Seven reasons to (still) doubt the existence of number adaptation: A rebuttal to Burr et al. and Durgin

Sami R. Yousif [1], Sam Clarke [2], & Elizabeth M. Brannon[1]

1. Department of Psychology & Neuroscience, University of North Carolina, Chapel Hill
2. Department of Philosophy, University of Southern California
3. Department of Psychology, University of Pennsylvania

Abstract

Does the visual system adapt to number? For more than fifteen years, most have assumed that the answer is an unambiguous "yes". Against this prevailing orthodoxy, we recently took a critical look at the phenomenon, questioning its existence on both empirical and theoretical grounds, and providing an alternative explanation for extant results (*the old news hypothesis*). We subsequently received two critical responses. Burr, Anobile, and Arrighi rejected our critiques wholesale, arguing that the evidence for number adaptation remains overwhelming. Durgin questioned our old news hypothesis — preferring instead a theory about density adaptation he has championed for decades — but also highlighted several ways in which our arguments do pose serious challenges for proponents of number adaptation. Here, we reply to both. We first clarify our position regarding number adaptation. Then, we respond to our critics' concerns, highlighting seven reasons why we remain skeptical about number adaptation. We conclude with some thoughts about where the debate may head from here.

Introduction

The phenomenon of number adaptation occupies a funny place in our hearts. All three of us were once convinced of the existence of number adaptation and cited it accordingly (see, e.g., Clarke & Beck, 2021; Fornaciai, Brannon, Woldorff, & Park, 2017; Yousif & Keil, 2020). This is the lens through which our recent critique of number adaptation (Yousif, Clarke, & Brannon, 2024) should be viewed. We are not protecting a theoretical position that we've wedded ourselves to. We are taking a critical look at number adaptation *despite* our prior theoretical commitments.

Our aim for this work was not to challenge the evidence that number is directly perceived (see Section #6.2 of our original paper) but instead to voice our growing concern that what looks like number adaptation is actually a more basic form of item-level adaptation. Here, we respond to two critiques of this suggestion. Burr, Arrighi and Anobile reject our concerns with number adaptation, saying that “adaptation to numerosity…has been far from refuted” (p. 2), and that “there exists overwhelming evidence for numerosity adaptation” (p. 15). Burr and colleagues contend that we *ought* to believe in number adaptation in principle — because adaptation has been observed for other perceptual attributes. “If [number] did not adapt,” they write, “it would be unique amongst perceptual attributes, worthy of very special attention” (p. 13). Ironically, we worry that many other forms of high-level adaptation have become widely accepted precisely because of the path that number adaptation paved. This is what makes the stakes in this debate so high. Perhaps, influenced by the fuzzy criteria that have been used to support number adaptation, other cases of high-level adaptation have been similarly misunderstood (see, e.g., Storrs, 2015; Yousif & Clarke, 2024). If one domino falls, others may follow. As foreshadowed in the final sentence of our original paper, this debate “raises questions about the nature and meaning of adaptation itself” (p. 14).

In contrast, Durgin suggests that our critique of number adaptation brings into focus “how fragile some findings may be” (p. 2) and applauds our “simpler, but not simplistic, approach to understanding a complex phenomenon” (p. 13). He explains that our work “both illustrates and encourages critical thinking about the nature of adaptation” (p. 13). Nevertheless, he argues that our theory is incomplete and favors his long-established view that density is the mechanism underlying putative number adaptation (see Durgin, 1995, 2008).

In what follows we first clarify our position and then respond to our commentators’ critiques, offering seven reasons why we continue to think that the evidence for number adaptation is unconvincing — and why we continue to think that our ‘old news hypothesis’ explains extant results better than the existing alternatives. We conclude with some thoughts about where this debate may head from here.

What we are arguing

Our claim is that apparent cases of number adaptation are unlikely to be driven by adaptation to number *per se*. We argue that (1) The evidence that has been marshalled in support of number adaptation is less convincing than typically assumed, and (2) This evidence (including a number of otherwise inexplicable anomalies in the prior literature) can be explained by at least one alternative theory — our *old news hypothesis* — which is (a) independently plausible, in that it only appeals to well-known principles of visual computation, and (b) explains a host of otherwise puzzling results in the existing literature.

The old news hypothesis is simple: The visual system filters out unchanging information in favor of the new. If you stare at a bunch of dots for thirty seconds, and you then see some new dots, the visual system will tend to filter out those dots that it determines the viewer has seen before (and that are therefore “old news” from the perspective of the visual system) so as to prioritize those it deems new. This can cause what *looks* like a genuine reduction in number, but, critically, without adaptation to number itself. Among other virtues, this old news hypothesis offers to explain why cues to dot identity (such as color and spatial position; see Experiments 1 and 2 in our previous article) modulate the magnitude of the effect: Changes of color or position can yield salient alterations to old items, rendering them newsworthy for the visual system once again. Additionally, our theory explains why adapting to a large number of dots yields a reduction in the perceived number of subsequent items while adapting to small collections fails to yield an apparent increase in the perceived number of subsequent items (see Experiments 4a and 4b)[1]. In fact, the old news hypothesis seems to naturally accommodate all robust number adaptation findings (see Table 1). So where do things stand?

