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Number adaptation: A critical look

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ABSTRACT

It is often assumed that adaptation — a temporary change in sensitivity to a perceptual dimension following exposure to that dimension — is a litmus test for what is and is not a "primary visual attribute". Thus, papers purporting to find evidence of number adaptation motivate a claim of great significance: That number is something that can be seen in much the way that canonical visual features, like color, contrast, size, and speed, can. Fifteen years after its reported discovery, number adaptation's existence seems to be nearly undisputed, with dozens of papers documenting support for the phenomenon. The aim of this paper is to offer a counterweight — to critically assess the evidence for and against number adaptation. After surveying the many reasons for thinking that number adaptation exists, we introduce several lesser-known reasons to be skeptical. We then advance an alternative account — the old news hypothesis — which can accommodate previously published findings while explaining various (otherwise unexplained) anomalies in the existing literature. Next, we describe the results of eight pre-registered experiments which pit our novel old news hypothesis against the received number adaptation hypothesis. Collectively, the results of these experiments undermine the number adaptation hypothesis on several fronts, whilst consistently supporting the old news hypothesis. More broadly our work raises questions about the status of adaptation itself as a means of discerning what is and is not a visual attribute.

1. Introduction

It is sometimes joked that vision science primarily serves to catalogue phenomena long known by magicians, cinematographers, and petty thieves. Occasionally, however, its discoveries offer to profoundly transform our understanding of what it means to see. Take the reported discovery of *visual number adaptation*. Since the pioneering work of Burr and Ross (2008) it has become widely accepted that observers visually adapt to the number of items in a seen collection, much as we adapt to other visible properties, like color, size, and motion. The claim is that prolonged exposure to a large number of seen items causes a middling number of items in that region to appear less numerous than they otherwise would. Conversely, prolonged exposure to a small number of items reportedly causes a middling number of items in that region to appear more numerous than they otherwise would.

These are stunning results. In canonical examples of visual number adaptation, observers enjoy obvious and phenomenologically striking aftereffects. If you adapt to 300 dots in a left-hand region of visual space, a test display containing 100 dots in that region will look remarkably sparse when compared to an otherwise identical collection of 100 dots in an un-adapted region (see Burr & Ross, 2008; see also Demo #1 in the supplemental materials on our OSF page). Since researchers have taken steps to rule out simpler explanations (e.g., by controlling for the total brightness and/or surface area of collections), received wisdom is that these results reflect adaptation to *the number* of items in seen collections. And because adaptation effects of this sort have been deemed rare or absent from thought and post-perceptual cognition (Block, 2022; Webster, 2015; c.f. Phillips & Firestone, 2022), number adaptation has been taken to suggest that number is a "primary" visual attribute, on a par with color and other low-level visual properties (Anobile, Cicchini, & Burr, 2016; c.f., Smortchkova, 2020). So, while numbers are abstract objects, located outside of space or time, number adaptation has been taken to establish that numbers nevertheless feature in the contents of human vision and visual experience; that, strange as it sounds, we literally *see* number.

Given the practical, philosophical, and theoretical implications of these claims, it is perhaps surprising that the existence of visual number adaptation has gone largely unchallenged (but see Dakin, Tibber,

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Greenwood, Kingdom, & Morgan, 2011; Durgin, 2008; Morgan, Raphael, Tibber, & Dakin, 2014). The aim of the present work is to critically assess evidence for the phenomenon. We begin our discussion by explaining why visual number adaptation appears to be an extremely well-supported empirical phenomenon, acknowledging that a cursory examination of the literature would seem to suggest that its existence has been established many times over (Section 2). We next outline unacknowledged concerns with extant evidence and note several published findings that seem to sit awkwardly with the existence of genuine number adaptation (Section 3). In doing so, a question arises: What would an alternative explanation for reported cases of the phenomenon look like? Section 4 answers to this question, introducing a simple and independently motivated *old news hypothesis* that explains key results traditionally marshalled in support of visual number adaptation. Section 5 then describes the results of 8 pre-registered experiments designed to pit the predictions of our *old news hypothesis* against those of the received *number adaptation hypothesis*. In each experiment, the predictions of our old news hypothesis were borne out, and the arguments in support of genuine number adaptation undermined. Section 6 considers the broader ramifications of these results.

2. The case for visual number adaptation

The evidence amassed in favor of visual number adaptation can seem truly overwhelming. To date, >30 studies have been published reporting its existence, with many of these studies finding clever ways to rule out non-numerical confounds as the primary drivers of the observed effects. Furthermore, the one prominent counterproposal advanced against the number adaptation hypothesis (which argues that number adaptation is better understood as density adaptation; see, e.g., Dakin et al., 2011; Durgin, 2008; Morgan et al., 2014) has ultimately proven unpersuasive, insofar as there have been compelling empirical responses (DeSimone, Kim, & Murray, 2020; but see Section 6). There are, therefore, strong prima facie reasons to accept visual number adaptation as a genuine empirical phenomenon.

