds [9].

While the role of perceptual (e.g., musicians vs. non-musicians), cognitive (e.g., dual task), and developmental (children vs. adults) factors on contextual effects has been largely investigated, psychological traits have been relatively neglected. Here, we focused on the role of math anxiety (MA), an interesting context to investigate whether history effects arise from sensory precision. MA is defined as a feeling of tension, apprehension, or fear related to mathematical tasks [37], negatively impacting math performance. Traditionally, two theories have debated the origin of the association between MA and math performance [38]: the reduced competency theory and the processing efficiency theory. The reduced competency theory [39] proposed that MA may arise as a consequence of early difficulties in mathematics: limited numerical or spatial skills could hinder the acquisition of effective mathematical strategies, which in turn might contribute to the development of MA. In contrast, according to the processing efficiency theory, MA impairs math performance by redirecting cognitive resources, such as working memory (WM), from solving problems to managing anxiety [40–42].

In line with the reduced competency theory, Maldonado and colleagues [43, 44] found lower numerosity perception precision (a basic numerical competence) in individuals with relatively high levels of MA. Building on these findings, the current study investigates whether individuals with higher MA, together with lower numerosity perception precision (higher discrimination thresholds), also exhibit heightened sensitivity to stimulus history effects during numerical judgments. This should be expected if history effects arise from sensory precision. To this aim, we re-analyzed data from the study by Maldonado and colleagues wherein we had measured numerosity perception precision and MA in a sample of neurotypical adults [44]. If sensory precision is the determinant of history effects, we expect to observe greater reliance on past stimulation in participants with high math anxiety (HMA) compared with those with low math anxiety (LMA), and history effects to correlate with participants' numerosity sensory thresholds.

Maldonado and colleagues [44] also measured visuo-spatial working memory (VSWM) span and found no significant correlation with MA, despite VSWM scores and sensory thresholds having a comparable amount of interindividual variance. Measuring VSWM scores also allowed us to seek evidence in support of a different

account of history effects, which posits that they could arise from post-perceptual alterations of visual traces stored in WM. Indeed, previous studies have shown that serial dependence intensifies over time as the delay between stimulus and response increases [45, 46], suggesting that stimulus representation becomes increasingly distorted during WM storage. Furthermore, in orientation reproduction tasks, serial dependence is modulated by the level of WM load: strongly loading WM increases the influence of the prior stimulus compared to the low-load WM condition [47, 48]. Similarly, in a line length reproduction task, high WM load increased central tendency biases compared to low WM load [49].

Although our measure of WM is limited to participants' span on the Corsi block-tapping test [50], if history effects are related to WM, we would expect similar effects between individuals with HMA and LMA, given their comparable VSWM spans, or a correlation between history effects and memory span. Additionally, we compared reaction times between individuals with HMA and LMA to determine whether any potential stronger history effects observed in HMA participants could be attributed to longer retention times, indicating a more prolonged persistence of numerical percepts in WM storage.

Finally, the relationship between serial dependence and central tendency is unclear. The few studies that have attempted to investigate both have provided mixed results: some suggested that they reflect a single underlying mechanism [51], while others proposed that they are independent and parallel processes [6, 9, 33]. Observing (or not) a correlation between the magnitudes of the two effects would support one of these possibilities.

Results

When performing the numerosity estimation task (Fig. 1a), individuals with HMA showed higher coefficients of variation (CVs), indicative of lower precision ($M \pm \text{SEM} = 0.1 \pm 0.006$), compared to those with LMA ($M \pm \text{SEM} = 0.07 \pm 0.003$; $t(35.49) = -3.81$, $p < 0.001$, Cohen's $d = 1.11$, Fig. 1b), consistent with our previous reports [43, 44]. Since central tendency and serial dependence have been shown to scale with sensory precision, we first tested whether individuals with HMA exhibit heightened sensitivity to stimulus history effects during numerical judgments compared to those with LMA. To this aim, we divided the sample of participants into two sub-samples, one with HMA and one with LMA based on their AMAS scores, and compared central tendency and serial dependence effects between the two groups.

Following Anobile et al. [9], for each participant, we fitted average responses with a linear-logarithmic model and extracted the log component (λ) as an index of central tendency (Eq. 1, Fig. 2a). The model provided similar good fits for the two groups (average $R^2 = 0.97$ for HMA group; average $R^2 = 0.98$ for LMA group; $U = 339$, $p = 0.1$, rank-biserial correlation = 0.3). The central tendency index, on average, was significantly higher in the HMA group ($M \pm \text{SEM} = 0.26 \pm 0.04$) compared to the LMA group ($M \pm \text{SEM} = 0.13 \pm 0.03$, $U = 172$, $p = 0.043$, rank-biserial correlation = 0.35, Fig. 2b), suggesting a relatively stronger attraction of numerical estimates towards the

