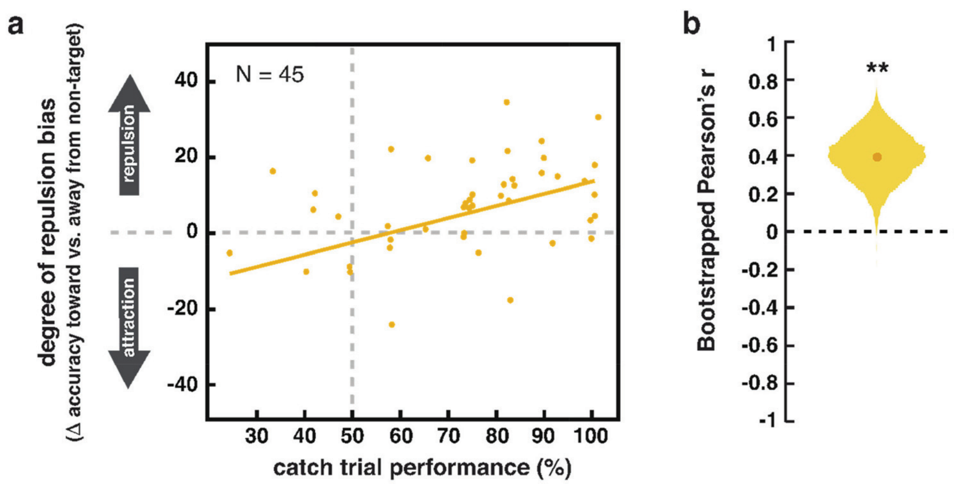
Appendix

Additional Data and Analyses of "An Adaptive Perspective on Visual Working Memory Distortions"

Figure A1

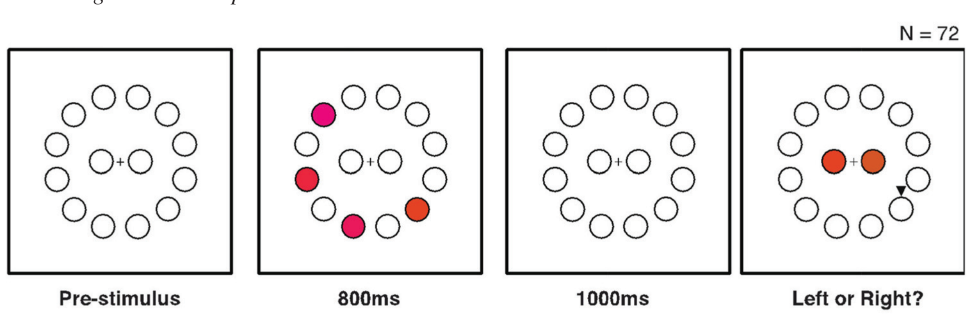
Results From a Control Experiment (N = 45) Replicating Experiment 2



Note. In this experiment, only foils distorted by 6° relative to the correct color were used (towards and away from the nontarget—similar to Experiment 1), while we also included 10% of catch trials (similar to Experiment 2). Participants were an entirely new and independent set of 45 naïve Amazon mechanical Turk workers. (a) The degree of repulsion bias (indexed as the difference in accuracy between trials with foils distorted toward, and trials with foils distorted away from the nontarget color), plotted against people's general level of engagement with the memory task (indexed by performance on catch trials). Each dot represents a single subject. These data demonstrate stronger biases away from the nontarget color in participants with higher levels of task engagement. (b) We bootstrapped the data in (a) 5,000 times: On each bootstrap we sampled 45 subjects with replacement, and recalculated the correlation between repulsion bias and general task engagement. This gives a distribution of bootstrapped Pearson's *r*, which is depicted in the violin plot. The dot in the middle indicated the mean bootstrapped correlation ($r = 0.39$). The double asterisks indicate a *p*-value of $p < .01$. See the online article for the color version of this figure.

Figure A2

Task Progression in Experiment 3



Note. Participants had to remember a set of four colors (shown at randomly selected locations from a set of 12 possible locations, with at least one empty placeholder between items). The four colors were presented for 800 ms, after which participants remembered them during a 1-s memory delay. Subsequently, participants saw a location cue (triangle) indicating which memory item to respond to, as well as two response options presented directly left and right of fixation. Participants chose between the correct (cued) color and a foil color. See the online article for the color version of this figure.