Consider the original demonstration provided in Burr and Ross's (2008) supplementary materials (Fig. 1A) — perhaps the most famous illustration of visual number adaptation, one which many readers will have encountered previously. In this example, observers are instructed to stare at a central fixation point on a screen for 30 s. To the left and right of this fixation point are collections of dots which vary in number.

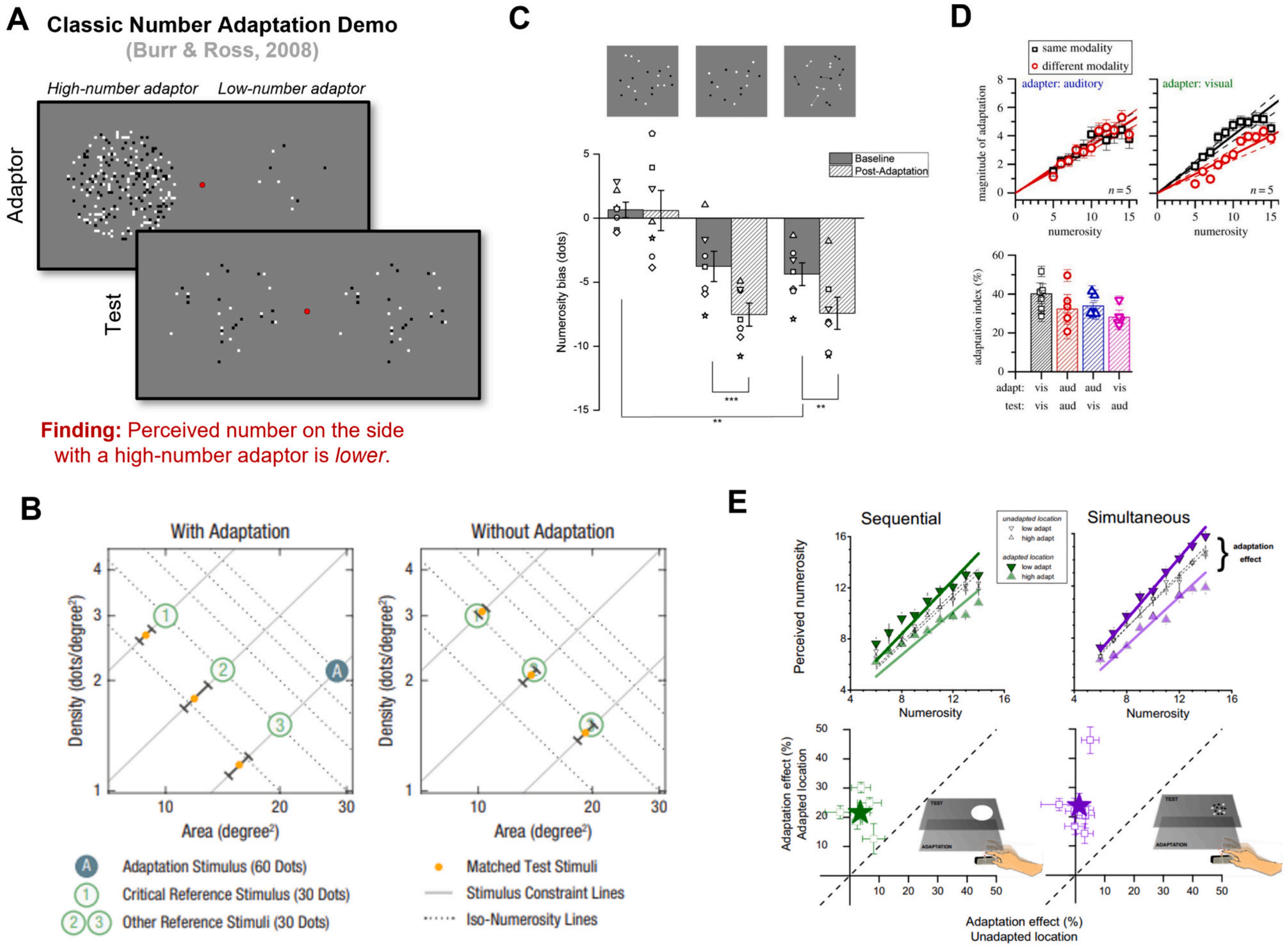

Fig. 1. (A) Burr and Ross (2008) example of number adaptation, found in their supplementary materials. Having stared at a central fixation point on the original adaptor image (top) for 30s, two identical collections in a test display (bottom) appear to contain a different number of dots. (B) Some argued that such results are simply explained by visual adaptation to density, not number. However, Desimone et al. (2020) varied the size of the spatial envelopes in which dots were located to empirically disentangle number and density – their results were taken to undermine the density adaptation hypothesis. (C) Connecting pairs of dots into single dumbbell shaped objects reduces perceived number. Thus, the right display looks like it contains fewer dots than the left display, even though both contain 20 dots (by comparison, the middle display contains 10 dots, thereby matching the quantity of bounded objects in the connected array). This manipulation of perceived number is said to influence number adaptation accordingly. (D) Arrighi, Togoli, and Burr (2014) report that subjects who adapt to a large number of heard tones, perceive a collection of seen dots to be smaller in number than in a baseline condition, where observers do not first adapt to heard tones or seen dots. (E) Anobile et al. (2016) reported that the number of taps that an observer produces in the left-or-right region of space affects seen number in comparable ways. Thus, producing a large number of taps on the left causes a middling number of dots in a display on the left of a screen to appear less numerous than it otherwise would. You can try this for yourself: Do you experience the effect?

In particular, a collection to the left of the fixation point contains many dots (∼200) while a right-hand collection contains significantly fewer (∼10). Having stared at the central fixation point for 30 s, the original collections are replaced with two new collections (in the regions of space previously occupied by the original adaptors). But while both new collections contain an identical yet middling number of dots (∼ 30), observers find that they now look markedly different. Specifically, the right-hand collection appears (at least briefly) to contain significantly *more* dots than the left. Burr and Ross's explanation is that observers have adapted to the large number of dots in the left-hand region of the original image, yielding a repulsive after effect such that the middling number of dots in the adapted region comes to appear less numerous. Meanwhile adaptation to the small number of dots in the right-hand region of the original image has caused the middling number of dots in that region to appear more numerous than it otherwise would. In either case, visual adaptation to the *number* of dots is seen to yield a repulsive visual aftereffect that operates independently of the dots and their low-level properties (e.g., their size, shape, and color). Thus, when observers adapt to a large number of dots such that a middling collection appears less numerous, it is claimed that "no particular dots seem to be missing" (Burr & Ross, 2008, p. 426; see also Munton, 2021). Rather, observers see the dots, but adaptation alters the numerical value their visual systems attribute to the collection.

