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Brief article

Adaptation to number operates on perceived rather than physical numerosity

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ABSTRACT

Humans share with many animals a number sense, the ability to estimate rapidly the approximate number of items in a scene. Recent work has shown that like many other perceptual attributes, numerosity is susceptible to adaptation. It is not clear, however, whether adaptation works directly on mechanisms selective to numerosity, or via related mechanisms, such as those tuned to texture density. To disentangle this issue we measured adaptation of numerosity of 10 pairs of connected dots, as connecting dots makes them appear to be less numerous than unconnected dots. Adaptation to a 20-dot pattern (same number of dots as the test) caused robust reduction in apparent numerosity of the connected-dot pattern, but not of the unconnected dot-pattern. This suggests that adaptation to numerosity, at least for relatively sparse dot-pattern, occurs at neural levels encoding perceived numerosity, rather than at lower levels responding to the number of elements in the scene.

1. Introduction

Even under conditions where we cannot count individual items, we can make rapid and reasonably accurate estimates of the number of items or *numerosity* of a scene. This capacity has been demonstrated in young infants and many animal species (Butterworth, 1999; Dehaene, Spelke, & Pica, 2008; Hauser, Carey, & Hauser, 2000; Pepperberg, 2006; Whalen, Gallistel, & Gelman, 1999; Xu & Spelke, 2000, Gallistel & Gelman, 1990). It has recently been shown that perception of numerosity is susceptible to adaptation: adapting to stimuli of high-numerosity causes a noticeable underestimation of a subsequent stimulus, while adapting to low numerosities causes overestimation (Burr & Ross, 2008). Adaptation is one of the more powerful techniques in psychophysics, usually regarded as strong proof for the existence of specialized neural mechanisms.

However, the idea that adaptation reveals specific numerosity mechanisms has been challenged (Durgin, 2008), with suggestions that the adaptation occurs via more general texture-like mechanisms. It is well known that size and texture are subject to adaptation (Anstis, 1974; Blakemore & Sutton, 1969); so adaptation to clouds of dots may be mediated via this indirect route (Durgin, 1995, 2008; Durgin & Huk, 1997; Durgin & Proffitt, 1996). One crucial distinction between numerosity and density is that numerosity perception seems to require the prior segmentation of elements in perceptual objects (Anobile, Cicchini, & Burr, 2015; Anobile, Turi, Cicchini, & Burr, 2015). One clear demonstration of this is that connecting pairs of items reduces perceived numerosity (Franconeri, Bemis, & Alvarez, 2009; He, Zhang, Zhou, & Chen, 2009: see Fig. 1a). Connecting elements with a line presumably links them perceptually, so they tend to be seen as a single object, rather than pairs of objects. Not only does this change the perceived numerosity, but also the selectivity of repetition BOLD adaptation (He, Zhou, Zhou, He, & Chen, 2015). Interestingly, underestimation also occurs when dots are arranged in a specific configuration (such as a symmetrical pattern) (Apthorp & Bell, 2015), indicating that that perceptual organization – i.e. detection of symmetry and redundancies, in this case – precedes number estimation.

Here we test whether adaptation acts upon perceived or physical number. We measure the effect of adapting to 20 dots, then testing with patches of the same numerosity, either in isolation or connected pairwise. The adapter had no effect on the numerosity of unconnected dots, but robustly reduced that of pair-wise connected dots. This shows that adaptation operates on mechanisms for numerosity, rather than more basic visual features, like the number of dots.

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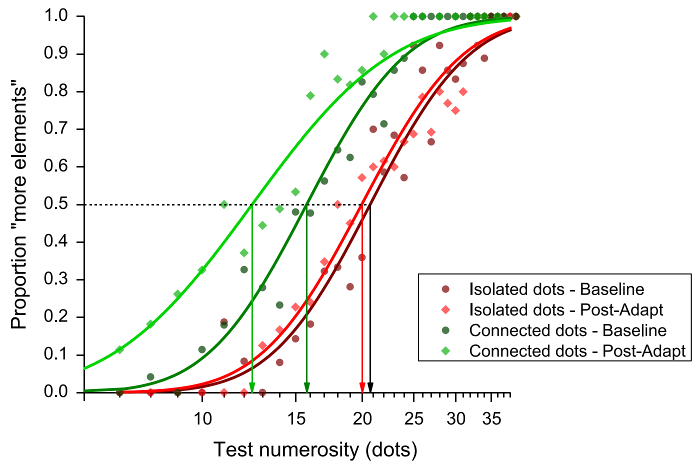