Seven reasons to doubt number adaptation

1. "Old news" (still) explains the observed effects. As preempted above, one of the key claims made in our target article was that many putative number adaptation effects can be explained by our alternative hypothesis — the *old news hypothesis*. Burr and colleagues reject this assessment, emphasizing the *magnitude* of the experimental results we reported and took to support our hypothesis. As they see it, these "…effects were not huge by usual standards in vision research" (p. 7), and not large enough to explain away the need for number adaptation. So, while they accept that cues to item identity, such as overlap and color, affect the strength of number adaptation, they deny that these cues to item identity can fully explain away the results of canonical number adaptation experiments. Thus, it is claimed that number adaptation must still be occurring if we are to fully account for the (sometimes dramatic) effects under consideration.

We're unconvinced. To make their point, Burr and colleagues focus on our overlap experiment (Experiment 1 from our original paper) in which we showed that number adaptation is stronger when dots from the test display occupy the same spatial locations as dots from the large number adaptor. For us, this served as a proof of principle, showing that one particularly strong cue to dot identity (location) influences the reductions in estimated quantity associated with visual number adaptation. But while it is true that these effects are modest — a fact we never hid — we were at pains to note that the effect of overlap cannot be straightforwardly measured by comparing the 100% overlap and 0% overlap conditions, as Burr and colleagues mistakenly assume. This is because there is no such thing as a true 0% overlap case. The visual system doesn't just track items which perfectly overlap in space; it tracks objects across space and time. If shifting a dot by a small amount altered its identity, object tracking would be impossible. For this reason, two dots which do not overlap at all may still be treated as the same[2], such that many dots in the 0% overlap displays are still being filtered from awareness. This effectively makes it

[1] There is disagreement about whether reverse number adaptation is genuine. However, our point here is that, regardless of what we make of the conflicting evidence regarding reverse number adaptation, no one has been able to put forward a compelling visual demonstration of the sort that we would typically expect from canonical cases of perceptual adaptation.

[2] This is something that can be easily demonstrated: Create two different images with two dots that are in slightly different positions. Flicker back and forth between the two images. What you see is not two different dots at two different points in space. You see one object which moves through space. The visual system treats these two dots as one object via *apparent motion*. This effect is even apparent in number adaptation stimuli, including the original images provided by Burr and Ross (2008). By rapidly alternating between the adaptor and test display, you can see this apparent motion for yourself.

impossible to identify the extent to which overlap does or does not drive the observed effects found in canonical visual number adaptation studies.

Fortunately, the *old news hypothesis* makes additional predictions. If the visual system has tolerances that allow for dots to be treated as overlapping despite slight spatiotemporal shifts, then we might expect the effect of overlap to be greater in the periphery (where receptive fields are larger; Alonso & Chen, 2009). According to Burr and colleagues, this is true (see Arrighi et al., 2014, p. 5). However, to our knowledge, there is no published evidence to this effect. Thus, we collected such data for ourselves. We ran a preregistered experiment (https://osf.io/eh3ws/), and found that the effect of overlap was considerably greater when the displays were more peripheral, $t(19)=3.87$, $p=.001$, $d=.87$ (see Figure 1). Such evidence favors the *old news hypothesis*, insofar as there is no reason for a pure number adaptation account to predict different levels of adaptation in peripheral vs. focal vision. Indeed, this would be a quirk of number adaptation, since canonical cases of adaptation — e.g., to color and motion — operate normally in focal vision. To compound matters, number adaptation is virtually eliminated when individual items change color (see Grasso et al., 2022; Experiment 2 of our original paper). This evidence seems to straightforwardly favor the old news hypothesis over the number adaptation hypothesis: On our account, a change in color renders old information newsworthy again, thus eliminating the opportunity for adaptation or visual filtering.

That said, Burr and colleagues do provide some evidence against the old news hypothesis. They note that, contrary to what we documented in our original paper[3], Caponi et. al (2024) found clear evidence of adaptation in displays with moving dots. This evidence could be seen to favor the number adaptation hypothesis insofar as motion — like color changes — should render old dots newsworthy again. Thus, to observe adaptation to number in the presence of motion could be seen as evidence that number adaptation persists despite a change in "news". To investigate this further, we ran another version of our original experiment. The second time around, we found evidence of an adaptation effect. Therefore, we believe the available evidence suggests that number adaptation — or at least a behavioral effect consistent with number adaptation — is possible in dynamic displays.