We encourage readers to try or re-try Burr and Ross's original example for themselves (see also Demo #1 in our own supplemental materials). There is no denying that something happens: The test display really does look markedly different after the initial period of adaptation. Even so, you might wonder why this phenomenologically salient difference should be seen to reflect adaptation to the *number* of items in the displays, rather than some other feature of the dots or collections.

Burr and Ross's answer is that non-numerical confounds were controlled in their experiments. For instance, while the dots in their canonical demonstration (see Fig. 1A) were all identical in size, Burr and Ross varied the size of the dots in a subsequent study to ensure that observers were not simply adapting to the total surface area of the collections, or the total perimeter of the dots (this is reminiscent of the way classic investigations of non-symbolic number discrimination control for non-numerical confounds by varying the size of test items; e.g., Xu & Spelke, 2000 with human infants, or Brannon & Terrace, 1998 with non-human animals). In addition, the judged collections always contained an (approximately) equal number of black and white dots and were always presented on a middling grey background. This meant that collections were always equated for brightness, indicating that the reported effects could not be explained by known effects of adaptation to luminance. Despite controlling for these confounds, Burr and Ross reported number adaptation effects that were staggering in size: Adaptation to 400dots for 30 s caused a 70% reduction (!) in the perceived number of dots in a 100-dot collection (though recent estimates appear more conservative: Burr, Anobile, & Arrighi, 2018 report that these effects are "large, up to a factor of two in each direction" [p. 3], with Aagten-Murphy & Burr, 2016 reporting that perceived number is "shifted by up to 50%" [p. 2]).

The most prominent challenge to the number adaptation hypothesis has been that these effects merely reflect the visual system's known tendency to adapt to the density of seen collections, rather than number itself (Dakin et al., 2011; Durgin, 2008; Morgan et al., 2014). This was a legitimate concern when faced with initial reports of number adaptation: The collections of dots used in Burr and Ross's displays always occupied a uniformly sized region of space on the screen. So, while dot size sometimes varied, collections containing a larger number of dots tended to be significantly denser than collections containing a middling number of dots, while collections containing a middling number of dots tended to be denser than collections containing a small number of dots. However, subsequent work is said to have successfully addressed these concerns. Perhaps most notably, Desimone et al. (2020) controlled density in an especially elegant way, by varying the size of the spatial envelopes in which dots were located, and nevertheless found evidence for visual number adaptation.

