Short Report

PERCEPTION

# Repulsive Serial Effects in Visual Numerosity Judgments

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**Abstract**
We investigated how the approximate perceived numerosity of ensembles of visual elements is modulated by the numerosity of previously viewed ensembles depending on whether the first ensemble is held in visual working memory or not. We show that the numerosity of the previously seen ensemble has a repulsive effect, that is, a stimulus with high numerosity induces an underestimation of the following one and vice versa. This repulsive effect is present regardless of whether the first stimulus is memorized or not. While subtle changes of the experimental paradigm can have major consequences for the nature of interstimulus dependencies in perception, generally speaking the fact that we found such effects in a visual numerosity estimation task confirms that the process by which human observers produce estimates of the number of elements bears analogies to the processes that lead to the perception of visual dimensions such as orientation.

**Keywords**
adaptation, numerosity, sequential effects, visual working memory

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## Introduction

Human observers are able to visually estimate the numerosity of ensembles of elements when the number of elements and the time available make counting impossible (e.g., Barth, Kanwisher, & Spelke, 2003; De Marchi, 1929; Dehaene, 2011). Estimates of numerosity can be encoded as approximate quantities, akin to other magnitude estimates (e.g., Meck & Church, 1983). Similar to perceptual attributes, the precision of the encoding tends to decrease as a function of magnitude (e.g., Anobile, Cicchini, & Burr, 2014; Whalen,

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Gallistel, & Gelman, 1999) and can be integrated optimally across saccades (Hübner & Schütz, 2017) and the encoding is topographical in parietal cortex (Harvey, Klein, Petridou, & Dumoulin, 2013). Furthermore, the finding that the perceived numerosity of arrays of stimuli viewed in the periphery seems to be affected by crowding (Anobile, Turi, Cicchini, & Burr, 2015; Valsecchi, Toscani, & Gegenfurtner, 2013) indicates that the individuation of the ensemble elements leads to numerosity perception. It has been suggested that numerosity can be sensed directly (e.g., see Anobile, Cicchini, & Burr, 2016) based on the fact that perceived numerosity can be adapted, similar to other visual attributes (Burr, Anobile, & Arrighi, 2018; Burr & Ross, 2008; Durgin, 1995; Zimmermann, 2018).

Multiple studies in recent years have begun to highlight the fact that perception is influenced by the recent and quite remote history of stimulation in ways which go beyond simple adaptation, particularly in the case of ambiguous stimuli (e.g., Harrison & Backus, 2014; see Scocchia, Valsecchi, & Triesch, 2014). One of the crucial findings in this respect is that when human observers are asked to repeatedly perform perceptual judgments within a stable environment, they tend to use the information from previous trials to inform the current judgment (Cicchini, Anobile, & Burr, 2014; Fischer & Whitney, 2014). This is evidenced by the observations that perceptual estimates converge toward the center of the range of stimuli which the observer is exposed to (e.g., Jazayeri & Shadlen, 2010; Olkkonen, McCarthy, & Allred, 2014). Repeated judgments of numerosity have also been reported to be positively correlated (Corbett, Fischer, & Whitney, 2011). More relevantly to the current study, Fornaciai and Park (2018) recently showed that the perceived numerosity of an ensemble of dots can be attracted toward the one of a previously viewed ensemble, even if the observers are required to ignore it.

Contrary to adaptation, which by definition implies a negative correlation between previous stimulation and perception, the pooling of information across trials tends to generate positive correlations. These two apparently contradictory phenomena might in fact coexist, as has been shown by Chopin and Mamassian (2012). They found both positive and negative correlation between previously experienced orientations and perceived orientation depending on the intervening time. Attraction and repulsion can also influence perception at different stages. A recent study by Fritsche, Mostert, and de Lange (2017) showed that judgments of perceived orientation can be attracted toward the previously seen stimulus if tested by means of a reproduction task and repelled if tested by means of a comparative judgment, possibly suggesting that repulsive effects emerge in working memory (WM).