This is no silver bullet for the number adaptation hypothesis, however. The old news hypothesis does not predict that motion will *always* eliminate adaptation. (Obviously, this will depend on things like the speed and predictability of the motion. For instance, display in which dots move by one pixel every ten seconds is not likely to influence the newsworthiness of the display.) Rather, the old news hypothesis predicts that varying the positions and motion trajectories of the dots should attenuate the *strength* of the effect (insofar as it reduces the likelihood that individual

[3] In our original article, we included an experiment in which we did a standard number adaptation task, but with a twist: The dots moved around the display (during adaptation, and at test). We explained that motion might cause otherwise "old" news to become "new" again. Therefore, "large-number adaptation *may* be eliminated in a dynamic display..." (emphasis added; p. 8). True to that prediction, we found a null effect. But we also expressed some concern about this null effect: Given the bimodality of the data, we stated that this result "should be interpreted with caution" (p. 8).

dots can be tracked and identified across the adaptor and test displays).[4] Nevertheless, better understanding the signature limits of these effects is likely to be fruitful moving forward.

2. Phenomenology matters. In our original paper, we found that number adaptation is not bidirectional: Large number adaptors make middling-number targets appear less numerous, but low-number adaptors seem to have no effect[5]. Burr and colleagues reject this claim, pointing to other papers that have reported reverse adaptation (Aagten-Murphy & Burr, 2016; Aulet & Lourenco, 2023). In fact, Burr and colleagues replicated 'reverse' number adaptation again for their reply. Their effects were so strong, they said, that there was "no need for statistics" (p. 9). Yet we find this difficult to square with the fact that Burr and colleagues do not provide, nor have ever provided, an appreciable demonstration of reverse adaptation. If the effects are so strong — robust enough to transcend statistical measure! — experiments shouldn't even be necessary. They should be readily apparent. Indeed, this claim is bolstered by the data Burr and colleagues themselves provided. They report that reverse adaptation increases perceived number by 16% (p. 9), well within the discriminable range for most human adults (Samford & Halberda, 2023). Further, their Figure 2D shows that the largest effect (at the participant level) was greater than 25%. Practically and psychophysically, this is a massive difference (see Figure 2). It is in this light that the absence of any such appreciable demo is so conspicuous. Without phenomenological evidence of adaptation, behavioral effects can be attributed to response biases or task demands (see Point #6).

Remember: Adaptation effects are more than mere *behavioral* aftereffects; they are said to be *perceptual* aftereffects. Indeed, in canonical cases of adaptation, it is natural to think that phenomenology *is* the phenomenon. Without a corresponding phenomenology, what would have licensed the claim that adaptation effects are strictly perceptual in nature?[6]

---

[4] Burr and colleagues provide a demo of their motion adaptation study and claim that this clearly demonstrates the effect. Although we accept that the reported effects are genuine, we did not find the provided demonstration as compelling as they say (especially in contrast with classic demos, like that from Burr and Ross [2008]). Additionally, their demo deviates from ours in several critical ways (most notably, the dots move around the display much less). Readers are encouraged to view these demonstrations themselves and form their own opinions.

[5] Burr and colleagues argue that one reason we may have failed to find reverse adaptation is because our "dense field[s] of 100 dots" were "more a 'texture' than a countable array" (p. 9-10). This argument may seem plausible on the surface. However, we reported canonical adaptation (large adaptors reducing perceived number of test displays) with these ranges — and so did Burr and Ross (2008; see also Experiment 2 of Durgin's reply). What should we make of the fact that canonical number adaptation operates over dense displays but reverse adaptation (putatively) does not? We're not sure. It is at junctures like these that we think the phenomenon of number adaptation begins to unravel: There arise so many unique caveats and conditions for every observed effect that it becomes challenging to house them all under one theoretical roof. We note that Durgin endorses this worry (though in response to a different caveat about the number adaptation hypothesis) "...like Yousif et al. (2024), we doubt that the assumptions of idealized number adaptation theory should be so deeply dependent on such details" (p. 6).

[6] We aren't alone in valuing phenomenology. In his book about adaptation, discussing the specific case of number adaptation, Ned Block writes, "However, standard psychophysical approaches fail to consider an obvious way of avoiding criterion issues. In the numerosity experiment just described, it briefly *looks* as if there are more dots on the

The problem of phenomenology is also a concern for the claimed existence of cross-modal adaptation. Burr and colleagues point to "*eight* independent studies, with different adaptation conditions, different laboratories, different participants, and different lead authors" (p. 4) which all report cross-modal effects[7]. Given that these effects are seemingly so replicable, it remains unclear why they are unable to offer a demonstration of the cross-modal phenomenon. If these replications truly reflect number adaptation of the same fundamental kind as that probed by canonical demonstrations, then shouldn't these effects also be readily appreciated in a demonstration? Again: without phenomenological evidence of adaptation, behavioral effects can be attributed to response biases or task demands (see Point #6).

3. Secondary evidence provided by Burr and colleagues is not diagnostic. Burr and colleagues contend that we omitted several key studies "that are difficult to explain without the concept of adaptation" (p. 2), emphasizing three distinct types evidence: (1) neural data, (2) pupillometric data, and (3) confidence ratings/reaction times. However, it seems to us that these bodies of evidence do not bear on our proposal.