There have now been many demonstrations of number adaptation that could seem to stand as decisive evidence of its existence. For instance, Fornaciai, Cicchini, and Burr (2016) sought to establish that adaptation operates on number (and not simply non-numerical confounds) by connecting dots with thin lines, effectively turning pairs of dots into single dumbbell-shaped objects (see Franconeri, Bemis, & Alvarez, 2009; He, Zhang, Zhou, & Chen, 2009). This manipulation reduced the number of bounded (visual) items in seen collections (Palmer & Rock, 1994; Spelke, 1990), thereby changing their *perceived* number, more-or-less independently of other physical properties of the collections (e.g., area, density). In so doing, Fornaciai and colleagues provided evidence that adaptation is influenced by the number of perceived items, independently of those items' low-level properties (Fig. 1C). After adapting to 20 unbounded dots, for instance, observers reported experiencing a reduction in number for displays of 20 paired dots (putatively because the connections reduced their perceived number) but *not* for displays of 20 unconnected dots (putatively because the adaptor and target were now perceived as equinumerous). This is a compelling manipulation of perceived number, since the addition of connecting lines in an adaptor *increases* the total surface area, perimeter, and density of the items, but *decreases* perceived number.

Perhaps even more striking, Burr's group has published several cases of *cross-modal* number adaptation (Figs. 1D & 1E). They report that adaptation to a large sequence of *heard* tones causes a middling number of *seen* items to appear less numerous, and vice versa (Arrighi et al., 2014). Similar work has found that number adaptation generalizes from touch to vision (Togoli & Arrighi, 2021) and from vision to action (e.g., in the form of manual taps on a tabletop; Anobile, Cicchini, & Burr, 2016). What's crucial is that these cross-modal studies seem to naturally eliminate non-numerical confounds as the primary drivers of these effects. After all, in an auditory-visual adaptation effect, the repulsive aftereffects described cannot be put down to properties like the area, density, size, or brightness of seen collections since the sequences of heard tones won't have those properties. Conversely, lower-level properties of the heard tones — for instance, pitch, duration, and loudness — are not visible. As such, it seems that these lower-level properties cannot be all that observers are adapting to. Hence, cross-modal studies appear to offer independent and near-decisive evidence that observers genuinely adapt to perceived number and not just low-level properties of observed collections (Block, 2022; Burr, 2017; Burr et al., 2018; Clarke & Beck, 2021).

3. Initial grounds for doubt

Faced with evidence of this sort, the existence of visual number adaptation seems hard to resist. Familiar illustrations of 'number adaptation' yield dramatic alterations to visual phenomenology that readers can freely experience for themselves; early investigations of the phenomenon ruled out simpler explanations by varying the size and brightness of the items enumerated; there has only been one serious counterproposal to the number adaptation hypothesis (the proposal that observers are merely adapting to dot density) and this has been undermined by subsequent studies; and, finally, there is compelling evidence that number adaptation operates independently of low-level confounds (e.g., from studies that manipulate number independently of area and density using well-known numerical illusions, or by taking a cross-modal approach). Perhaps, then, the existence of visual number adaptation is settled.

Despite this mountain of evidence, we think closer inspection of the number adaptation literature reveals several reasons to be skeptical.

First, it is an underappreciated fact that number adaptation is remarkably brittle. For instance, in a recent study, Grasso, Anobile, Arrighi, Burr, and Cicchini (2022) reported that changing the color of test displays as compared with the original adaptors *eliminated the number adaptation effect entirely*. That is, when observers adapted to a large collection of blue dots before being presented with a middling-sized collection of green dots in an overlapping region of space, Grasso and colleagues found no evidence of number adaptation — participants simply discriminated the number of items in the test display as they would have had they skipped the adaptation phase completely. This is a surprising finding given that number adaptation is supposed to be sufficiently abstract that it transcends modalities, generalizing from vision to audition, or action to vision (e.g., Anobile, Cicchini, & Burr, 2016; Arrighi et al., 2014). Indeed, it is the reported existence of such cross-modal adaptation effects that is often touted as definitive proof that the relevant effects pertain to number and not simply low-level confounds (Anobile, Cicchini, & Burr, 2016; Burr, 2017; see also: Block, 2022, p. 87–88; Clarke & Beck, 2021).[1] But how could it be that number adaptation is sufficiently abstract to generalize from vision to audition, but not from blue dots to green dots? Even *within* color space, a change from blue to green is about as minimal an intervention as one could conceive.