The idea that positive biases can emerge in WM during perceptual decisions is compatible with previous findings showing that the contents of WM can bias the way stimuli presented during the retention period are perceived. The nature of the bias is, however, dependent on the specific perceptual phenomenon which is evaluated. While the perceived orientation of a stimulus is repelled from the orientation of a stimulus which is currently being held in WM (Scocchia, Cicchini, & Triesch, 2013), in the case of bistable structure-from-motion, the direction of the memorized stimulus was promoted compared to the opposite interpretation (Scocchia, Valsecchi, Gegenfurtner, & Triesch, 2013). Mixed results have been reported in the case of binocular rivalry (Gayet, Brascamp, Van der Stigchel, & Paffen, 2015; Scocchia, Valsecchi, Gegenfurtner, & Triesch, 2014).

In this study we investigate how the recent stimulation history and the contents of WM affect perceived numerosity. The approach of this study is similar to the one of previous reports (Scocchia, Cicchini et al., 2013; Scocchia, Valsecchi et al., 2013; Scocchia, Valsecchi, Gegenfurtner et al., 2014), with the main difference that our observers were trained to compare the numerosity of the test stimulus with an arbitrary reference numerosity.

Different groups of observers were asked to either memorize or ignore the first stimulus which was presented in a trial and to judge the numerosity of the second. We did not observe any specific effect due to WM, and our results indicate that perceived numerosity was repelled from the numerosity of the previously viewed stimulus, that is, we observed adaptation-like effects, independently of whether the first stimulus was memorized or not.

# Methods

## Observers

Thirty-three students (mean age 25.4, 20 women) from the Justus-Liebig-Universität Giessen volunteered for participation in the study in exchange for 8€/hour. Nineteen observers were tested in the Memory group, although the data from one observer were discarded because they were not able to perform the memory task over chance and 14 observers were tested in the Ignore group. We planned to interrupt data collection for each group after a minimum of 12 observers were tested and as soon as the bidirectional Bayes Factor for the effect of the first stimulus ($BF_{10}$), computed with a Cauchy prior and an r-scale of .707, reached a value of 5 or 1/5 (Schönbrodt, Wagenmakers, Zehetleitner, & Perugini, 2017). All participants were naïve as to the purpose of the study and provided written informed consent in agreement with the Declaration of Helsinki. The study protocol was approved by the local ethics committee at the University of Giessen (LEK FB6 2017-08).

## Stimuli

Stimuli were circular arrays of dots, white (108 $cd/m^2$) and black (0.16 $cd/m^2$) in equal proportion, presented over a gray (53.4 $cd/m^2$) background. The diameter of the single dots was 0.24°, whereas the diameter of the dot array was 13.7°. The minimum allowed distance between the centers of any two dots was 0.28°.

Stimuli were generated with Matlab (MathWorks, Natick, MA) and the PsychToolbox (Brainard, 1997) and displayed on an Eizo ColorEdge CG245W monitor (22 inches, 1,920 × 1,200 pixels resolution, 60 Hz refresh rate). Participants sat at about 40 cm from the computer screen, with their head placed on a chin rest.

## Experimental Procedure

*Numerosity judgments.* The trial structure in the different conditions is described in Figure 1. In all cases, the trial involved a numerosity judgment whereby the observers viewed an array of dots for 200 ms and had another 2,800 ms of time in order to report whether the numerosity of the dots was larger or smaller than 100 by pressing the up or down arrow key. Observers were trained on the numerosity task in a presession where they did not perform any other task and were given feedback after each trial as to whether their judgment was correct or wrong and about the correct number of elements. The training was interrupted after at least 70 trials and when the observer proved to be correct 12 times in a row of 15. The stimuli were generated from a Gaussian distribution with mean 100 and standard deviation 30.