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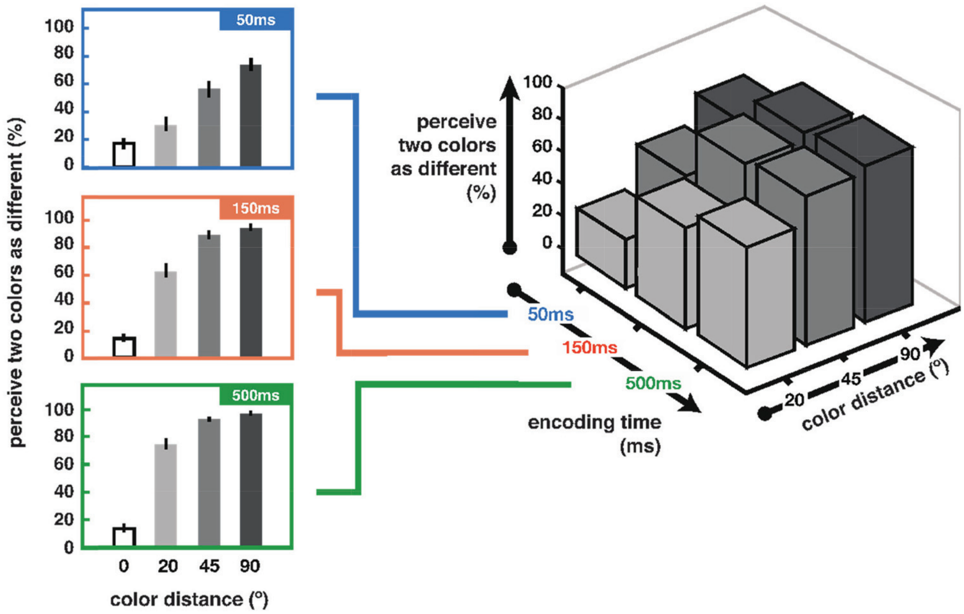
Figure A3

Results From a Same-Different Color Discrimination Task as a Control for Experiment 4



Note. This control experiment probed whether two colors can or cannot be perceptually discriminated at various encoding times and color distances: Two colors that were either exactly the same (50% of trails) or differed by 20°, 45°, or 90° in CIE l*a*b* color space (50% of trials) were simultaneously presented for either 50 ms (blue), 150 ms (orange), or 500 ms (green). Participants on Amazon Mechanical Turk (18 in total) reported whether the two colors were the same or different. Each participant completed 90 trials in total. The 3D bar plot (right) shows accuracy as a function of encoding time and color distance. Repeated-measures ANOVA's demonstrate both main effects of encoding time, $F(2, 34) = 36.7$, $p < .001$; color distance, $F(3, 51) = 212.5$, $p < .001$); and an interaction, $F(6, 102) = 9.32$, $p < .001$). This means that participants could not tell two colors apart when they were presented very briefly and were very similar to one another (i.e., encoding time of 50ms and color distance of 20°). The inability of subjects to tell two very similar colors apart at very short encoding times explains why repulsion biases were not found in these extreme cases. See the online article for the color version of this figure.

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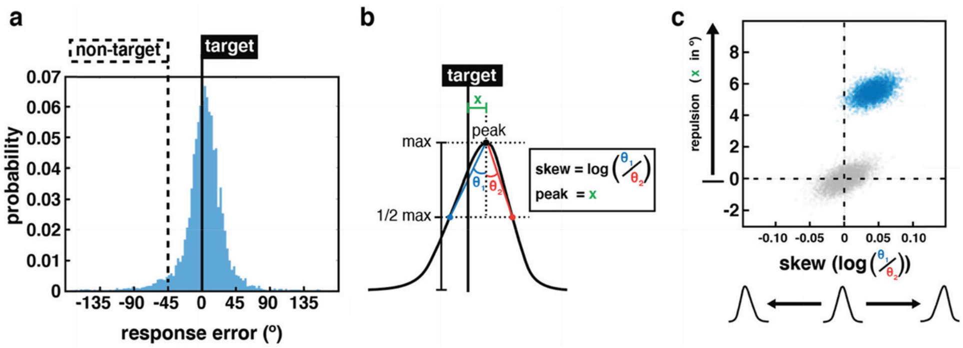
Figure A4