Second, we note that many documented cases of visual number adaptation fail to elicit phenomenologically compelling effects. For instance, the phenomenological effects of cross-modal adaptation seem distinctly underwhelming (to illustrate, we invite readers to compare the examples provided in supplementary materials to Arrighi et al., 2014 with those from Burr & Ross, 2008 or to try tapping their hands on a desk before looking at a collection of dots [c.f. Togoli & Arrighi, 2021]). Similarly, claimed instances of 'reverse adaptation' (wherein a small-number display causes a middling-number display to appear more numerous) are difficult to experience directly. Try for yourself: Examine the original demonstration from Burr and Ross (2008), but this time covering up the more numerous adaptor (or see Demo #5 in our supplementary materials). Given that you are now adapting to a low number on the left, you should see the right test image as containing a larger number than the left test image. Do you?

While a lack of phenomenologically compelling demonstrations is not decisive, it raises questions about what exactly is going on in these studies, motivating the thought that cases of this sort will likely differ in important ways from more familiar examples of number adaptation.

Finally, it is worth noting that number adaptation is unlike paradigm instances of visual adaptation in several interesting respects. First, canonical forms of visual adaptation are *retinotopic*. Number adaptation is not. Number adaptation has been reported as *spatiotopic* or "not completely retinotopic" (Burr et al., 2018, p. 2), though some cases of number adaptation appear to be neither spatiotopic nor retinotopic (e.g., Arrighi et al., 2014). Second, number adaptation is argued to depend on the deployment of visuospatial attention in ways that paradigm cases of visual adaptation do not. For instance, Grasso, Anobile, Caponi, and Arrighi (2021) found that visually adapting to a single high-number collection yields a stronger reduction in the perceived number of items in a middling test display than when observers adapt to two collections (e.g., one high and one middling [or neutral] in number) simultaneously. Once again, this is atypical: Other canonical kinds of adaptation, like orientation adaptation, are not influenced by the presence of multiple adaptors, as Grasso and colleagues themselves show. While these differences do not refute the existence of number adaptation, they are unexpected in the sense that they are not independently predicted by the number adaptation hypothesis. Should some alternative to the number adaptation hypothesis straightforwardly predict these results, that would be a mark in its favor.

With these complications in view, the remainder of this paper will be devoted to offering, motivating, and testing an alternative to the number adaptation hypothesis which we think offers a simple explanation for extant evidence, and straightforwardly predicts the above discrepancies. For brevity, we call our proposed alternative *the old news hypothesis.*

4. The old news hypothesis

To introduce our hypothesis, consider Burr and Ross's original demonstration of number adaptation, provided in the supplementary materials to their (2008) study and discussed above (Fig. 1A/Demo #1 in our supplementary materials). In this example, observers are presented with two collections: one collection contains a large number of dots to the left of a central fixation point, and one collection contains a small number of dots to its right. After staring at the central fixation point for 30 s the original collections are replaced with two novel collections of dots in the same spatial locations as the original adaptors. But while both novel collections contain an identical yet middling number of dots, observers now find that the collection on the right appears to contain more dots. The difference here is phenomenologically striking and hard to deny.

According to the orthodox number adaptation hypothesis, this effect is a direct result of having adapted to a large number of dots in the left region of space, and a small number of dots in the right. In both cases this yields a repulsive numerical aftereffect. Thus, adaptation to a large number on the left causes the middling number of dots on the left to appear less numerous than they otherwise would, while adaptation to a small number on the right causes the middling number of dots on the right to appear more numerous than they otherwise would. Crucially, however, "no particular dot disappears from the test patch" and "new dots are not created" (Burr et al., 2018, p.3). The accepted interpretation is, thus, that observers adapt to number in abstraction from other properties of the collections, yielding a repulsive and bidirectional aftereffect. According to Burr and Ross (2008), this is akin to motion adaptation, in which an item's perceived direction of movement is distorted independently of its perceived spatial position (Addams, 1835; Crane, 1988; c.f. Bayne, 2010) or chromatic adaptation which alters perceived illumination independently of color (Smithson & Zaidi, 2004).

The old news hypothesis rejects this suggestion. It explains the above result by instead appealing to the visual system's known tendency to filter out old information and to prioritize newsworthy content (McBurney, 2010, p. 406; Bonneh, Donner, Cooperman, Heeger, & Sagi, 2014; Block, 2022, p. 99).[2] As such, it proposes that if/when the dots located in a test display are visually represented as *the same objects* from the original adaptors (and, thus, *as old news*), visual sensitivity to these is reduced as compared with dots that are represented as new. Consequently, there is a real sense in which old dots "disappear" from view, or otherwise fail to be registered by the observer.