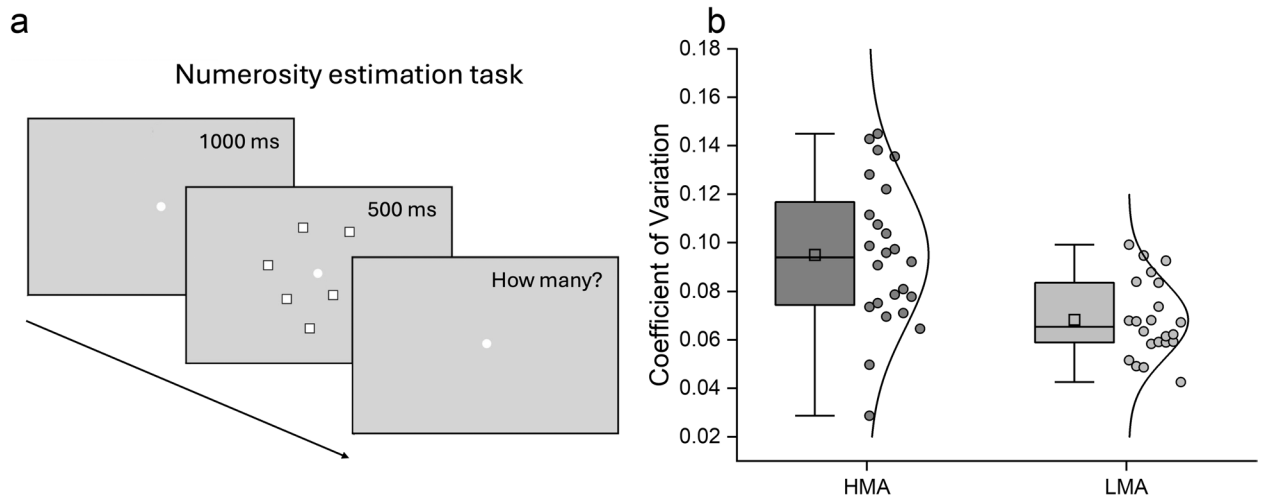

Fig. 1 Sensory thresholds in a numerosity estimation task were significantly higher in HMA participants compared to LMA. **a** Schematic representation of the numerosity estimation task. **b** Coefficient of variation (CV) distributions for HMA and LMA groups: filled circles represent individual participants, boxes represent the interquartile range (25th–75th percentile), whiskers indicate the minimum and maximum values excluding outliers, the horizontal line within each box marks the median, and the small square within each box represents the mean

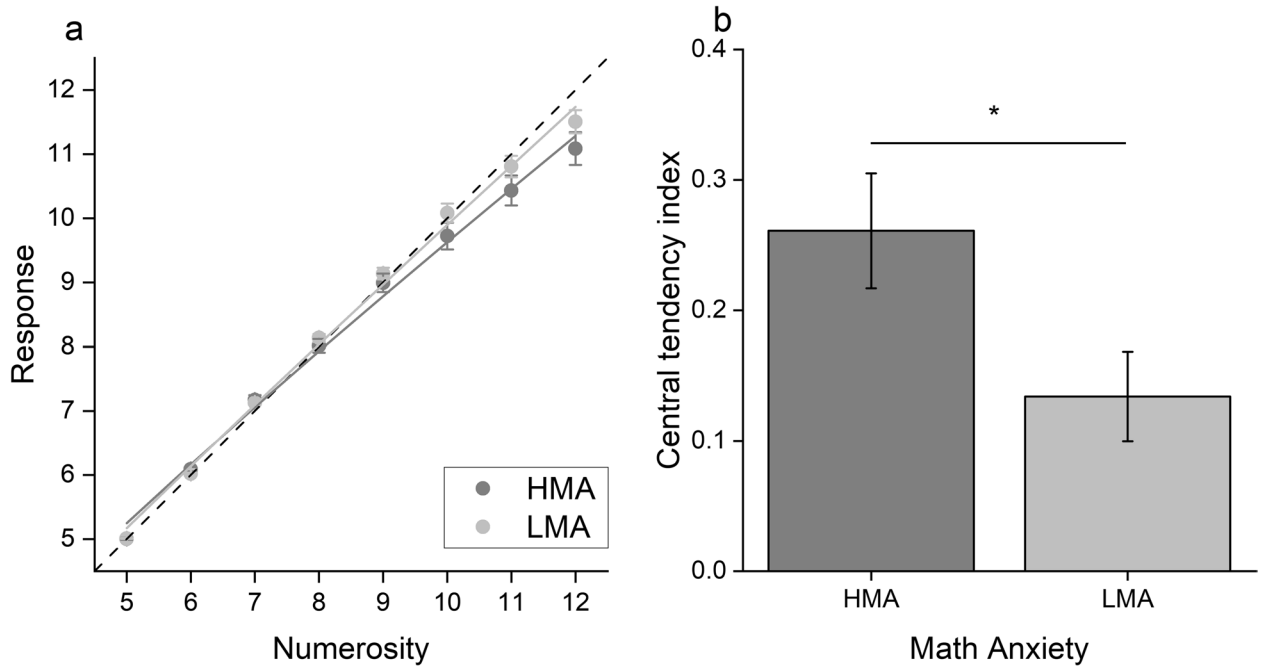

Fig. 2 Central tendency in numerical estimates is influenced by MA. **a** Mean response of participants with HMA (dark gray) and LMA (light gray) as a function of stimulus numerosity. Data were fitted using a linear-logarithmic model. **b** Mean central tendency index (λ) was significantly higher in the HMA group compared to the LMA group (*$p < 0.05$). Error bars represent the standard error of the mean in both panels

mean of the tested numerical range in individuals with higher levels of MA.

We then investigated whether serial dependence effects differed between individuals with HMA versus LMA. To this aim, we plotted participants' responses as a function of stimulus numerosity, separately for trials preceded by small or large numerosities (Fig. 3a, b). We then calculated the delta in numerical estimates between 1-back large and small, averaged across numerosities, for both HMA and LMA groups. As a control, we performed the same analysis after splitting trials according to the magnitude of the subsequent (1-next) rather than the previous numerosity (see methods). The delta in responses was significantly higher for participants with HMA ($M \pm SEM = 0.32 \pm 0.06$) compared to the LMA group ($M \pm SEM = 0.13 \pm 0.06$). Importantly, this was true only when trials were sorted according to the 1-back ($U = 144.5$, $p = 0.009$, rank-biserial correlation = 0.45, Fig. 3c), and not when divided according to the 1-next ($t(44) = -1.16$, $p = 0.25$, Cohen's $d = 0.34$, Fig. 3d), ruling out statistical artifacts. Consistent with the absence of serial dependence for future stimuli, the delta 1-next was not significantly different from zero in either group (HMA group: $t(23) = 0.02$, $p = 0.99$, Cohen's $d = 0.003$; LMA group: $t(21) = -1.95$, $p = 0.07$, Cohen's $d = 0.42$).

