To appear in *The Proceedings of the 45th Meeting of The Cognitive Science Society*. A much longer paper, containing 4+ additional experiments and an extended discussion of the motivations for our positive proposal, is in progress. Please get in touch if you would like to see a draft.

Do humans visually adapt to number, or just itemhood?

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Abstract

Visual number adaption is a widely accepted phenomenon. This paper advances an alternative explanation for putative cases of the phenomenon. We propose that such cases may simply reflect observers adapting to the items in perceived displays, rather than their numerical quantity. Three experiments motivate consideration of this novel proposal and call into question the evidential basis for received formulations of the number adaptation hypothesis.

Keywords: Number Sense; Visual Adaptation; Approximate Number System

Introduction

In a classic paper, Burr and Ross (2008) argue that humans visually adapt to number. They report that prolonged exposure to a large number of seen items at some location *l* causes a middling number of subsequently presented items at *l* to appear *less numerous*. Conversely, they report that prolonged exposure to a small number of items at *l* causes a middling number of items presented at *l* to appear *more numerous*.

These findings are widely interpreted as evidence that number is a "primary" visual attribute, akin to visual features like color and shape (Burr and Ross, 2008; Anobile et al. 2016; Block 2022). While there has been some pushback against these claims (see Dakin et al., 2011; Durgin, 2008), existing critiques focus primarily on confounds like density, which were subsequently ruled out in carefully controlled experiments (Desimone et al., 2020).

In fact, there are now many published reports of number adaptation (for review, see Anobile et al., 2016). Perhaps most striking are cases of *cross-modal* adaptation where adaptation to a large sequence of heard tones is reported to cause a middling number of seen items to appear less numerous, and vice versa (Arrighi et al. 2014). Importantly, cross-modal paradigms eliminate non-numerical confounds as the primary drivers of these effects. Given that cross-modal studies cannot be explained by the area or density of displays, or other low-level properties that are not shared across modalities, such studies seem to provide powerful evidence in favor of the number adaptation hypothesis.

How strong is the evidence for number adaptation?

Faced with such evidence, the existence of visual number adaptation might seem to be decisively established. But closer inspection reveals that matters are less clear-cut. For a start, it should be noted that even if cases of cross-modal number adaption are genuine, the effects in question lack the compelling perceptual phenomenology associated with Burr and Ross's original examples (compare the supplementary materials from Arrighi et al. [2014] with those from Burr and Ross [2008]). Moreover, recent results are difficult to reconcile with the cross-modal finding. For instance, Grasso et al. (2022) found that changing the color of test items as compared with adaptor items eliminated the number adaptation effect entirely. This is puzzling: How could it be that the number sense is sufficiently abstract to generalize from vision to audition, but not from blue dots to green dots?

Motivated in part by these concerns, we conducted a series of experiments to explore an alternative explanation for Burr and Ross's original results. According to this alternative, humans adapt to the *items* in perceived collections, but do not adapt to their numerical quantity.

An alternative proposal: *items*, not number

Consider the basic set up used by Burr and Ross (2008). Observers were first presented with a collection containing a relatively large number of items, to the left or right of a central fixation point. After staring at the central fixation point for e.g., 30 seconds, the original collection of dots disappeared and observers were presented with two novel collections, each containing an identical yet middling number of dots, on the left *and* right sides of the fixation point. At this point, observers were asked which of the novel collections appeared more numerous. Burr and Ross discovered that observers were significantly more likely to report that a collection of dots, located in a region of space that previously contained the larger number of dots, appeared less numerous. (see 'Supplementary Data' in Burr & Ross [ibid.] for a compelling illustration).

According to the *number adaptation hypothesis*, observers visually adapted to a *large number* of dots in the first display, leading to a repulsive aftereffect, such that the subsequent test display, containing a middling number of dots in the adapted region, appeared less numerous.