Regarding both the neural and pupillometric evidence: Consider the fact that, in the canonical demonstration of number adaptation, there is *phenomenological* evidence of adaptation *right in front of our eyes*. Through this lens, it is perhaps unsurprising that the impression of reduced number would have a corresponding physiological response (whether in the pupil, or in the brain). All views on the table — number adaptation, density adaptation, and *old news* — predict as much.

If we take adaptation to be any decreased neural signal following exposure to a stimulus (see "repetition suppression" or "fMR-Adaptation"; Grill-Spector & Malach, 2001), then people adapt to virtually everything — including, for instance, the concept "umbrella" (see Grill-Spector et al., 2006). Does this mean that the concept of "umbrella" is a primary visual attribute? Surely not. Neural evidence might point towards *some kind* of adaptation (e.g., "repetition suppression"), but not the kind that Burr and Ross (2008) were talking about when they equated the perceptual processing of number with the perceptual processing of features like color. At least, that's what we have assumed. If Burr and colleagues mean to equate neural fatigue with perceptual adaptation, that would be a reasonable stance. This would, however, force them to abandon any claims that their results are indicative of *perceptual* processing (insofar as neural fatigue is not specific to perceptual systems).

---

right than on the left. I have shown these displays in many classes and I have to assure the audience that I have not tricked them with a video that starts with more dots on the right and shifts to equal numbers of dots. There is no reason to expect criterion effects to fade. This is not the first-person experience of a criterion effect. It is a robust effect that you can experience for yourself despite the absence of laboratory conditions. This point might fall on deaf ears in the psychophysics community because of suspicion of "introspective" reports, but a rational reader should be persuaded by it" (Block, 2022; p. 75).

[7] Actually, their point about the replicability of cross-modal adaptation is even stronger. They go out of their way to point out that even "undergraduates doing a student project" (p. 4) managed to observe the cross-modal effects that we twice failed to replicate.

Regarding the confidence / reaction times data: Insofar as we accept that perceived number is reduced in the canonical case of number adaptation (via some filtering of the items enumerated), we would predict that response times would indeed be higher at points of subjective equality (as shown by Maldonado Moscoso et al., 2020). Nevertheless, this is, again, not diagnostic of perceptual processing. If you showed football fans pairs of football teams at random and ask them which one is stronger, people will be faster to respond when the skill gap is higher and slower to respond when the skill gap is lower. Or if you asked people to categorize animals as either fish or birds, you'd find that people were slower to categorize penguins than either cardinals or clownfish. This is a straightforward prediction of prototype theory which is nowhere regarded as evidence of perceptual processing (see Rosch, 1978).

In sum: All parties agree that (a) some kind of adaptation is occurring and (b) as a consequence, there is a perceived reduction in number following adaptation to a high-number stimulus. The neural, physiological, and psychophysical evidence cited by Burr and colleagues coheres with this. However, our disagreement is not about the *consequences* of putative number adaptation but about the *causes* of it. Is the observed adaptation occurring because of a perceptual computation occurring over the dimension of number *per se?* None of these types of evidence will help us to answer this question.

4. *Neutral number adaptation is not neutral*. One of the most striking empirical observations made in our original paper is the fact that adaptation is observed for items which are equal in number: An adaptor with 24 dots decreases perceived number of a target with 24 dots (see, e.g., Experiments 4 and 5; Yousif et al., 2024). This pattern is straightforwardly at odds with the number adaptation hypothesis. In their reply, Burr and colleagues offered no explanation for why such neutral adaptation would occur[8].

Durgin, meanwhile, independently replicated our findings on neutral adaptation[9]. In a study that he and a student conducted two years ago — without any knowledge of our views on number adaptation — he found exactly what we did: "…there was clear evidence that 'neutral adapters' of 24 dots produced downward aftereffects on number matches to 24 dots presented in the adapted region" (p. 6). This fact alone provides reason to doubt the existence of number adaptation, as it has traditionally been framed: The number adaptation hypothesis predicts that displays of equal number should have no effect on each other. Indeed, this is a key assumption behind the design of some studies (see, e.g., Grasso et al., 2023).

---

[8] In reviewing this paper, Burr clarified that he agrees that adaptation occurs in otherwise neutral displays, insofar as there are factors other than number which simultaneously influence adaptation.

[9] It could be said that the existence of neutral adaptation poses a challenge to the *density adaptation hypothesis* championed by Durgin. *Ceteris paribus*, displays equal in number should also be equal in density, meaning that neutral number adaptation is also neutral density adaptation. The only hypothesis that cleanly predicts these results is our *old news hypothesis*, as far as we can tell. However, as Durgin helpfully clarified in reviewing our rebuttal, he accepts that multiple factors could be contributing to adaptation at once, and therefore that neutral adaptation is not necessarily at odds with density adaptation. He said the same of asymmetries between canonical and reverse adaptation (see also Sun & Baker, 2017). We accept this position. Indeed, we agree that isolating one single dimension responsible for a given repulsive aftereffect is difficult, if not impossible.