Overall, the results suggest that the two history effects tested here, central tendency and serial dependence, most strongly influence numerical estimates in individuals with HMA.

We next investigated whether history effects were predicted by participants' sensory precision or by their memory scores. As shown in Figs. 2 and 3, participants with higher CV (lower sensory precision) also had stronger history effects. Indeed, participants' CV correlated positively with both central tendency and delta 1-back magnitudes (central tendency index: rho = 0.37, $p = 0.011$, Fig. 4a; delta 1-back: rho = 0.46, $p = 0.001$, Fig. 4b). Interestingly, VSWM scores were not correlated with either central tendency (rho = 0.08, $p = 0.6$) or delta 1-back magnitudes (rho = 0.06, $p = 0.69$). Overall, these results suggest that sensory precision rather than memory span predicts history effects.

According to the WM account, a longer retention of the memory trace would increase its susceptibility to distortions from prior stimuli. To assess whether individuals with HMA maintained the trace in WM longer than those with LMA, we compared reaction times between the two groups. The results showed no differences ($U = 311$, $p = 0.31$, rank-biserial correlation = 0.18), suggesting comparable retention times across groups.

We then asked whether the link between the two history effects and MA holds over and above sensory threshold levels, to suggest the presence of additional factors potentially measured by the MA questionnaire. Both

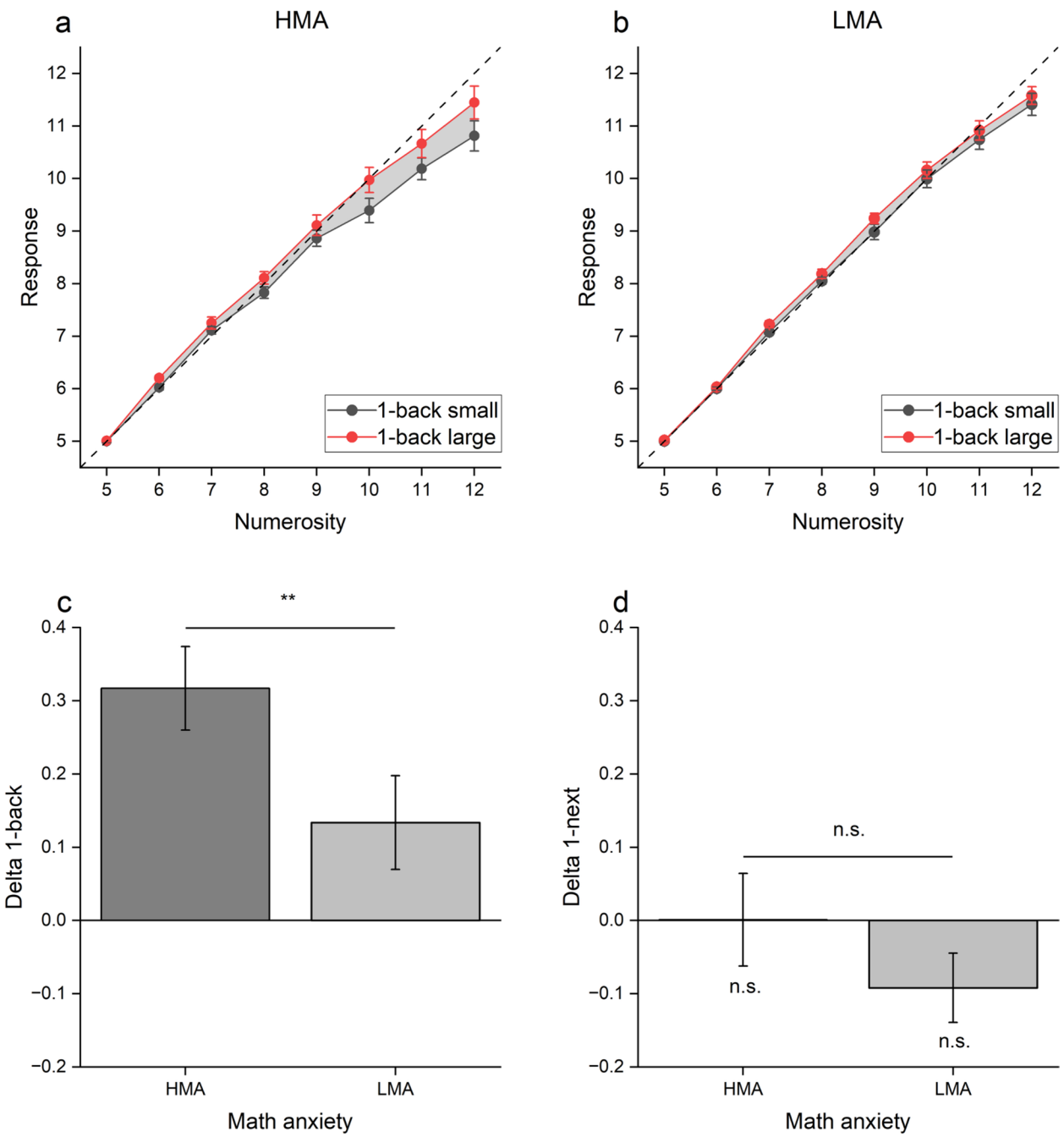

Fig. 3 Participants with HMA exhibit stronger reliance on previous numerosity compared to those with LMA. Mean response of participants with HMA (**a**) and LMA (**b**) as a function of physical numerosity. **c** Mean delta 1-back (difference in responses to current numerosity between large and small 1-back conditions) was significantly higher in HMA participants compared to LMA participants (**$p < 0.01$). **d** Mean delta 1-next showed no significant deviation from zero nor group differences between HMA and LMA groups. Error bars represent the standard error of the mean across all panels