Our *item adaptation hypothesis* offers an alternative explanation. On this view, observers do not adapt to *the number* of dots in a display. Rather, they adapt to the items it contains, such that if/when items in a subsequent display are perceived to be *the same items* as those adapted to, visual acuity to these items is reduced — as is known to occur in the case of 'perceptual scotomas' (New & Scholl, 2008) or in the 'Troxler effect', where unchanging visual content disappears from view. Thus, the item adaptation hypothesis

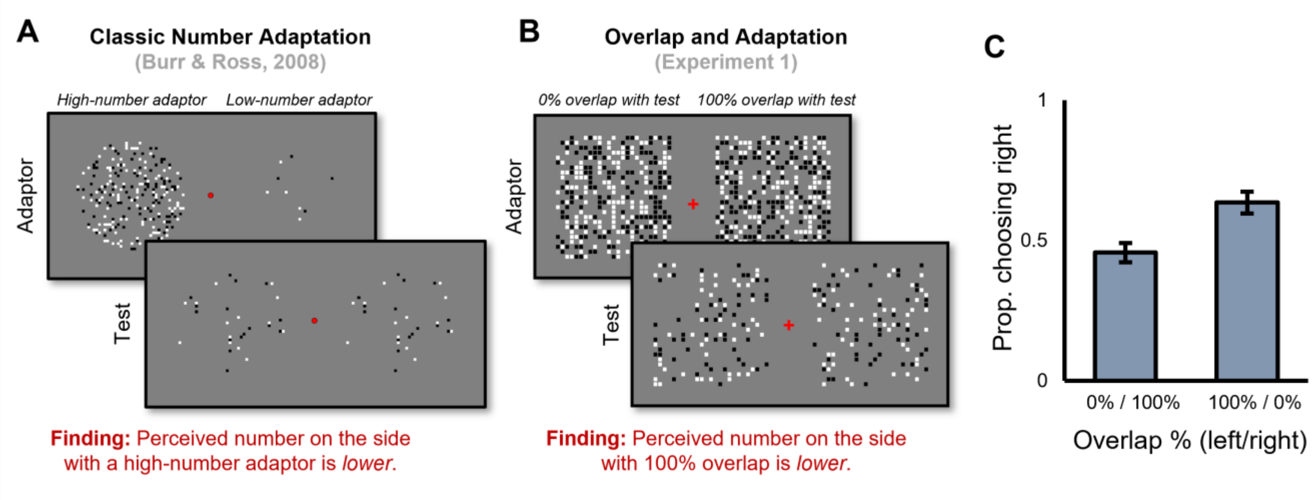

Figure 1. Example of a classic number adaptation trial, as in Burr & Ross (2008) (A). Example of a typical number adaptation trial in Experiment 1 (B). Simplified results from Experiment 1 (C).

holds that observers visually adapt to items in the first display, and this reduces the salience of such items in a spatially overlapping test display, since items in overlapping regions of space are more likely to be represented *as* items form the original adaptor. As such, visually adapting to items causes observers to see fewer items in an adapted region, but not because they adapt to number itself.

Both hypotheses make a common prediction in the above example. Yet, crucially, their predictions diverge under other conditions. For one, the number adaptation hypothesis holds that observers adapt to an ensemble percept encoding the approximate number of items. Thus, the number adaptation hypothesis predicts that the relevant adaptation effects are largely unaffected by properties of the enumerated items themselves (c.f., Grasso et al. 2022) and that "no particular dot disappears from the test patch" (Burr, Anobile & Arrighi 2017: 3). By contrast, the item adaptation hypothesis predicts that cues to object identity across adaptor and test displays, such as spatial overlap or proximity, cause items to disappear and that this is precisely what drives the effect. Indeed, Experiment 1 of the present study shows that the degree of spatial overlap between the items in the adaptor stimulus and the items in the test stimulus strongly influences observer responses, consistent with the item-adaptation hypothesis.