Despite the training, pilot data indicated that observers had relatively large individual differences in their subjective 100-element-equivalent numerosity (e.g., De Marchi, 1929). For this reason, the numerosity of the test stimulus presented in each trial was chosen based on an adaptive staircase method similar to the one used by Valsecchi and Gegenfurtner (2016). The algorithm was initialized with a sample of 100 simulated trials which yielded

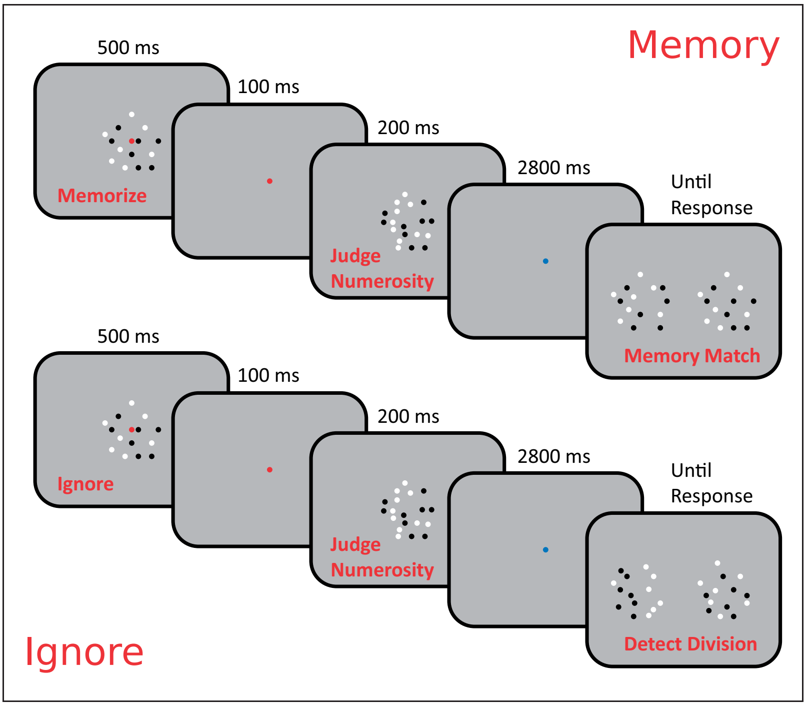


**Figure 1.** Experimental procedure for both groups. The Memory observers memorized the first dot pattern for a later match-to-sample (they had to indicate whether the left or the right pattern matched the memory sample, right in this example). The Ignore observers ignored the first stimulus and indicated which of the two final arrays had a horizontal division between black and white dots (left in this example). The numerosity judgment (larger or smaller than 100) had to be completed before the appearance of the display with two arrays. Stimuli are not drawn to scale.

a mean of 100 when fitted with a Gaussian Cumulative Distribution Function (cumulative distribution function [CDF]) using the Psignifit Toolbox (Schütt, Harmeling, Macke, & Wichmann, 2016). As the experimental session proceeded, the simulated trials were progressively substituted with the responses provided by the observers, so that by the 100th trial the stimulus was only based on the observers' own responses. The numerosity in each trial was randomly sampled from the probability distribution function (PDF) corresponding to the CDF fitted on the 100 trial sample. Note that the 100-element-equivalent numerosity measure is *inversely* related to perceived numerosity. If in a given condition perceived numerosity increases, a lower number of elements is sufficient to generate the subjective impression of a 100 element array.

*Memory group.* Observers performed the numerosity judgment during the retention phase of a memory task (Figure 1). They memorized an array of dots at the beginning of the trial for later recognition in a two-alternative forced-choice, match-to-sample task. The initial presentation lasted 500 ms and the Inter Stimulus Interval (ISI) between the memory array and the numerosity judgment array was 100 ms. For the match-to-sample task, the observers were shown two arrays of dots, to the left and to the right side of the screen. One of the two arrays was identical to the memorized one, and the other had the same numerosity, but a subset of the points was randomly rearranged. The proportion of dots being rearranged was also individually titrated aiming at achieving 75% correct performance. The proportion in individual trials was generated from the Gaussian PDF corresponding to the CDF fitted on the observer's accuracy as a function of array similarity. Observers were informed that the two options differed by the position of a subset of points and that the difficulty of the task would vary between trials.

*Ignore group.* Observers were advised to ignore the first stimulus and to identify which of the two arrays of dots in the final display had a horizontal division between black and white dots. The proportion of dots segregated between the two halves of the divided stimulus was individually titrated aiming at achieving 75% correct performance, once again using the Gaussian PDF corresponding to the CDF fitted on the observer's responses. Observers were encouraged to base their judgments on their overall impression and not to engage in counting the black and white dots.