central tendency and serial dependence effects correlated positively with the AMAS score (central tendency index: rho = 0.42, $p = 0.004$; delta 1-back: rho = 0.33, $p = 0.027$); however, partialling out sensory precision strongly decreased the predictive power of MA on history effects (rho = 0.3, $p = 0.046$; rho = 0.14, $p = 0.34$, for central tendency index and delta 1-back respectively, Fig. 5). These results suggest that most of the interindividual variability

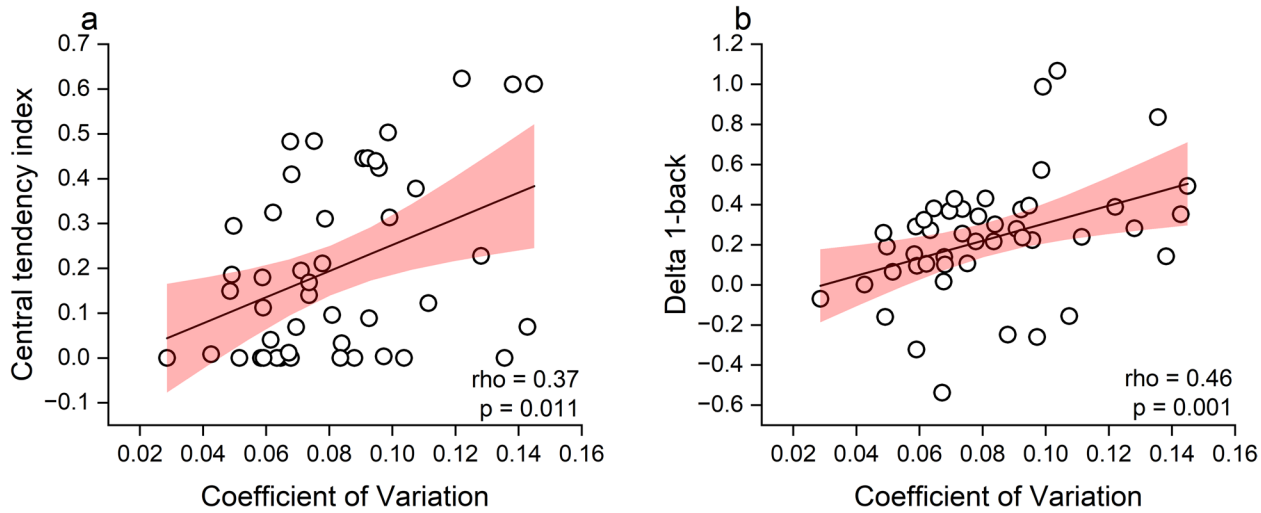

Fig. 4 Both central tendency and serial dependence correlate with the precision of numerical estimates. **a** Significant correlation between central tendency index and CV. **b** Significant correlation between delta 1-back and CV. Open circles indicate individual data points, the black line shows the regression line, and the red area indicates the 95% confidence interval

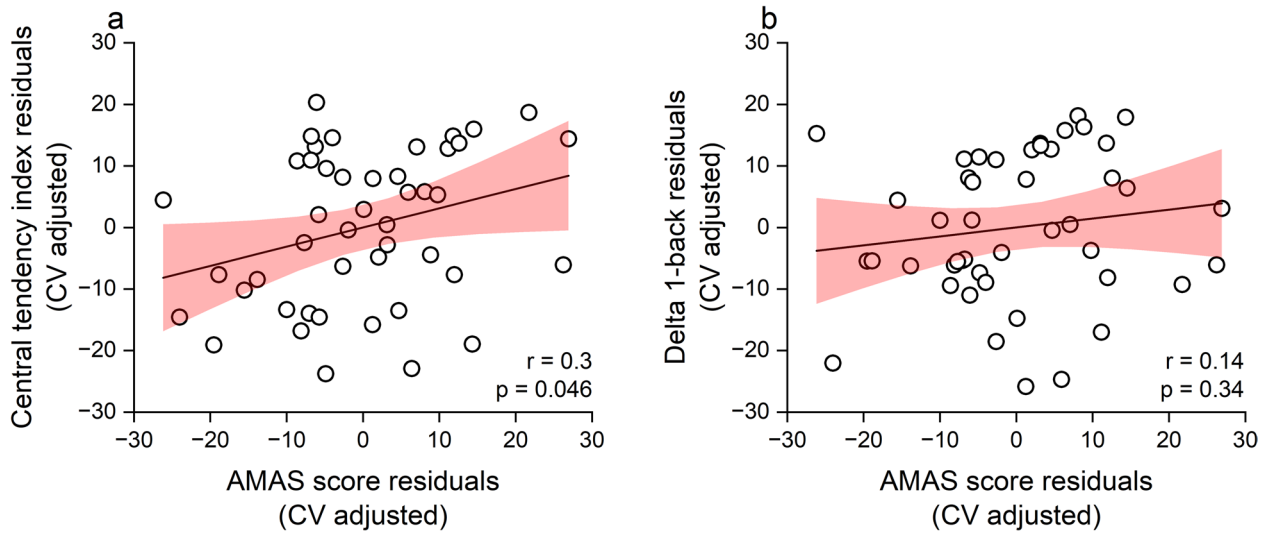

Fig. 5 Controlling for sensory precision reduces the predictive power of MA on history effects. To illustrate the Spearman partial correlation results between history effect indices and MA (controlling for CV), we converted the original variables into ranks and then computed rank residuals using a linear regression with CV as the predictor. **a** A significant trend was observed between central tendency index rank residuals and AMAS scores, though it did not survive correction for multiple comparisons. **b** No significant correlation was found between delta 1-back rank residuals and AMAS scores. Individual data points are represented by open circles; the regression line is shown in black, and the 95% confidence interval in red

in history effects was explained by the interindividual variability in sensory precision.