5. *Number adaptation is brittle*. In our original paper, we argued that it is suspicious that changing item-level properties like color eliminates number adaptation (e.g., Grasso et al., 2022). At the very least, such findings indicate that number adaptation effects are significantly more complex, or brittle, than is typically acknowledged.

Burr and colleagues argue that number adaptation is not "brittle" but rather "selective". But how can we hold that number adaptation is selective to low-level features, like color, if we also hold that it generalizes across *modalities* and across *time* — i.e., operating over maximally abstract representations of number — simultaneously (see Arrighi et al., 2014)? If there is a way to make sense of this seeming contradiction, it is not obvious to us.

6. Response biases / task demands / criterion shifts should be the default hypothesis, not the alternative. It wasn't so long ago that the field of cognitive science largely accepted that wearing heavy backpacks could make hills look steeper (a la Bhalla & Proffitt, 1999). This "discovery" led to a cottage industry of other so-called "top-down effects", whereby a cognitive state was said to directly influence perceptual experience. These days, not only has the original claim been debunked (see Durgin et al., 2009; Firestone, 2013), but the entire collection of "top-down effects" has been questioned (Firestone & Scholl, 2016).

One of the primary "pitfalls" in the literature on top-down effects was insufficient care in ruling out task demands. As Firestone & Scholl (2016) put it: "Contamination by demand characteristics seems especially likely in experiments involving a single conspicuous manipulation…" (p. 10). Most extant number adaptation experiments involve such conspicuous manipulations. Consider the experimental setup from a participant's perspective: You stare at a screen for up to 30 seconds at a time that either has a large number of dots or a small number of dots, and then you make a judgment about the number of some dots. You are told that you are to ignore the thing you stared at all that time — but surely there's some reason you were told to stare at it, right? The experimental design isn't obfuscated at all; naïve participants can easily guess what the experiment is generally about[10]. (In contrast, the more subtle difference in overlap tested in some of our experiments *cannot* be easily inferred.)

There is also empirical evidence that supports our suggestion that response biases play some role in these effects. Consider, for instance, *symbolic number adaptation*. Using a clever design involving bistable images of digits, Luo and colleagues (2024) documented bidirectional number adaptation of *Arabic numerals*. Adapting to the number 9, for instance, caused a bistable 6/8 to be more likely perceived as a 6, whereas adapting to the number 5 had the opposite effect. Given that no magnitude information is contained in the perceptual input of a symbolic numeral, such findings are not easily explained by appeal to a perceptual mechanism. Instead, such findings seem likely to result from decision-level processes. Herein lies the problem: If decision-level

[10] We know that participants can infer the basic logic of canonical number adaptation studies because we asked them: Every one of the hundreds of participants who completed an adaptation study in our lab over the last two years answered some routine debriefing questions about the task. The vast majority reasoned that the relative number of dots was critical to our hypotheses.

processes can result in bidirectional aftereffects in some cases, then we must be sure to rule out such processes in all other cases (if the goal is to make claims about perception). This is doubly true if the effects are not accompanied by clear phenomenological alterations (see Point #2).

7. Other possible explanations, like density adaptation, have not been adequately ruled out. Prior to our investigation, there had been only one prominent challenge to the number adaptation hypothesis. Durgin (2008) argued that the original effects documented by Burr and Ross (2008) should be better understood as effects of adaptation to density, rather than number (see also Dakin et al., 2011; Morgan et al., 2014). Proponents of number adaptation have responded to these concerns empirically and contend that they have fully dissociated number adaptation from density adaptation (see Anobile et al., 2014; DeSimone et al., 2020). However, as we pointed out at the end of our original paper, and as Durgin emphasizes in his reply, the manipulations used in these experiments rely on a faulty manipulation whereby the spatial envelopes of the adaptors and targets (i.e., the space in which dots are able to appear) are non-overlapping. But in Demo #7 of our target paper, we demonstrate — in a way that readers can easily appreciate for themselves — that spatial overlap can have surprising perceptual consequences. On the basis of this demonstration alone, we think that any evidence purporting to separate number adaptation from density adaptation should be revisited. In practice, this means that number adaptation still faces the uphill battle of separating itself from other spatial confounds (a task which is notoriously difficult, if not impossible; see Leibovich et al., 2017; Yousif & Keil, 2021) at least in the absence of genuine cross-modal findings (but see Clarke & Beck 2021).

Where should we go from here?

What we hope results from this dialogue is a path towards stronger tests of number adaptation — no matter where the chips ultimately fall. It will be difficult to make progress, though, if there is no consensus about the empirical effects themselves. While we successfully replicated many classic number adaptation findings in our original article, there were several cases where we found a substantively different pattern of results. The most notable of these cases was for cross-modal number adaptation, which we twice failed to replicate. We wrote, “Of course, we should not abandon an influential theory because of a single failed replication (or two!). However, we made every effort to replicate these cross-modal effects (including two pre-registered experiments and multiple rounds of pilot data collection) and repeatedly failed. If any doubt remains about the validity and replicability of cross-modal number adaptation, we propose a collaborative, pre-registered, multi-site test with other interested research groups” (p. 11-12). We remain committed to this endeavor, and we are actively pursuing such a collaboration.