*Adaptation manipulation.* The numerosity of the first dot array which was presented in each trial could be low or high, where low and high were defined as 50% and 150%, respectively, relative to the current estimate of the subjective 100 element-equivalent numerosity. This implies that the actual numerosities used for the initial arrays were neither constant across observers, nor were they constant across trials, nor were they proportional to the exact numerosity of the test array which was presented in a given trial. This ensured that the first array numerosity was not informative relative to the second array numerosity.

*Experimental design.* As mentioned earlier, the Memory and Ignore conditions were tested in two different groups of observers. Testing was conducted over 200 trials, where the first array numerosity (50% or 150%) was counterbalanced and randomly interleaved. Consequently, all of the PSEs were computed from psychometric curves obtained from samples of 100 trials. Observers took 45 to 60 minutes to complete the experimental session and the preceding training procedure.

## Results

Inspecting the subjective 100-element-equivalent numerosity, that is, the numerosity of the arrays which yielded equal probability of being judged as smaller or larger than 100 (Figure 2) reveals that, despite the considerable interindividual differences and in both groups, observers judged higher array numerosities to be equivalent to 100 if they were exposed to a large array at the beginning of the trial, compared to the trials where the initial array was small. This indicates that being exposed to a large array at the beginning of the trial decreases the perceived numerosity of a stimulus presented later on. The exact value of the Bayes $\text{Factor}_{10}$ was 5.275 for the Memory group and 5.269 for the Ignore group. Being exposed to a first stimulus with large numerosity produced an increase in the subjective 100-equivalent numerosity from 99.7 units to 113.7 units, that is, 13.1% of the average value.

## Discussion

Two main results emerged from our study:

(1) The perceived numerosity of a dot array was repelled from the numerosity of a stimulus presented directly before its onset.

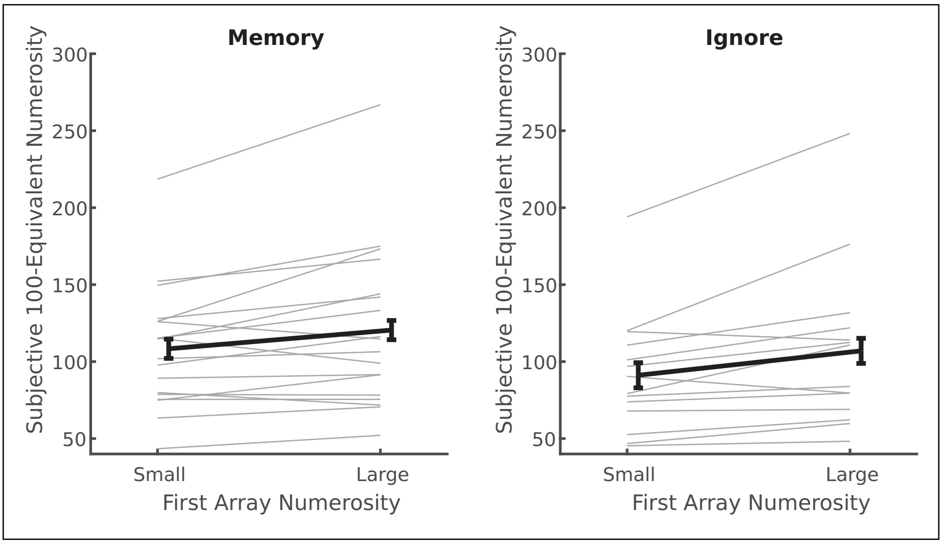


**Figure 2.** Subjective 100-element-equivalent numerosity in the Memory and Ignore groups, as a function of First Array Numerosity. Average data and 95% confidence intervals (Morey, 2008) are plotted as thick lines and individual data as thin lines. Subjective 100-element-equivalent numerosity was consistently larger in both groups when the numerosity judgment array was preceded by a large array, as compared to the case where a small array preceded it, indicating that being initially exposed to a large array, independent of whether it was memorized, caused the subsequently presented array to be perceived as relatively less numerous.