Finally, to assess whether the two history effects would tap into shared mechanisms, we correlated their magnitudes across participants. As shown in Fig. 6, central tendency and delta 1-back were not correlated, suggesting at least partially separate processes (rho = 0.17, $p = 0.27$, $\log_{10}\text{BF} = -0.5$).

Discussion

There is now substantial evidence that current perception strongly depends on previous stimuli, as in the case of serial dependence and central tendency phenomena. While these "history effects" have been observed across a wide range of tasks and sensory features, their underlying mechanisms remain unclear. In the current study, we asked whether one possible source of variability in

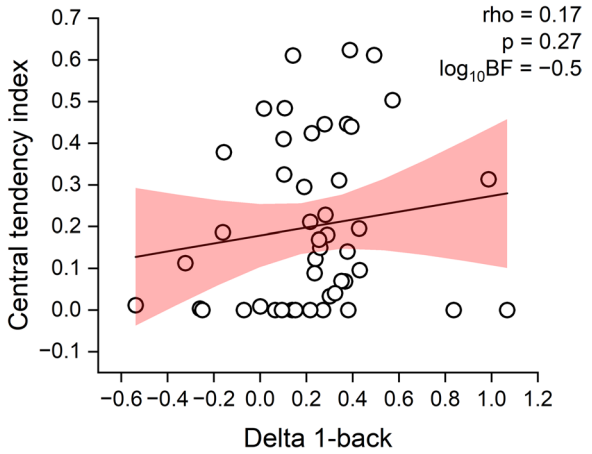

Fig. 6 No correlation between central tendency and serial dependence effects. No significant correlation was found between central tendency index and delta 1-back. Data points (open circles), regression line (black), and 95% confidence interval (red) are shown

history effects lies in individual differences in psychological traits, specifically anxiety. We found that participants with higher levels of math anxiety relied more on past stimuli, showing stronger central tendency and serial dependence in a visual numerosity task compared to those with lower levels of math anxiety.

This finding aligns with a growing body of research suggesting that affective experience plays an active role in shaping perceptual processing, rather than being a mere post-perceptual reaction [52, 53]. For example, goal-directed motivations can bias size perception: thirsty individuals tend to overestimate the height of a glass [54], and nicotine-deprived smokers tend to overestimate the length of a cigarette [55]. Other affective states, such as stress and relaxation, also affect visual perception: stress increases susceptibility to visual illusions [56], whereas meditation has been shown to reduce their strength [57, 58].

Particularly relevant to the present work, anxiety has been shown to influence early stages of visual processing. For instance, Phelps and colleagues [59] found that briefly presenting a fearful face prior to a tilted Gabor patch improved orientation discrimination, and that this effect could not be reduced to a mere shift in covert attention. Since orientation discrimination relies on contrast sensitivity, this suggests that emotional cues can enhance low-level visual perceptual mechanisms. In a subsequent study, the same group investigated how this effect is modulated by trait anxiety [60]. Individuals with high-trait anxiety showed impaired contrast sensitivity at the target location when attention was captured by a fearful face presented elsewhere, indicating greater difficulty in disengaging from threat. Anxiety has also been shown to affect other perceptual processes, such as time perception. For instance, Liu and Li [61] grouped participants based on trait anxiety, induced either a calm or an anxious state, and tested their reproduction of 2-s duration words. They found that high-trait anxious individuals underestimated duration, while low-trait anxious individuals overestimated it in the anxious compared to the calm condition.

The present study contributes to this literature by demonstrating that math anxiety can modulate reliance on prior stimulus history during numerosity perception. Notably, the strength of history effects among individuals with high versus low math anxiety was predicted by interindividual differences in sensory precision, as measured by the coefficient of variation. This suggests that the influence of math anxiety on history effects may be mediated by diminished sensory precision.

These findings fit well with previous studies showing that the magnitude of central tendency and serial dependence are both predicted by sensory thresholds [9] and are most evident under conditions of higher sensory noise, such as in cases of deprived attentional resources [36]. The link between history effects and perceptual uncertainty has also been reported for perceptual properties beyond numerosity, such as time [8, 34], length [35], or orientation perception [62, 63]. For instance, in an orientation reproduction task, Cicchini et al. [62] found that history effects scaled with stimulus sensory uncertainty: less precisely encoded stimuli (e.g., low spatial frequency, obliquely oriented Gabors) exhibited stronger serial dependence compared to easier stimuli (e.g., cardinal orientations). Furthermore, fMRI research has shown that the sensory uncertainty driving serial dependence is mirrored in the probability distributions decoded from visual cortex activity [63].