In a second experiment, we consider 'reverse number adaptation' — cases where adapting to a small number of items causes a middling number of items to appear more numerous (as reported in Burr & Ross, 2008). Here, the number adaptation and item adaptation hypotheses again lead to different predictions. The number adaptation hypothesis predicts that a low-number adaptor should cause a middling-number target to appear more numerous, whereas the item adaptation hypothesis makes no such prediction (and, if anything, makes the prediction that a middling-number adaptor should cause a middling-number target to appear less numerous). To address this, we first replicate an apparent case of reverse adaptation (Experiment 2a). Similar to Burr & Ross (2008), observers adapt to one stimulus on each side of a fixation point (one with a low number, one with a middling number that was 10% smaller than the value of the test stimuli. As in prior work, we found that observers subsequently perceive the side on which they had adapted to a smaller number to now look more numerous. However, in Experiment 2b we took the stimuli from Experiment 2a and split each trial in half. Observers compared the same test stimuli as in the other experiment, but were adapted to only one of the two adaptors on each trial. We found exactly what the item-adaptation hypothesis predicts: Perceived number is reduced on the side with the middling adaptor, not increased on the side with a low number adaptor. While these findings do not establish that the item adaptation hypothesis is true, or that number adaptation fails to exist, they raise the possibility that item adaptation explains away phenomenologically compelling cases of 'number' adaptation.

Experiment 1

A key prediction of the item adaptation hypothesis is that alleged cases of number adaptation are driven by cues to item identity across adaptor and test displays. For instance, we expect that adaptation to a large number of items causes a test display, containing a middling number of items, to appear significantly less numerous when the items from both displays share a common location as compared with cases in which they do not. This is because spatial proximity is an important cue to item identity (Flombaum et al. 2009). The number adaptation hypothesis does not predict these effects. It holds that observers adapt to an ensemble representation of number which abstracts away from properties of the items enumerated (including spatial location); as such, it maintains that "no particular dot disappears from the test patch" (Burr, Anobile & Arrighi 2017: 3) and holds that the observed effects are not driven by cues to item identity. To test this, our first experiment manipulates the percentage of spatially overlapping items in adaptor and test displays, to determine if and how this affects changes in perceived numerosity.

Method

In this and subsequent experiments, the sample size, primary dependent variables, and key statistical tests were all determined prior to data collection.

Participants 20 undergraduate students participated in exchange for course credit (after exclusions; see below). Typically, adaptation studies rely on 'expert' participants: Individuals who understand the basic idea of adaptation and understood how to appreciate subtle visual phenomena (for discussion on the challenges of adaptation experiments in naive participants, see Kominsky & Scholl, 2020). In contrast, we specifically opted to use naive participants. All participants were unaware of the design as well as the hypotheses. Because of this, we had to be careful to exclude any participants who responded in a way that was not in the spirit of the task (e.g., participants who responded based on what they *thought* the answer was rather than what they *saw*). We preregistered specific criteria for excluding participants based on a thorough debriefing interview after the study. One participant was excluded for this reason. Two additional participants were excluded because of unreasonably high response times. Participants sat approximately 60cm from a 20in by 11.25in monitor. All subsequent calculations of visual size are based on these values.

Stimuli Stimuli were composed of square dots arranged in a grid shape (see Fig. 1B). For each stimulus, exactly half of the dots were white, and exactly half of the dots were black. Though the stimuli varied in number, all of the stimuli were arranged in a 25x25 grid, resulting in 625 possible 'cells'. Each dot was randomly placed in one of the 625 cells. There was a small buffer between each dot in the grid to insure the dots could be individuated (20% of the width of an individual square). An individual dot was approximately .30° of visual angle. An entire stimulus covered approximately 12° of visual angle. The background was grey.

There were two kinds of stimuli in this experiment: Adaptor stimuli and test stimuli. Both the adaptor stimuli and the test stimuli abided by the constraints outlined above. Adaptor stimuli always appeared before the test stimuli, and, for this experiment, were always greater in number than the test stimuli. The key manipulation in this experiment is the extent to which items in the adaptor and test stimuli 'overlap'. On some trials the adaptor and test stimulus would have 100% spatial and color overlap such that every dot present in the test stimulus was in an identical spatial location and of an identical color as a dot in the adaptor stimulus. On other trials the adaptor and the test stimulus had 0% overlap such that every dot present in the test stimulus was presented in a cell that was in the adaptor stimulus. Other than this constraint, the positions of the dots in both stimuli were fully randomized. Each trial always contained two adaptors and two targets (one on the left side, one on the right side). One of the adaptor/target pairs always had 100% overlap, and the other always had 0% overlap.