For proponents of number adaptation, there is a clear path to vindication. If reverse adaptation and cross-modal adaptation could be compellingly demonstrated — by way of an unambiguous visual demonstration — little wind would remain in our sails. This is the point we most want to stake our claim on: If, following this debate, no party can provide phenomenologically compelling demonstrations of either reverse number adaptation or cross-modal number adaptation, then we would suggest that both cases should be disregarded as evidence of (perceptual) number adaptation. In the absence of such evidence, we maintain that there is insufficient reason to claim that perceptual number adaptation is genuine. At the very least, we would urge that a lack of phenomenological alterations strongly indicates that any adaptation involved is of a fundamentally different kind from that tapped by Burr and Ross (2008), in the impressive demos that accompanied their groundbreaking work.

We shouldn't throw the adaptation baby out with the number bathwater just yet, but there is cause for concern here. Certainly, it seems that the standards for what constitutes *perceptual* adaptation have eroded in the years since number adaptation was discovered; we reckon there was a time when "adaptation" to symbolic numbers wouldn't have been considered "adaptation" at all, or at least not adaptation of a sort that could plausibly bear on the contents of perception. Now, such cases are rampant. Perhaps, then, it is a good time for the field to pause and revisit the phenomenon of perceptual adaptation — not just number adaptation — with fresh eyes.

References

Aagten-Murphy, D., & Burr, D. (2016). Adaptation to numerosity requires only brief exposures, and is determined by number of events, not exposure duration. *Journal of Vision*, *16*, 1-14.

Alonso, J., & Chen, Y. (2009). Receptive field. *Scholarpedia*, *4*, 5393.

Anobile, G., Arrighi, R., Togoli, I., & Burr, D. C. (2016). A shared numerical representation for action and perception. *eLife*, *5*, e16161.

Arrighi, R., Togoli, I., & Burr, D. C. (2014). A generalized sense of number. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1797), 20141791.

Aulet, L. S., & Lourenco, S. F. (2023). Visual adaptation reveals multichannel coding for numerosity. *Frontiers in Psychology*, *14*, 1125925.

Bhalla, M., & Proffitt, D. R. (1999). Visual–motor recalibration in geographical slant perception. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1076-1096.

Block, N. (2022). *The border between seeing and thinking*. Oxford University Press.

Burr, D., Anobile, G, & Arrighi, R. (2024) Number adaptation: reply. *Cognition*.

Burr, D., & Ross, J. (2008). A visual sense of number. *Current Biology*, *18*, 425-428.

Caponi, C., Castaldi, E., Grasso, P., & Arrighi, R. (2024). *Feature selective adaptation of numerosity perception* (p. 2024.05.16.594539). bioRxiv. https://doi.org/10.1101/2024.05.16.594539

Clarke, S., & Beck, J. (2021). The number sense represents (rational) numbers. *Behavioral and Brain Sciences*, *44*, e178.

Dakin, S. C., Tibber, M. S., Greenwood, J. A., Kingdom, F. A., & Morgan, M. J. (2011). A common visual metric for approximate number and density. *Proceedings of the National Academy of Sciences*, *108*, 19552-19557.

DeSimone, K., Kim, M., & Murray, R. F. (2020). Number adaptation can be dissociated from density adaptation. *Psychological Science*, *31*, 1470-1474.

Durgin, F. H. (1995). Texture density adaptation and the perceived numerosity and distribution of texture. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 149-169. https://doi.org/10.1037/0096-1523.21.1.149

Durgin, F. H. (2008). Texture density adaptation and visual number revisited. *Current Biology*, *18*, R855-R856. https://doi.org/10.1016/j.cub.2008.07.053

Durgin, F. H. (2024). Refreshing the conversation about adaptation and perceived numerosity: A reply to Yousif, Clarke and Brannon. *Cognition*.

Durgin, F. H., Baird, J. A., Greenburg, M., Russell, R., Shaughnessy, K., & Waymouth, S. (2009). Who is being deceived? The experimental demands of wearing a backpack. *Psychonomic Bulletin & Review*, *16*, 964-969.

Firestone, C., & Scholl, B. J. (2016). Cognition does not affect perception: Evaluating the evidence for "top-down" effects. *Behavioral and brain sciences*, *39*, e229.

Fornaciai, M., Brannon, E. M., Woldorff, M. G., & Park, J. (2017). Numerosity processing in early visual cortex. *NeuroImage*, *157*, 429-438.

Grasso, P. A., Anobile, G., Arrighi, R., Burr, D. C., & Cicchini, G. M. (2022). Numerosity perception is tuned to salient environmental features. *iScience*, *25*. 1-13.

Grasso, P. A., Anobile, G., Caponi, C., & Arrighi, R. (2021). Implicit visuospatial attention shapes numerosity adaptation and perception. *Journal of Vision*, *21*, 1-12.