To see how this offers to explain Burr and Ross's original demonstration, consider that adaptation to a large number of items in the left-hand region of the original adaptor display provides many more opportunities for the visual system to (rightly or wrongly) identify items in the left-hand test display *as* items from that original adaptor (and, thus, as *old news* to be filtered out, when there are new dots to see). Why? Because spatial proximity is known to be one of the strongest cues to item identity for the visual system (Flombaum, Scholl, & Santos, 2009) and adapting to a large number of dots in a spatial region makes it statistically more likely that some of those dots will overlap or sit adjacent to dots in a subsequent test display. In this way, adaptation to a

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[1] This point is even acknowledged by staunch critics of a number sense. For example, Leibovich, Katzin, Harel, and Henik (2017) note that cross-modal studies provide "[a] very strong line of evidence" that number is the relevant perceptual dimension (p.5). But while they are at pains to reject this conclusion (suggesting, instead, that they involve a more general "sense of magnitude"), the counterarguments that they advance simply target a related but orthogonal suggestion: that the numerical acuity in question is innate and congenital (c.f., Izard, Sann, Spelke, & Streri, 2009).

[2] In emphasizing as much, the old news hypothesis is agnostic as to whether the function of *delivering the news* is unique to perception, and it is also agnostic on whether this is perception's *primary* function (compare Block, 2022 and Philips and Firestone (2022) for conflicting positions on both points).

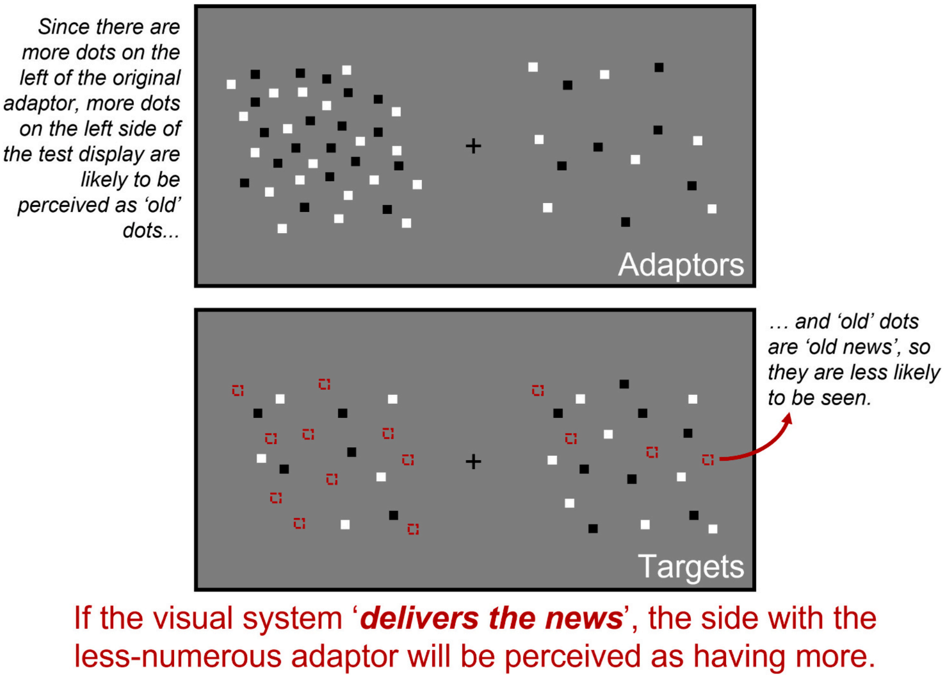
collection with more items on the left should tend to result in more dots from the left collection of the test display being interpreted as old dots from the original adaptor. Since the visual system filters out old news to prioritize conscious awareness or sensitivity to dots that it deems 'new', the upshot is that observers literally end up *seeing* fewer of the dots in the left-hand test display (see Fig. 2 for a visual explanation) — all without any adaptation to *the number* of items in the collections.