Asymmetry of Experiment 4 Error Distributions



Note. (a) An example error distribution from all 24 participants combined, in the condition showing the strongest repulsion bias (i.e. encoding time of 150 ms and color distance of 45°). First, note how the peak of the error distribution is not aligned with the cued color, but instead is shifted away from the nontarget color. Second, note how the shape of the distribution is asymmetrical, with the side away from the nontarget being steeper. (b) Due to the possible presence of nontarget responses (i.e. where a subject mistakenly reports the color of the nontarget instead of the target), we did not wish to measure skewness using circular skewness measures on the raw response distribution. Instead, we first derived a kernel density estimator (KDE). The peak of the distribution (x) was defined as the degree of error with maximum probability. The skewness was defined by the log ratio between the angle toward (θ_1) versus away (θ_2) from the nontarget color at half maximum height of the KDE ($\log(\theta_1/\theta_2)$). (c) A scatter plot showing the relationship between skew and peak. Each dot represents skew and peak on one bootstrapping iteration (of 5,000 total iterations) calculated by randomly resampling the data from 24 participants with replacement (data from the condition shown in (a). The horizontal zero line represents scenarios with no shift in the distribution peak, while the vertical zero line represents scenarios without any skew (thus, the 0,0 point represents a perfectly symmetrical distribution). We found both a systematic shift of the peak ($p < .001$ from bootstrapping) as well as skew ($p < .01$ from bootstrapping). Furthermore, the shape of the dot cloud shows that stronger repulsion is associated with a stronger skew ($r = 0.45$; $p < .001$). To test the validity of the metrices, we reanalyzed the same data with randomized signed errors and plotted in gray color. The randomized signed errors distribution centers at zero in both skew (x-axis) and bias (y-axis) suggesting that the significant bias and skew were not spurious. See the online article for the color version of this figure.

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Figure A5

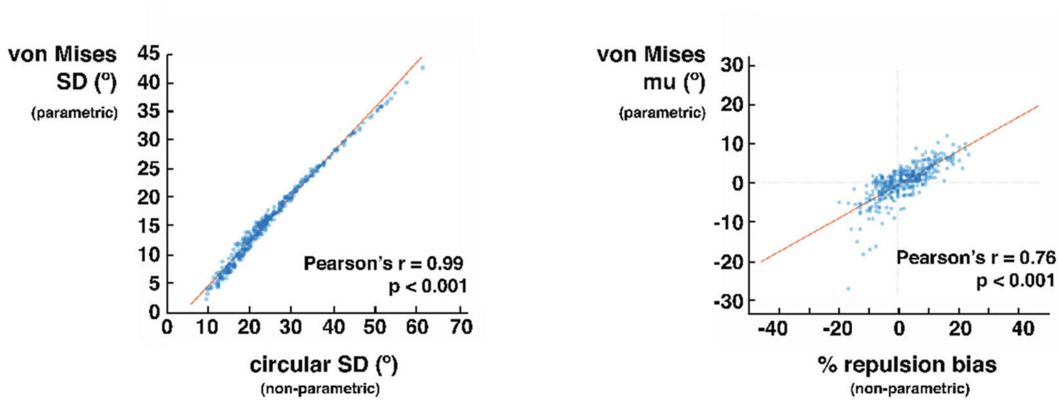
Parametric Versus Nonparametric Quantifications of Memory Precision and Bias in Experiment 4

von Mises SD

encoding time (ms)	color distance (°): 0	20	45	90	135
50	11.64 (± 0.57)	15.38 (± 0.44)	18.31 (± 0.52)	19.97 (± 0.61)	21.45 (± 0.64)
150	10.14 (± 0.72)	13.04 (± 0.54)	16.82 (± 0.50)	20.68 (± 0.48)	20.56 (± 0.68)
500	7.62 (± 0.59)	10.89 (± 0.66)	13.80 (± 0.69)	18.07 (± 0.66)	18.58 (± 0.80)