Grill-Spector, K., & Malach, R. (2001). fMR-adaptation: a tool for studying the functional properties of human cortical neurons. *Acta Psychologica*, *107*, 293-321.

Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences*, *10*, 14-23.

Leibovich, T., Katzin, N., Harel, M., & Henik, A. (2017). From "sense of number" to "sense of magnitude": The role of continuous magnitudes in numerical cognition. *Behavioral and Brain Sciences*, *40*, e164.

Levari, D. E., Gilbert, D. T., Wilson, T. D., Sievers, B., Amodio, D. M., & Wheatley, T. (2018). Prevalence-induced concept change in human judgment. *Science*, *360*(6396), 1465-1467.

Luo, J., Yokoi, I., Dumoulin, S. O., & Takemura, H. (2024). Bistable perception of symbolic numbers. *bioRxiv*, 2024-06.

Maldonado Moscoso, P. A., Cicchini, G. M., Arrighi, R., & Burr, D. C. (2020). Adaptation to hand-tapping affects sensory processing of numerosity directly: Evidence from reaction times and confidence. *Proceedings. Biological Sciences*, *287*(1927), 20200801.

Morgan, M. J., Raphael, S., Tibber, M. S., & Dakin, S. C. (2014). A texture-processing model of the 'visual sense of number'. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1790), 20141137.

Phillips, I., & Firestone, C. (2022). Visual adaptation and the purpose of perception. *Analysis*.

Powell, L. J., Hobbs, K., Bardis, A., Carey, S., & Saxe, R. (2018). Replications of implicit theory of mind tasks with varying representational demands. *Cognitive Development*, *46*, 40-50.

Rosch, E. (1978). Principles of categorization. In *Cognition and categorization* (pp. 27-48). Routledge.

Sanford, E. M., & Halberda, J. (2023). Successful discrimination of tiny numerical differences. *Journal of Numerical Cognition*, *9*, 196-205.

Storrs, K. R. (2015). Are high-level aftereffects perceptual? *Frontiers in Psychology*, *6*, 122278.

Sun, H. C., & Baker, C. L. (2017). Texture density adaptation can be bidirectional. *Journal of Vision*, *17*, 1-10.

Yousif, S., & Clarke, S. (2024). Size adaptation: Do you know it when you see it? *Attention, Perception, & Psychophysics.*

Yousif, S. R., Clarke, S., & Brannon, E. M. (2024). Number adaptation: A critical look. *Cognition*, *249*, 105813.

Yousif, S. R., & Keil, F. C. (2020). Area, not number, dominates estimates of visual quantities. *Scientific Reports*, *10*, 13407.

Yousif, S. R., & Keil, F. C. (2021). How we see area and why it matters. *Trends in Cognitive Sciences*, *25*, 554-557.

Author Note

The pre-registration and raw data for the one experiment reported here can be found on our OSF page, along with all of the materials for our original article: https://osf.io/eh3ws/ .

Tables & Figures

	Number adaptation	Density adaptation	Old news hypothesis
Uncontroversial evidence			
Canonical number adaptation demo (Burr & Ross, 2008)	✓	✓	✓
Number adaptation is stronger in the periphery (see evidence presented here; Arrighi et al., 2014)	?	?	✓
Color changes reduce/eliminate number adaptation (Grasso et al., 2022)	?	?	✓
"Neutral" number adaptation (Yousif et al., 2024)	✗	?	✓
The neural/physiological evidence (see Burr et al., 2024)	✓	✓	✓
"Dynamic" number adaptation (Yousif et al., 2024; Caponi et al., 2024)	?	?	?
Controversial evidence			
Cross-modal adaptation (if genuine); c.f. Arrighi et al., 2014; Yousif et al., 2024	✓	?	?
Reverse adaptation (if genuine); Burr & Ross, 2008	✓	✓	✗
Reverse adaptation (if non-genuine); Yousif et al., 2024	✗	✗	✓

Table 1. A comparison of the three prominent theories contrasted in this paper: number adaptation, density adaptation, and the *old news hypothesis*. Evidence is sorted by whether it is controversial or not. Checkmarks indicate a piece of evidence that is consistent with that theory; X marks indicate evidence that is inconsistent with that theory; question marks indicate uncertainty about how a piece of evidence relates to a theory. This table reflects our views to an extent, and the classification of some cells is surely up for debate. For instance, we included question marks for all theories in the "dynamic number adaptation" row because, despite our agreement that there are repulsive behavioral aftereffects following exposure to dynamic displays, it remains unclear whether, or how much, motion influences said aftereffects. More work is needed to pass judgment on this case (and others).