More generally, the findings of the current study support the account that frames history effects as perceptual biases influencing the phenomenological appearance of visual stimuli [12, 64]. According to this "perceptual" account, past visual information is integrated with the current percept to reduce noise and generate a "continuity field" that promotes visual stability over time [12, 13]. Consistent with this idea, previous studies on numerosity perception have shown that serial dependence effects display typical characteristics of low-level sensory processes, such as being spatially/retinotopically localized to the position of the inducer stimulus [19, 21]. These effects persist even when post-perceptual processes are minimized by the stimulus presentation procedure, such as when the stimuli to be compared are presented simultaneously rather than sequentially to minimize the involvement of working memory [21]. Moreover, an EEG study

found that early visual evoked potentials (VEPs) elicited by dot arrays were systematically biased by the numerosity of the preceding stimulus, even in passive-viewing paradigms, thus independently of decisional processes [22]. Taken together, this evidence points to a perceptual nature of serial dependence in numerosity perception.

On the other hand, previous research has shown that serial dependence intensifies as the temporal delay between stimulus and response increases, suggesting that history effects arise from post-perceptual processes [45, 46]. Additionally, both central tendency and serial dependence are modulated by memory load [47–49].

Although the current study is limited by measuring WM proficiency solely through the Corsi test [50], we found that the coarser sensory precision observed in HMA participants, rather than their WM span, was the key factor explaining their stronger reliance on past stimulation. These findings could not be explained by differences in reaction times between groups, either, and therefore not by differences in WM retention time. Overall, our results support the hypothesis that history effects are primarily perceptual rather than mnemonic phenomena.

However, at least for serial dependence, the two accounts may not be mutually exclusive and could potentially be reconciled. Research has shown that the transition of a visual percept into WM leads to a loss of sensory precision [65]. Consequently, prolonging the retention interval between stimulus and response could reduce the reliability of the current sensory input, potentially explaining some effects attributed to the WM/decisional stage [45, 46]. This hypothesis aligns with the Bayesian model, which suggests that when the current stimulus is less precise, reliance on prior knowledge—and consequently, history effects—increases [2, 66, 67]. Yet, perceptual and post-perceptual/memory biases may coexist and jointly interfere with current perception. Much evidence suggests that serial dependence in numerosity perception exhibits several hallmarks of high-level processing. For example, serial dependence effects have been observed even between memorized stimuli and regardless of their presentation order [24]. Moreover, history biases in numerosity perception depend on attention and are amplified when participants attend to the inducer stimulus [20, 21, 28]. These biases also require stimulus awareness, as they are suppressed when backward masking prevents conscious perception [26, 68]. In addition, the effect occurs regardless of numerical format (e.g., the number of sequential visual flashes biases the perceived numerosity of dot arrays [23]), although it does not impact different sensory modalities (e.g., acoustic stimuli [23]) or different stimulus dimensions (i.e., inducer numerosity biases subsequent perceived numerosity, but not perceived duration [29]). A subsequent study showed that both symbolic numbers and feedback on numerosity estimates induced serial bias in dot arrays presented in the following trial [27]. Finally, using the connectedness illusion, a recent study found that serial dependence acts on *perceived* rather than on *physical* numerosity, suggesting that it operates at a level where stimuli are segmented into perceptual units [26].

Overall, these findings suggest that although priors may distort perceptual representations, they likely originate from high-level processing stages, at the level of abstract information processing and judgment. Serial dependence may arise at high levels of the visual hierarchy while still affecting lower levels, producing a perceptual bias that alters stimulus appearance rather than memory or judgment [20, 27]. Within this framework, high-level areas may modulate lower-level regions via top-down signals. Priors may originate in the parietal cortex, which is known to encode numerical representations regardless of stimulus format (simultaneous vs. sequential [69]) and to be sensitive to attentional modulation [70, 71], both key characteristics of serial dependence effects. This aligns with previous fMRI studies showing that another history effect, adaptation, can alter both the pattern of activity elicited by numerosity and the preferred numerosity within the numerosity maps in the parietal cortex [72, 73]. These high-level areas may then propagate top-down signals to influence earlier stages of visual processing. This interpretation is supported by evidence showing that signatures of serial dependence during numerosity tasks can be read out from early VEPs, and with the observation that backward masking—known to disrupt top-down signals—suppresses the effect [20, 22, 26, 68].

These considerations can also be applied to other domains of perception, such as orientation. A seminal fMRI study by John-Saaltink and colleagues [74] demonstrated that, in the context of orientation perception, the previous stimulus modulates neural representations in V1. Building on the surround tilt illusion, Cicchini and colleagues [75] disentangled the site of generation from the site of action of priors. They found that serial dependence was strongest for a neutral stimulus preceded by an illusory one when the *perceived* orientations matched, suggesting that priors are high-level constructs that incorporate the effect of the illusion. Conversely, when an illusory stimulus was preceded by a neutral one, serial dependence was strongest when their *physical* orientations matched, indicating that priors act on early sensory input before it is biased by flanking stimuli. More broadly, these findings align with predictive coding models, which propose that priors are generated at higher processing levels and subsequently fed back to earlier stages, where they are tested against sensory input [76].

Beyond the theoretical and neural considerations discussed above, a further aim of our study was to investigate any potential influence of additional factors (e.g., arousal) captured by the MA questionnaire on determining history effects. To this end, we correlated history effects with MA while controlling for sensory precision. Given that individuals with HMA may experience increased arousal during math-related tasks, and arousal affects perception and decision-making [77], this factor warrants consideration. In the current study, controlling for sensory precision strongly decreased MA's predictive power, though a trend remained for central tendency. These findings suggest that sensory precision accounts for most of the variability. Nonetheless, future research should explore whether MA (and arousal), possibly measured through more refined psychophysiological indices, can predict history effects over and above sensory precision.