Design & Procedure Each participant completed 42 trials. The trials were counterbalanced such that half of the trials had 100% overlap on the left side and the other half had 100% overlap on the right side. Additionally, on one-third of the trials, the left-side adaptor had a 'low' number (10% greater than the subsequent test stimulus) and the right-side adaptor had a 'high' number (300 dots, regardless of the number the subsequent test stimulus would have); on another one-third of the trials, the opposite was true; and on a final one-third of the trials, both adaptors had 300 dots. Additionally, we varied and counterbalanced the number of dots in the test stimuli: For two-sevenths of the trials, one side had 80 dots while the other had 100; in another two-sevenths of the trials, one side had 120 dots while the other had 100; all remaining trials had 100 dots on both sides. Altogether, this design allowed us to assess (1) How the adaptor number, (2) How the target number, and (3) How the degree of overlap between the adaptor and the target affected participants' responses. The key question in this experiment is whether the degree of overlap influences apparent effects of number adaptation.

Results

First, we confirmed that the numerical value of the adaptor influenced participants' responses (as the number adaptation hypothesis would predict). We evaluated the difference between the trials where a high-number adaptor appeared on the left side versus the trials where a high-number adaptor appeared on the right side. This difference was indeed significant, in the direction that would be predicted by the number adaptation hypothesis, $t(19)=4.85$, $p<.001$, $d=1.08$. We then asked whether overlap between the adaptor and the test stimuli influenced participants' responses. First collapsing across the numerical value of the adaptors we compared the proportion of trials for which the right arrays were judged as larger for all trials on which the right side had 100% overlap with the proportion of trials for which the right arrays were judged as larger for all trials on which the left side had 100% overlap. As shown in Figure 1C, there was indeed a significant difference between these conditions, $t(19)=3.58$, $p=.002$, $d=.80$. Moreover, this difference was significant no matter how we analyzed the data. For instance, this difference was significant for only those trials for which the overlap differed, but the number in the target stimuli was held constant ($p=.001$) and for the subset of trials for which the overlap differed but the number in the target stimuli *and* the number in the adaptors was held constant ($p=.04$). In other words, participants consistently indicated that the side of the screen with more item overlap was *less* numerous.

Discussion

Experiment 1 demonstrates that the spatial overlap of items across adaptor and test displays significantly alters putative visual number adaptation. Specifically: if observers adapt to a large number of items, a middling number of items in a