von Mises mu

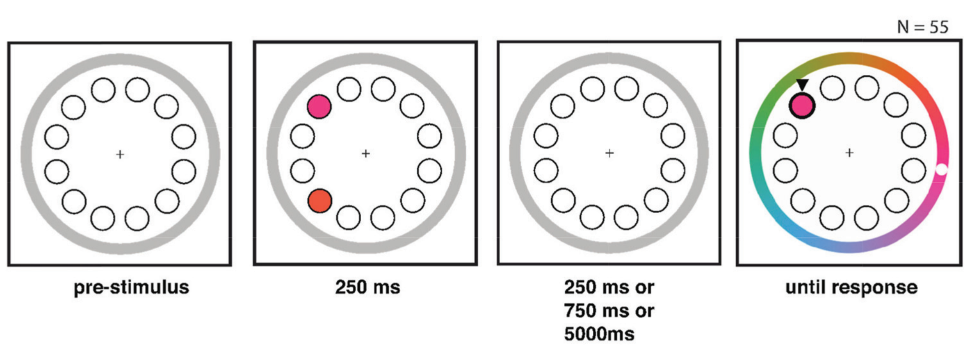
encoding time (ms)	color distance (°): 0	20	45	90	135
50	-0.46 (± 0.63)	-0.59 (± 0.81)	3.51 (± 0.61)	-0.81 (± 0.66)	-2.06 (± 0.87)
150	1.01 (± 0.66)	1.37 (± 0.62)	2.79 (± 0.61)	-0.02 (± 0.64)	-1.04 (± 0.80)
500	-0.21 (± 0.56)	2.04 (± 0.49)	1.21 (± 0.57)	-1.41 (± 0.61)	-0.90 (± 0.70)



Note. For this experiment we nonparametrically quantified memory precision as the circular standard deviation (with smaller standard deviations indicating higher precision) and we quantified biases as the difference in the percentage of responses that were toward vs. away from the nontarget color (with a negative bias indicating attraction, and positive bias indicating repulsion). To validate these measures, we also parametrically fit the data using a von Mises distribution with two independent parameters to reflect memory precision (vmSD) and bias (mu). We found a high agreement between parametric versus nonparametric measurements (Pearson's r = 0.99 and 0.76, for precision and bias, respectively; both $p < .001$). The correspondence between these measures is shown in the scatter plots at the bottom of this figure. Furthermore, we repeated our statistical analyses with the parametric von Mises parameter estimates (tables in the top of this figure), showing significant differences in memory precision as a function of encoding time, $F(2, 46) = 13.7$, $p < .001$; color distance, $F(4, 92) = 21.09$, $p < .001$); and an interaction, $F(8, 184) = 3.76$, $p < .001$. The repulsion bias is marginally impacted by encoding time, $F(2, 46) = 3.08$, $p = .056$, significantly impacted by color distance, $F(4, 92) = 9.54$, $p < .001$) and there is a significant interaction, $F(8, 184) = 2.66$, $p < .01$. Note that the mixture modeling assumes that the error distribution follows a symmetric circular distribution. However, the true error distributions were skewed which makes it less accurate in estimating the true biases and the memory strengths. See the online article for the color version of this figure.

Figure A6

Task Sequence in Experiment 5



Note. Two color stimuli were presented for 250 ms, and the color distance between the two items was fixed at 45°. The memory delay period was either 250 ms, 750 ms, or 5,000 ms. After the delay, participants were cued to report one of the two memory items with an arrow cue, and they moved a white dot along a continuous color-wheel to choose the color that matched their memory as closely as possible. For clarity, the gray circle and color-wheel are shown wider here than they were presented during the actual experiment. See the online article for the color version of this figure.

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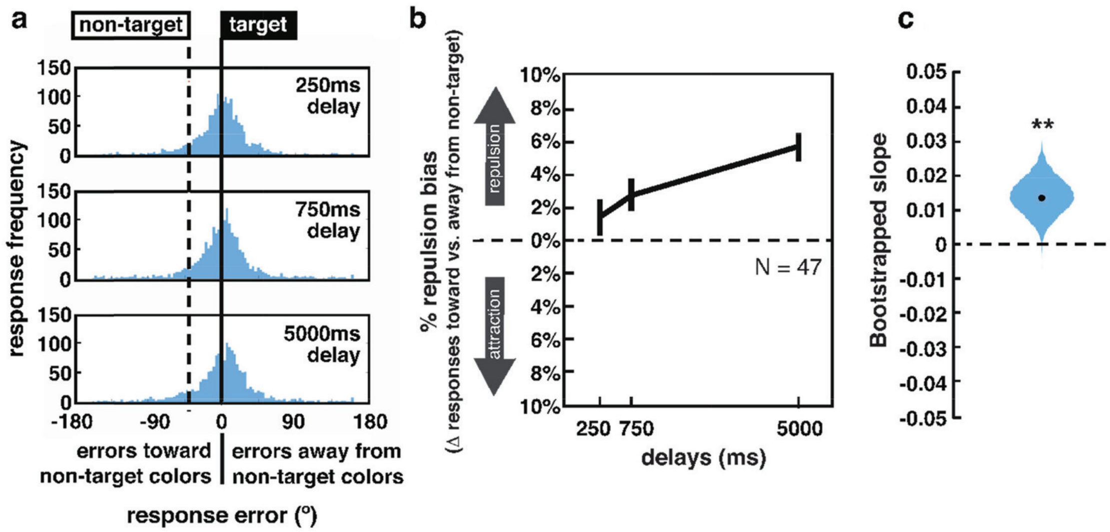
Figure A7