Another limitation of our design concerns the numerosity range used in the task. Responses to small numerosities are typically highly accurate, which can mask the strength of history effects. In our analyses, the central tendency bias was mainly driven by the underestimation of stimuli above the average numerosity, while responses to low numerosities remained near veridical. This pattern may have limited our ability to fully capture central tendency biases in participants with HMA. Therefore, future studies employing a higher numerosity range may be necessary to better assess how central tendency varies with math anxiety.

A final goal of the study was to clarify whether central tendency and serial dependence reflect a single mechanism or represent independent processes. Although current perception can be shaped by both the distribution range and the immediately preceding stimulus, most studies typically focus on one of these two phenomena. Only a few researchers have attempted to relate these two history effects. For instance, Tong and Dubé [51] proposed a unified model, validated through three estimation experiments focusing on line length and spatial frequency. According to their model, responses to a given stimulus depend on a fidelity-based weighted sum of two memory representations [51]: the probability density distribution of the current stimulus and a Gaussian mixture model of previous stimuli. In this model, more recent items, characterized by higher fidelity, are given greater weight. This fidelity-driven integration of memory traces is proposed to underlie both central tendency and serial dependence effects [51].

Conversely, Saarela et al. [6] analyzed participants' responses in color and line length tasks using a GLMM with serial dependence and central tendency as predictors. They found that both phenomena contributed significantly and independently, supporting the idea that these two history effects are distinct. Further evidence for their independence comes from correlational studies, which have found no significant association between central tendency and serial dependence in numerosity [9] and body size perception [33]. While the relationship between central tendency and serial dependence effects warrants further investigation, our results are in line with these latter studies showing no significant correlation between these two phenomena, suggesting that they may tap into separate or at least partly independent mechanisms.

Conclusions

Overall, the results suggest that the influence of past stimulation on current numerosity perception is amplified in individuals with higher math anxiety, as evidenced by stronger central tendency and serial dependence effects. These effects correlated positively with sensory precision but not with visuo-spatial working memory span, suggesting they are likely primarily perceptual in nature rather than mnemonic. Finally, no correlation was found between serial dependence and central tendency, suggesting that they might represent independent processes.

Methods

Participants

A total of 51 adults (78% female) aged 19 to 54 years ($M \pm SD = 22.5 \pm 7.4$ years) took part in the experiment by Maldonado Moscoso et al. [44]. All participants had normal or corrected-to-normal visual acuity. Four participants did not complete the experiment and were therefore excluded from the analysis.

Measures

Math anxiety

MA was measured through the Italian version [78] of the Abbreviated Math Anxiety Scale (AMAS, [79]). This questionnaire comprises nine items divided into two subscales: math learning anxiety (five items) and math testing anxiety (four items). Participants are asked to rate their anxiety levels during math-related events on a Likert scale from 1 to 5, with higher scores reflecting higher MA severity.

Visuo-spatial working memory

VSWM was assessed using a computerized task based on the Corsi block-tapping test [50]. In each trial, nine red squares (3°×3°) were presented on the screen, with a fixation point displayed at the top center. After 500 ms, the squares sequentially turned yellow, one at a time, with a 1-s interval between each color change. Participants

were instructed to tap on the squares to reproduce the sequence, either in the same order (forward condition) or in reverse order (backward condition). The forward and backward conditions were administered in separate trial blocks. Following a practice trial with a sequence of two squares, the task started with sequences of three squares. If participants correctly recalled at least one of two sequences of the same length, the sequence length was increased by one square. The VSWM span was defined as the maximum sequence length correctly reproduced at least once.

Numerosity estimation

Each trial began with a black central fixation point that turned white after 1 s and remained on screen for the entire experiment. After 1 s, an array of white squares (0.4°×0.4°) with black borders was presented around the center of the monitor for 500 ms, followed by a blank screen. On every trial, squares were displayed within 106 randomly selected locations covering a 6°×6° area. Participants were asked to estimate the numerosity of each array as quickly and accurately as possible. An experimenter (blind to the numerosity) pressed the spacebar as soon as the participant had provided the response (to record response time), typed the estimated number on the numeric keypad, and then pressed the enter button to start the next trial (after an interval of 500 ms). Numerosity arrays ranged from 2 to 12. Each participant completed 150 trials. Trials with numerosity estimates exceeding 24 (twice the highest numerosity shown) or response times longer than 5 s were classified as outliers and excluded from the analysis (2% of the trials). Numerosity estimation precision was quantified (for each numerosity) by the coefficient of variation (CV), defined as the ratio of the standard deviation to the mean of the response distribution. Since responses within the subitizing range are typically highly accurate, we computed CVs only for numerosities between 5 and 12. These values were then averaged across numerosities to obtain an overall precision index. One participant with an average CV more than 3 standard deviations above the group mean was identified as an outlier and excluded from the analysis, which therefore included a total of 46 participants.

Procedure

The experiment was performed in a quiet room. Participants were first administered a pencil-and-paper version of AMAS and then tested with the computerized tasks (VSWM and numerosity estimation tasks). Each participant sat at a viewing distance of 57 cm from an LG 27 monitor subtending 56° by 32°, with a resolution of 1920×1080 and a refresh rate of 60 Hz. The sequence of stimuli was generated and presented with Psychtoolbox routines for MATLAB (RRID: SCR_001622, ver. 2010a, The MathWorks, Inc., Natick, MA, USA).

Statistical analysis

We divided the sample into LMA group (22 participants, AMAS score < 24) and HMA group (24 participants, AMAS score ≥ 24) based on the median AMAS score.