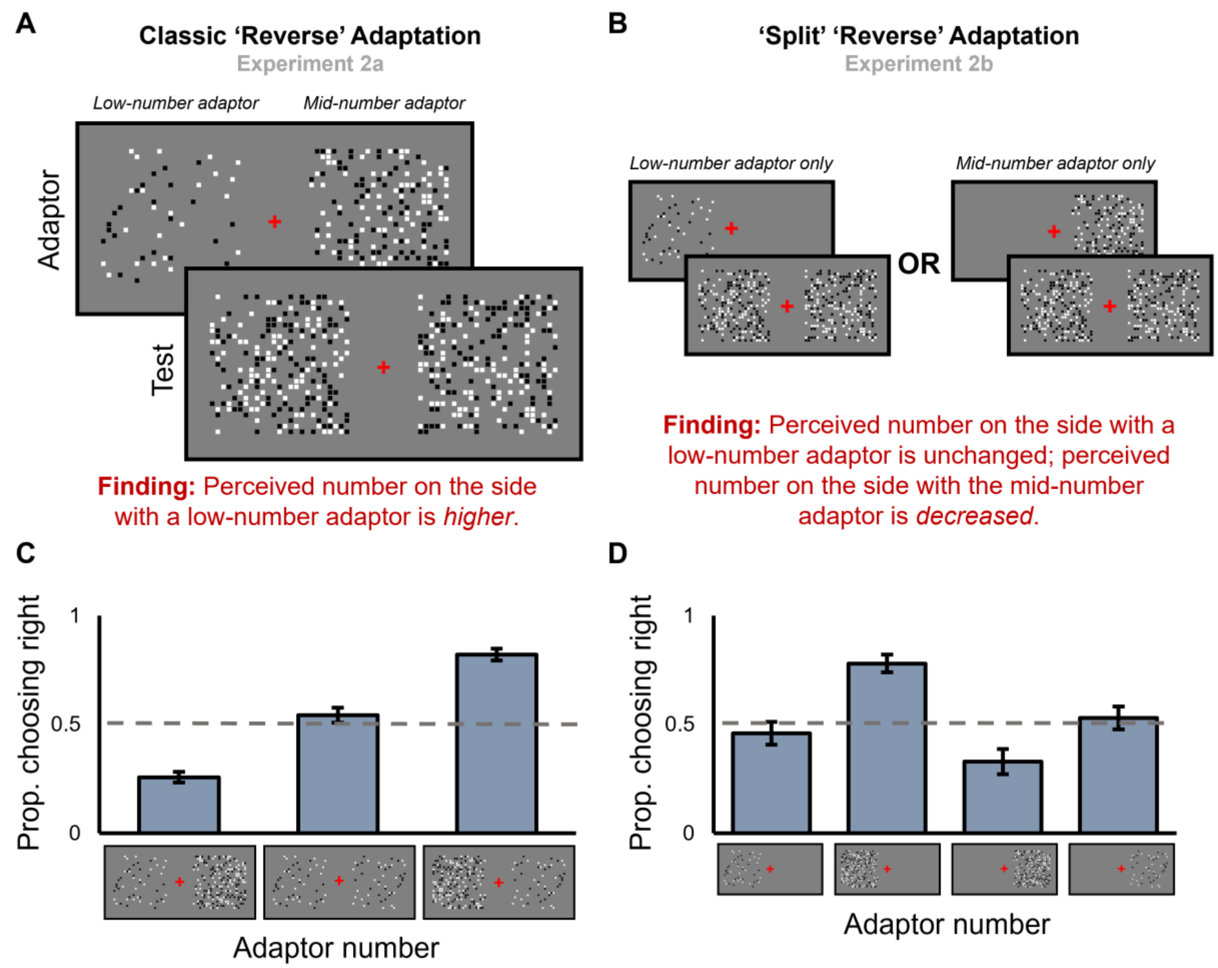

Figure 2. Example of a 'reverse adaptation' trial from Experiment 2a (A). Example of 'split' trials from Experiment 2b (B). Results from Experiment 2a (C) and Experiment 2b (D). Error bars represent +/- 1 SE. Notably, the effects in Experiment 2b seem to be driven *not* by the low-number adaptor but by the intermediate-number adaptor.

subsequent test display appears significantly less numerous when those items share the spatial location of items in the adaptor compared to cases in which they do not. This finding undermines received formulations of the number adaptation hypothesis which maintain that adaptation to a large number of dots reduces the number of dots visually attributed to test displays despite maintaining that "no particular dot disappears from the test patch" (Burr, Anobile & Arrighi 2017: 3). Moreover, it highlights an overlooked confound in existing studies: As far as we can tell, the positions of dots in prior studies are fully randomized such that, naturally, more numerous adaptors are more likely to overlap with dots in corresponding targets. These results are, however, precisely what the item adaptation hypothesis would predict.

Experiments 2a and 2b

Experiment 1 provided provisional motivation for the item adaptation hypothesis, showing that cues to item identity significantly affect the extent to which visual adaptation to a large number of items causes a middling number of items to appear less numerous. However, cases of "reverse" adaptation, where adapting to a *small* number of items causes a middling number of items to appear *more* numerous, have also been reported (Burr & Ross, 2008). At first blush, such results are in tension with the item adaptation hypothesis. For while item adaptation can explain why observers fail to see items in test displays, and thus report these collections to appear less numerous, it does not predict that adaptation to a small number of items would cause subjects to 'see' items that are not there in a subsequent test display. Thus, the item adaptation hypothesis is committed to the bold prediction that there will be no reverse number adaptation. This prediction should come as a surprise, given that there are several documented cases of reserve adaptation (e.g., see also Arrighi et al., 2014). What explains those cases? Experiments 2a and 2b were designed to address this question.