One might be tempted to reject this "old news hypothesis" on the grounds that it is not parsimonious. Why entertain a new explanation for a phenomenon that already has an agreed-upon explanation? The answer, we think, is that the "old news hypothesis" should be viewed as the default explanation, since it is motivated by known principles of visual perception. A myriad of long-established and well-known phenomena — including binocular rivalry, Troxler fading, and motion induced blindness — reflect the visual system's general tendency to filter out old information. Readers are especially encouraged to look online at demonstrations of Troxler fading, in which one can see, within a matter of seconds, what it looks like for 'old information' to be filtered from awareness by the visual system (Troxler, 1804). These phenomena often result in "observers fail[ing] to be consciously aware of objects and events" that are presented "right in front of" them (New & Scholl, 2008, p. 653). In cases of motion induced blindness, for instance, "fully visible and attended objects" disappear entirely from conscious awareness when they are left largely unchanging and are presented onto "global moving patterns" (New & Scholl, 2008, p. 1). While the mechanisms of Troxler fading and motion induced blindness differ in important ways (Bonneh et al., 2014), the visual system's tendency to filter out old news is so pervasive that many theorists have gone so far as to conjecture that the primary function of human vision is that of *delivering the news* (Block, 2022; McBurney, 2010). Hence, if we limit ourselves to Burr and Ross's original example, discussed above, it could seem that the old news hypothesis *is* the most parsimonious explanation for apparent number adaptation. Without independent motivation, it is the number adaptation hypothesis that seems ontologically extravagant.

The old news hypothesis is further supported when we consider that it offers to straightforwardly explain the discrepant findings noted in Section 3. First, take Grasso et al. (2022) finding that changing the color of the dots in adaptor and test displays (e.g., from blue to green) eliminates number adaptation entirely. As we have discussed, this is puzzling from the perspective of visual number adaptation: How is it that number adaptation reaches across modalities (see Arrighi et al., 2014) but not across a minimal color change? By contrast, this puzzling result is easily accommodated by the old news hypothesis: Changing the color of an old dot renders it newsworthy once again by resulting in something *new* for the visual system to make salient for the observer. Approached through the lens of the old news hypothesis, changes to the color of the dots *should* eliminate apparent cases of number adaptation.

Second, the old news hypothesis can explain Grasso et al., 2021) finding that adaptation to two displays (one which is high in number and one which is middling in number and, thus, matches its target in number) yields a weaker adaptation effect than when observers adapt to a single (high adaptor) display. Since familiarization to a middling number adaptor will result in *some* opportunities for items in spatially overlapping test displays to be deemed *old news* (familiar dots), the old news hypothesis predicts that observers would experience a modest reduction in the number of perceived items therein. This inevitably results in a smaller contrast with a contralateral display whose perceived number has been more dramatically reduced and does not require that we invoke any effects of visuo-spatial attention to explain the result — a welcome conclusion, we think, since adaptation effects are (by all accounts) normally considered immune to such effects (ibid.).

Finally, the old news hypothesis explains why reverse number adaptation (i.e., adaptation to a small number of items such that a middling number of dots then appears more numerous than it otherwise would — Demo #5 in our supplementary materials) is phenomenologically underwhelming. Readers are again encouraged to experience this for themselves. Prima facie, nothing happens! This is exactly what the old news hypothesis predicts. The old news hypothesis explains canonical cases of number adaptation by appealing to the fact that 'old' information is filtered from awareness, thereby reducing perceived number. This explanation, by definition, is unidirectional; it could not explain why a stimulus would appear more numerous. Yet as far as we can see (and as we will go on to show, in the following section) it does not appear that there are cases in which a stimulus is perceived as more



Since there are more dots on the left of the original adaptor, more dots on the left side of the test display are likely to be perceived as 'old' dots...

... and 'old' dots are 'old news', so they are less likely to be seen.

If the visual system '***delivers the news***', the side with the less-numerous adaptor will be perceived as having more.

Fig. 2. The 'old news' hypothesis offers to explain Burr and Ross (2008) example by positing that observers fail to see 'old' objects in the test display, since the visual system prioritizes presentation of 'the news' (McBurney, 2010, p. 406; Block, 2022, p. 99).

numerous as a result of adaptation.

Still, we are not suggesting that any of these arguments decisively establish the old news hypothesis as true, nor that they refute the existence of visual number adaptation. We are simply noting that there is an alternative explanation for classic cases of visual number adaptation that is well-motivated and deserves to be investigated further. This alternative explanation — *the old news hypothesis* — is parsimonious in that it appeals only to well-known mechanisms of visual filtering and has the virtue of neatly explaining various (otherwise puzzling) results that complicate the evidence for visual number adaptation. With this in view, the remainder of this paper describes the results of 8 pre-registered experiments, which were designed to empirically disentangle these two competing hypotheses.

5. Experiments

In what follows, we describe the results of 8 pre-registered experiments designed to test the predictions of our old news hypothesis. Experiments 1–4 demonstrate that canonical cases of number adaptation (e.g., Burr and Ross's original demonstration, discussed above) can be explained by our old news hypothesis, and thus provide no reason to posit number adaptation. Experiments 5–6 consider 'harder' cases which have been said to decisively establish the existence of number adaptation (e.g., connectedness studies and reported cases of cross-modal adaptation). To foreshadow: While many of these results ran contrary to the predictions of the number adaptation hypothesis, the old news hypothesis predicted them all. Our results therefore suggest that claims about the existence of number adaptation should be reevaluated, and more attention should be paid to alternative hypotheses, including the old news hypothesis.