(2) This repulsive effect occurred regardless of whether the stimulus was encoded for storage in WM or ignored.

The evidence concerning whether, and under what conditions, repulsive or attractive effects of recent stimulation dominate perception is not univocal. As we mentioned, Chopin and Mamassian (2012) found that orientations presented up to a few dozen trials before produced a negative tilt aftereffect, that is, a repulsive effect akin to ours, whereas the effect was positive for stimuli presented even further back in time. Similarly, Mattar, Kahn, Thompson-Schill, and Aguirre (2016) reported short-term adaptation-like and long-term pooling-like intertrial effects for face perception, again compatible with our findings. Our findings, however, appear in contradiction with the results of Fischer and Whitney (2014), who showed attractive effects for subsequent orientation stimuli. Part of the discrepancy might be explained by their use of longer stimulus onset asynchronies and fainter inducing stimuli, which might have avoided adaptation-like effects, but another difference between our two paradigms is that Fischer and Whitney (2014) measured perception with an adjustment task or with a simultaneous orientation comparison, whereas we used a comparison against a memorized standard. Using full-contrast stimuli might also have reduced the sensory uncertainty about numerosity, which is a determinant of positive serial dependencies (Cicchini et al., 2014). Finally, the difference in numerosity between the inducing and test stimuli might have been too large to trigger serial continuity (Anobile et al., 2014; Fischer & Whitney, 2014).

In principle, one could suggest that the inconsistency between our results and the ones of the previous studies which reported attractive sequential effects in orientation and face perception is due to numerosity perception being a fundamentally different phenomenon, but attractive effects have been reported recently in numerosity judgments as well (Fornaciai & Park, 2018). We suspect that the most relevant difference between our paradigm and the one by Fornaciai and Park (2018), aside from the slightly different timing of the stimuli, the fact that we used generally lower numerosities and the fact that our elements had mixed polarity and theirs did not, is the way numerosity was measured. In our paradigm, the observers immediately judged the numerosity of the test stimulus by comparing it with a memorized standard. In their paradigm, the observers had to encode the numerosity of the test stimulus in order to later compare it with a probe stimulus. Generally speaking, we believe future studies should investigate whether using stimuli of shorter duration and of lower contrast can change the sign of the sequential effects in numerosity perception, although it is clear that adaptation-like effects can be generated with very brief stimuli (Aagten-Murphy & Burr, 2016). Other open questions are the role of retinotopic overlap and item similarity.

The overall pattern of results becomes even more complicated if we consider studies that directly tested the effect of stimuli held in WM. Repulsive effects, enhanced by WM, have been reported in the case of orientation judgments (Scocchia, Cicchini et al., 2013). At the same time, the tilt aftereffect enhancement due to the coherence in orientation between WM content and inducer, which was observed by Saad and Silvanto (2013), is suggestive of an attractive effect which extends to an inducer presented immediately after the retention period. Our result that the numerosity of a stimulus has repulsive effects on the perceived numerosity of the next stimulus is partially coherent with the findings of Scocchia, Cicchini, et al. (2013) in the domain of orientation, although WM in our case did not seem to play a crucial role. However, note that in this study observers did not memorize the specific dimension which was evaluated during the retention period, whereas Scocchia, Cicchini, et al. (2013) had their observers both memorize and judge the orientation of the stimuli. There is evidence that when the visual attributes which are memorized and tested are as separate as shape and color, the biasing effect of WM contents might vanish (Gayet et al., 2015), and visual features which are not explicitly task-relevant are not encoded in early visual areas (Serences, Ester, Vogel, & Awh, 2009). The fact that the negative sequential effect is present in both groups, however, indicates at least that the level of attention associated with encoding the stimulus for later recognition is not crucial, which in turn might suggest that the encoding of numerosity is largely automatic.

In summary, our results confirm that human observers treat numerosity like other visual dimensions, given that stimulus history can bias numerosity judgments not unlike orientation judgments. This, however, does not imply that the effect of stimulus history is straightforward. In fact, findings from other studies in the literature show that both attractive and repulsive effects can be generated depending on the exact characteristics of the stimuli and the way numerosity is tested.

## Declaration of Conflicting Interests

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