Fig. 1. Psychometric curves for numerosity discrimination. Average psychometric functions were obtained pooling data of all the participants, plotting the proportion of trials in which the test stimulus appeared more numerous than the reference. Dark red and dark green curves refer to the baseline conditions either with isolated dots (dark red) or with dots connected by lines (dark green). Light red and light green curves refer to the post-adaptation performances, for the isolated and connected dots conditions, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Subjects

Seven subjects (two authors and five subjects naïve to the purpose of the experiment) participated in all experiments. All subjects had normal or corrected-to-normal visual acuity, and gave an informed written consent. Experimental procedures were approved by the Tuscan ethics committee and are in line with the declaration of Helsinki.

2.2. Apparatus and stimuli

The experiment was performed in a quiet and dimly illuminated room. Subjects sat in front of a 23-in. LCD monitor (mod. Acer S231HL) subtending 51 × 29 degrees of visual angle, at a viewing distance of 57 cm. Stimuli were generated with the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) for MatLab (ver. 2010b, The Mathworks, Inc.). All stimuli were patches of random-dots, presented within a circular window of 12° diameter. Each dot was 0.4° diameter, randomly black or white. Dot positions were chosen randomly from trial to trial (for adaptors and reference stimuli), respecting the conditions that two dots could not be separated by less than 0.75°. Stimuli with connected elements were calculated offline from a standard dot pattern (generated as described above) by joining iteratively dots with their closest neighbour (minimum line length 0.75°). If any line crossed another or encroached within 0.75° of another dot, the lines were discarded and regenerated iteratively until an acceptable pattern was created. If no uncrossed line combination was possible (which occurred with less than 1% of stimuli), a fresh dot-pattern was drawn and the procedure recommenced.

Adaptors comprised 20 isolated dots, and were identical to the unconnected stimuli. Probe stimuli appeared in the same position of the adapter, reference stimuli appeared on the opposite side of the screen and were varied from trial to trial, following a QUEST routine (Watson & Pelli, 1983) homing in on the point of subjective equality of the numerosity of the adapted probe patch, with an added Gaussian jitter of 0.15 log-units. The final estimate of PSE was taken as the median of the best-fitting cumulative Gaussian function to all the data of a particular condition (percentage “more elements than” against test physical numerosity). As a measure of precision we use Just Noticeable Difference (JND), the standard deviation of the underlying Gaussian function.

Probe stimuli were of three types (Fig. 2a), depending on condition: (left) 20 unconnected dots; (centre) 10 pairs of connected dots; (right) Unconnected dots with numerosity chosen for each subject to appear equal to the perceived numerosity of the connected patch.

2.3. General procedure

Trials started with subjects fixating at a small red dot in screen centre. The adaptor stimulus was centred 12.7° left or right of fixation (varying randomly between session), presented for 20 s in the first trial of each experimental session, and for 6 s in subsequent trials to top-up the adaptation. Adaptors were followed by a 500 ms pause, and then probe at the same position of the adapter, together with the reference stimulus at an equal distance on the other side of fixation, were presented for 150 ms. At the end of each trial, subjects indicated which stimulus appeared to contain more elements (guessing if unsure) by pressing the appropriate key. For each subject and for each condition, we first performed a baseline measurement without adaptation. Each subject completed at least two blocks of 40 trials for each experimental condition. The different adaptation conditions were separated by breaks of at least 40–50 min.

3. Results

Fig. 1 reports average psychometric functions obtained pooling the data over the entire group of subjects, and plotting proportion of trials in which the test stimulus was judged as more numerous as function of numerosity of the test stimulus. Four conditions are shown: isolated dots baseline and adaptation, connected baseline and adaptation. The results of the isolated dot condition show that numerical estimates after 20-dot adaptation (red diamonds) do not differ from baseline (dark red circles). The psychometric functions are very similar, both estimating PSEs (points of subjective equality, the median of the curve) around 20 dots, the physical reference numerosity: adaptation does not affect a test stimulus with the same numerosity. However, adaptation does affect perceived numerosity in the connected-dots condition. In baseline, perceived numerosity of dots joined by lines is systematically underestimated, as shown by the rightward shift of the dark green curve.