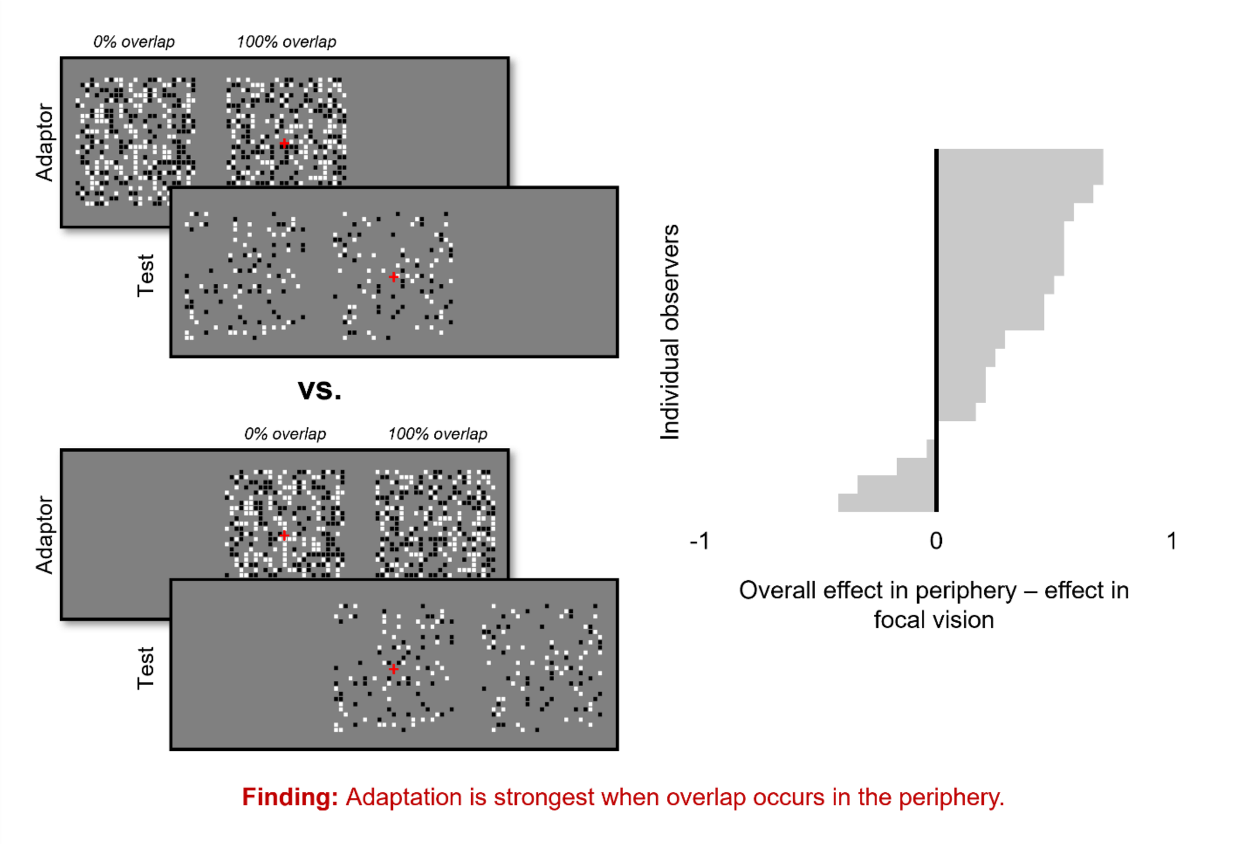

Figure 1. Number adaptation effects in the periphery vs. in focal vision. Bars further to the right indicate stronger adaptation in the periphery. Each bar represents a single observer.

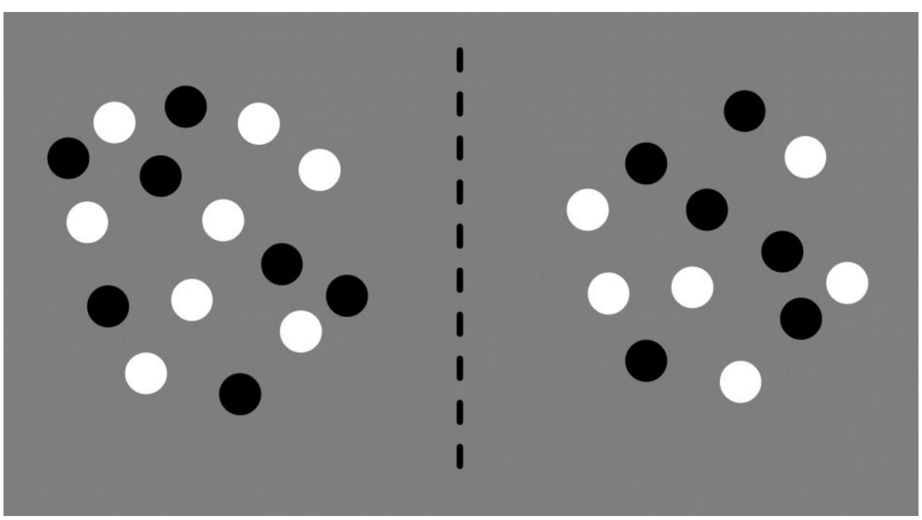

Figure 2. An example of two displays which differ in number by 25%. The difference is immediately apparent.