Method – Experiment 2a

Experiment 2a was designed to be as similar as possible to Experiment 1. The constraints of the stimulus design were identical. Only a few changes were made to the design, as explained below. Twenty new participants completed the study in exchange for course credit.

Unlike the previous experiment, this experiment is designed to test 'reverse adaptation' — cases where an adaptor of lower number causes a test stimulus of higher number to appear even more numerous (see Burr & Ross, 2008). The numbers for the test stimuli were identical to the previous experiment, except doubled. Thus, for two-sevenths of trials, one side had 160 dots while the other had 200; for another two-sevenths of trials, one side had 240 dots while the other had 200; and all remaining trials had 200 dots on both sides. Critically, the adaptor stimuli in this experiment were always *less* numerous than the targets. For one-third of the trials, the left side adaptor had a 'low' number (50 dots) and the right-side adaptor had a 'high' number (10% fewer than the corresponding test stimulus; i.e., between 144 and 216 dots, depending on the number of dots in the target); for another one-third of the trials, the opposite was true; and for a final one-third of the trials, both adaptors had 50 dots. For all trials, there was 0% spatial overlap between the adaptor and the test stimulus. Everything else about the design and procedure was identical to Experiment 1.

Results

There are three critical trial types: trials where the right adaptor had a low number, trials where the left adaptor had a low number, and trials where both adaptors had a low number (see Figure 2C). To simplify the analyses, we conducted pairwise comparisons between each of these trial types, averaging across other factors (e.g., the numbers of the test stimuli, which were counterbalanced). Compared to the baseline where both adaptors had a low number, participants should be more likely to choose the left side when the left adaptor has a low number. This is true: Participants chose the left side 74% of the time, $t(19)=7.72$, $p<.001$, $d=1.73$. Conversely, compared to the baseline where both adaptors had a low number, participants should be more likely to choose the right side when the left side had a high number. This is also true: Participants chose the right side 82% of the time, $t(19)=7.54$, $p<.001$, $d=1.69$. Finally, we can compare whether there is a difference in response between the trials where the high adaptor is on the left side versus the right. Unsurprisingly, given the previous results, this difference is also significant, $t(19)=19.59$, $p<.001$, $d=4.38$. This effect is massive and consistent with the number adaptation account.

Method – Experiment 2b

Experiment 2b was modeled on Experiment 2a. But where Experiment 2a involved 'double adaptor' trials (i.e., trials in which adaptors appeared on both sides of the screen at once), Experiment 2b used a 'single adaptor' design. Adaptors appeared on either the left or right side, but not both. The stimuli used in this experiment were the same as those used in Experiment 2a. The difference here is that trials from Experiment 2a were effectively 'split in half'. We showed participants the same test stimuli as in Experiment 2a, but with only one of the two corresponding adaptors visible beforehand. Critically, this design allowed us to assess the independent contribution of each adaptor on participants' responses. To accommodate the fact that the number of trials would be effectively doubled, we removed all trials in which the number on either side exceeded 200 dots to prevent participants becoming excessively fatigued. Additionally, we removed trials in which both adaptors had 50 dots. These trials were not functionally necessary to test our hypothesis. Having excluded these trials and otherwise doubled the trial number (because each adaptor was shown separately), we were left with a total of 40 trials. Everything else matched Experiment 2a.

Results

The critical question in this experiment is whether the change in participants' responses in Experiment 2a was driven by the low number adaptor (as the number adaptation hypothesis would predict) or the high number adaptor (as the item adaptation hypothesis would predict). There were four critical trial types: (1) trials where the left side had a low-number adaptor, (2) trials where the left side had a high-number adaptor, (3) trials where the right side had a high-number adaptor, and (4) trials where the right side had a low-number adaptor (see Figure 2D). According to the number adaptation hypothesis, trial types (1) and (4) should differ from chance. According to the item adaptation hypothesis, trial types (2) and (3) should differ from chance. The data are more consistent with the item adaptation hypothesis. Contrary to the number adaptation hypothesis, responses on both low-number adaptor trials (1) and (4) did not differ from chance, ts(19)<.80, ps>.40, ds<.20. However, responses on both high-number adaptor trials (2) and (3) did differ from chance, in opposite directions, exactly as would be predicted by the item adaptation hypothesis, ts(19)>2.90, ps<.01, ds>.65. This critical pattern can ultimately be distilled into a single statistical test, by taking the average of the difference scores between trial types (1) and (3) as well as (2) and (4). As predicted by the item adaptation hypothesis, this difference is significant, $t(19)=3.64$, $p=.002$, $d=.81$. In other words, reported cases of reverse adaptation (and Experiment 2a) appear to be driven *not* by increased perceived number after low-number adaptors, but instead by decreased perceived number after the control adaptors — contradicting a critical prediction of the number adaptation hypothesis.