To quantify the central tendency effect, we plotted participants' average responses (range 5–12, as for the CV analysis) as a function of stimulus numerosity. We then fitted the data using the mixed model provided by Anobile and colleagues [9].

$$y = A\left((1-\lambda)x + \lambda\frac{12}{\log_{10}12}\log_{10}x\right)$$

This mixed model, which includes both a linear and a logarithmic component, has been previously demonstrated to capture well central tendency in numerosity perception [9, 18, 36] as responses are typically highly accurate for low numerosities (within or near the subitizing range, [80]), then deviating from veridicality at larger ones. This non-linearity is quantified by the logarithmic component lambda (λ) spanning from 0 (fully linear) to 1 (fully logarithmic). We used this parameter (λ) as an index of central tendency, with higher values indicating stronger central tendency. Since the central tendency index violated the normality assumption in both the LMA group (Shapiro–Wilk test, $p < 0.001$) and the HMA group (Shapiro–Wilk test, $p = 0.031$), we used the Mann–Whitney U test for group comparison.

To measure serial dependence, we categorized previous numerosities as "small" or "large" depending on whether they fell below or exceeded the average of the numerosity distribution ($N = 7$), respectively. This procedure ensured that each current response was associated with an equal number of small (from 2 to 6) and large (from 8 to 12) previous numerosities (1-back). For each participant, we then separately calculated the average response to each numerosity, depending on whether it was preceded by a small ($N < 7$) or large ($N > 7$) numerosity. Although we used the full stimulus range (2–12) to classify preceding numerosities as small or large, we restricted the analysis of current responses to numerosities between 5 and 12 to ensure consistency with other analyses and minimize the influence of the subitizing range. For each numerosity, we then computed the difference between the obtained average responses (delta 1-back). Finally, these differences were averaged across all numerosities to obtain an aggregated index for each participant. Since the delta distribution for the LMA group was not normally

distributed (Shapiro–Wilk test, $p = 0.048$), we used the Mann–Whitney *U* test for comparison between groups. As a control for statistical artifacts, we tested for potential serial dependence effects on future numerosity. The analyses were the same, but in this case, the data were sorted depending on whether the current numerosity was succeeded (not preceded) by a small ($N < 7$) or large ($N > 7$) numerosity.

We then investigated whether history effects were predicted by participants' numerical estimation precision or their VSWM. To explore the relationship with VSWM, we first converted the span measures from both the backward and forward conditions into z-scores, using the mean and standard deviation of the entire sample. We then averaged the z-scores from these two conditions to derive a composite VSWM score. We applied Spearman's correlation analyses to investigate the associations of central tendency index and delta 1-back with CV and VSWM scores. We chose non-parametric Spearman's correlations because the central tendency index distribution (Shapiro–Wilk test, $p < 0.001$) and the delta distribution (Shapiro–Wilk test, $p = 0.025$) for the entire sample significantly deviated from normality.

Individuals with HMA may respond more slowly than those with LMA, leading to prolonged memory retention, which, according to the WM account, could increase susceptibility to stimulus history bias. To test this possibility, we compared reaction times between the two groups, focusing on numerosities between 5 and 12 to maintain consistency with the rest of the analyses. Since reaction times in the HMA group were not normally distributed (Shapiro–Wilk test, $p = 0.033$), we used a Mann–Whitney *U* test for this comparison.

We next investigated whether MA contributed to explaining the variability of history effects over and above sensory precision by correlating central tendency index and delta 1-back with AMAS scores using Spearman's partial correlation analysis, controlling for CV.

Finally, to investigate the relationship between serial dependence and central tendency, we performed a Spearman's correlation between central tendency index and delta 1-back. Significance of null correlations was assessed using both *p*-values and Bayes Factor [81], defined as the ratio of the likelihood of the alternative hypothesis (H_1: presence of a correlation) to that of the null hypothesis (H_0: no correlation). According to conventional interpretation, a logarithmic Bayes Factor ($\log_{10}BF$) > 0.5 is considered substantial evidence for the presence of a correlation, whereas $\log_{10}BF < -0.5$ indicates substantial evidence for its absence. Statistical analyses were performed using JASP (RRID: SCR_015823, version 0.19, JASP Team 2024) and MATLAB (RRID: SCR_001622, version R2021b, The MathWorks, Inc.). Notably, all results remained consistent when considering the full numerosity range (2–15).

Abbreviations

CV	Coefficient of variation
HMA	High math anxiety
LMA	Low math anxiety
MA	Math anxiety
VSWM	Visuo-spatial working memory
WM	Working memory

Acknowledgements
We thank Prof. Paola Binda for providing thoughtful comments to this study.

Authors' contributions
Conceptualization: I.B., E.C., P.M.M., G.A. Methodology: I.B., E.C., P.M.M., G.A. Investigation: I.B., P.M.M. Formal analysis: I.B., E.C. Writing original draft: I.B., E.C. Reviewing: I.B., E.C., P.M.M., G.A. All authors read and approved the final manuscript.

Funding
This research was funded by the European Union—Next Generation EU (PRIN 2022, Project 'RIGHTSTRESS—Tuning arousal for optimal perception', Grant no. 2022CCPJ3J, CUP: B53D23014530001) and by the European Union (EU) and Horizon 2020—grant agreement no. 832813—ERC Advanced 'Spatio-temporal mechanisms of generative perception—GenPercept'.

Data availability
All data generated or analysed during this study are included in this published article, its supplementary information files and publicly available repositories. The dataset supporting the conclusions of this article is available in the Zenodo repository at https://doi.org/10.5281/zenodo.16903606 [82].

Declarations

Ethics approval and consent to participate
Written informed consent was obtained from all participants before testing. The research was approved by the local ethics committee ("Commissione per l'Etica della Ricerca", University of Florence, 7 July 2020, No. 111).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 9 May 2025 Accepted: 15 September 2025
Published online: 14 October 2025

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