Results From a Control Experiment (N = 47) Replicating the Finding From Experiment 5 That Memory Biases Increase With Longer Delays



Note. Here, we collected 36 trials per condition per subject (a total of 108 trials per subject). (a) Error distributions at each delay, revealing a high number of responses biased away from the nontarget. (b) The quantified repulsion bias (i.e. percentage of responses away from the nontarget color) shows that repulsion grew monotonically stronger as the delay duration increased (1.4%, 2.7%, and 5.6% for delays of 250 ms, 750 ms, and 5,000 ms, respectively; $F(1, 46) = 6.62$, $p = .013$). Error bars represent ± 1 within-subject SEM. (c) To assess the increase of repulsion bias with delay, one can fit a line through the three points in (b) and calculate the slope—a positive slope indicates repulsion bias growing as a function of delay duration. Shown here is a distribution plot of bootstrapped slopes (5,000 iterations of resampling with replacement). The double asterisk indicates $p < .01$ confirming a statistically robust effect. See the online article for the color version of this figure.

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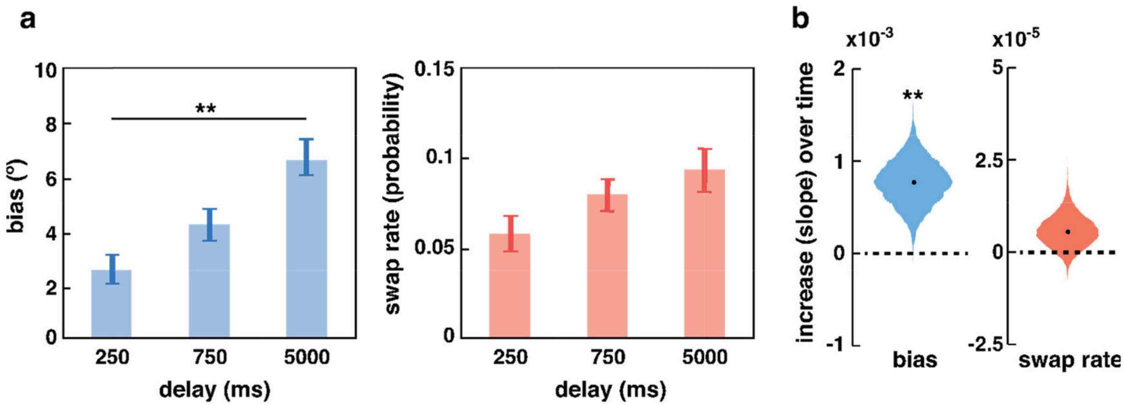
Figure A8
Results of Fitting a Mixture Model With Biases and Swap Errors in Experiment 5



Note. (a) Fitting a mixture model with swap errors to the data in Experiment 5 confirms that repulsion bias grows stronger with longer delay intervals (blue; $F(1, 54) = 10.2$; $p = .002$), confirming what we found with our nonparametric repulsion bias measure. The frequency of swap errors did not significantly change across time (red; $F(1, 54) = 1.87$; $p = .178$). (b) We computed slopes of bias and swap errors as a function of time—positive slopes indicating an increased repulsion or swap rate over time. We evaluated significance by resampling with replacement 10,000 times. Repulsion bias grew significantly stronger as the delay interval increased (blue), replicating our findings using a nonparametric bias measure. Swap errors did not increase significantly as the delay interval increased. These results suggest that the increase in repulsion bias that we found when using either parametric or nonparametric methods cannot be explained by a reduction in swap errors (if anything, swap errors increase with delay, numerically). The double asterisk indicates $p < .01$. See the online article for the color version of this figure.

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