Discussion

The item adaptation hypothesis makes a bold prediction: that adaptation to a small number of items does not cause a middling number of items to appear more numerous. Our results confirm this prediction and suggest that reported cases of reverse adaptation result from a *reduction* in the quantity of perceived items in contralateral displays not increased perceived number after adaptation to a low number.

General Discussion

Visual number adaptation is a widely accepted phenomenon, which has gone largely unquestioned in the scientific literature. We offer empirical evidence that calls into question its evidential support and motivates consideration of a simple alternative— that we do not adapt to the number of items in observed displays, but to the items themselves. Thus, when items in a subsequent test display are visually identified with adapted items from a previous display, their visual salience is reduced, and there is a sense in which observers are left seeing *fewer* items in test displays.

Consistent with this *item adaptation hypothesis*, Experiment 1 found that cues to object identity (spatial location) affect the strength of the adaptation effect described above, with an overlap in items from adaptor and test displays leading to significantly greater reduction in observed number. Experiments 2a and 2b then demonstrated that prior reports of *reverse* number adaptation (wherein, adaptation to a small number of items causes a middling number to appear *more* numerous) are better explained by a perceived reduction in the number of items in contralateral collections, rather than increased perceived number in the ipsilateral collections, just as the item adaptation hypothesis boldly predicts.

These findings support the item adaptation hypothesis and sit uneasily with orthodox formulations of the number adaptation hypothesis. However, questions remain. First, the mechanisms of item adaptation remain poorly understood. In cases of color adaptation, subjects may adapt to a single (large) item's color, such that a subsequent item of neutral color appears to be tinged some opponent value. Under these conditions, subjects still *see* the item. Thus, adapting to an item or its properties does not typically preclude our subsequent perception of it. This could seem to present a puzzle when considering the results described here. For our results suggest that prolonged exposure to a collection of items can, in some real sense, prevent subjects from seeing the items contained therein. What explains this discrepancy? One possibility is that item adaptation of the sort described in Experiment 1 is more likely to occur when adapted items are relatively small. Another is that these effects arise when attention is distributed over many items, as they must be in number adaptation studies. Clarity about the cases in which item adaptation does and does not occur is essential and will serve to sharpen our hypothesis moving forward.

Second, we have not addressed *all* the empirical evidence offered in support of the number adaptation hypothesis in this short paper. For instance, in our introduction, we noted that there have been reports of cross-modal number adaptation (Arrighi et al., 2014). Such findings cannot be attributed to spatial overlap and thus appear to avoid low-level confounds of the sort highlighted above. But while cases of cross-modal adaptation surely warrant further consideration, we do not yet think they convincingly undermine the item adaptation hypothesis. As discussed earlier, examples of cross-modal "number" adaptation (see, e.g., Arrighi et al., 2014) fail to yield phenomenologically striking aftereffects of the sort found in Burr and Ross's original study. Furthermore, these effects are not spatiotopic, whereas canonical demonstrations of number adaptation (including those studied here) are spatiotopic. Therefore, it remains unclear how these cross-modal effects should be interpreted; not least because it is odd to think that the mind possesses a visual sense of number that is sufficiently abstract to transfer from one modality to another (as in Arrighi et al., 2014) but *not* sufficiently abstract to transfer from one color of dots to another (as in Grasso et al., 2022). We are in the process of conducting additional studies to critically evaluate these claims.

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