5.1. Experiment 1 – Overlap

Our first experiment was intended to serve as a basic proof of principle. We tested whether 'number adaptation' is influenced by the degree of spatial overlap between dots in the adaptor and the target stimuli. We focused on spatial overlap given that spatial proximity is a particularly strong cue to item identity (Flombaum et al., 2009). Given that the old news hypothesis posits that dots are filtered out by the visual system when they are unchanging across the adaptor and test displays (and, thus, deemed 'old news') we predicted that increasing the amount of spatial overlap of dots between the adaptor and test stimulus would *increase* the amount of information that is filtered out and thus *decrease* the perceived number of items in the test stimulus. In other words, more overlap should result in a stronger and more robust adaptation effect.

To test this basic prediction, Experiment 1 had the following structure: On all trials, observers were presented with two adaptors (one on each side of the screen). One of the adaptors always had 100% overlap with its subsequent target, meaning that every dot present in the test display had been present in the same location, and with the same color, in the original adaptor. Meanwhile, the other adaptor always had 0% overlap with its subsequent target, meaning that every dot present in the target was in a location that had not been previously occupied by any dots in the adaptor. The adaptors and targets also varied in a number of systematic ways. (For a detailed description, see *Methods*.)

We found a canonical 'number adaptation' effect (see Fig. 3A-C). Observers were more likely to indicate that the left side had more dots when they had adapted to a higher number on the right (66% of the time; $t(19) = 3.71$, $p = .001$, $d = 0.83$), and they were more likely to indicate that the right side had more when they were adapted to a higher number on the left (74% of the time; $t(19) = 4.28$, $p < .001$, $d = 0.96$). Moreover, observers were sensitive to the number of dots that were present in the test displays. Averaged across all manipulations, observers selected the side with more dots in the test displays 61% of the time ($t(19) = 3.93$, $p < .001$, $d = 0.88$). Our critical question, however, was whether the degree of item overlap would influence adaptation. It did: Observers were strongly influenced by the degree of overlap between the items in the adaptors and targets. Collapsing across all other manipulations, observers were significantly more likely to indicate that the side with 0% overlap was more numerous (59% of the time, $t(19) = 3.58$, $p = .002$, $d = 0.80$). The same is true even if we look only at those trials for which the target number was equated; observers still chose the side with 0% overlap 61% of the time ($t(19) = 3.82$, $p = .001$, $d = 0.86$).

A reviewer helpfully pointed out that our design is slightly different from the designs of some other number adaptation studies in that it did not include a 400 ms delay between the adaptor and target stimuli (see, e.g., Burr & Ross, 2008). They wondered whether this could explain the overlap effect. We opted not to include this delay because we wanted our studies to resemble the demonstration of number adaptation that was originally popularized by Burr and Ross (2008), and which did not contain that delay. We also reasoned that results of inserting a 400 ms delay should not alter the conclusions from our experiment without the delay. For a start, if the overlap effect did not persist over 400 ms, as the reviewer speculated, this could still be explained by appeal to the old news hypothesis. After all, ensuring that all the dots momentarily disappear and subsequently pop back into existence is surely something that the visual system might wish to make salient to the subject. Thus, it is possible that a delay might eliminate the effect, precisely because old news was driving the original result. Secondly and conversely, if the results persisted, this would still be evidence that overlap was a relevant confound in number adaptation experiments. Finally, if the results persisted but the effects of overlap were reduced or weakened, it is possible that this could be attributed to the delay decreasing the visual system's certainty about which dots correspond to which other dots and, thus, which dots were old news (thereby *increasing* the influence of the *number* of dots, but *decreasing* the influence of precise spatial overlap). In other words, we felt that whether or not we observed an effect of overlap after a 400 ms delay would have no bearing on the validity of the old news hypothesis (or, for that matter, the number adaptation hypothesis). Nevertheless, for good measure, we replicated Experiment 1 with the 400 ms delay between the adaptors and the targets. Collapsing across all other manipulations, there was no effect of overlap ($t(19) = 0.37$, $p = .72$, $d = 0.08$). But looking only at our critical trials (as we pre-registered we would do), there was a significant, albeit weakened, effect of overlap ($t(19) = 2.58$, $p = .02$, $d = 0.58$). These data are included as Experiment S1 in the data file on our OSF page.

In sum, Experiment 1 establishes that overlap can significantly influence the strength of 'number adaptation' effects. This is consistent with our old news hypothesis, since overlap (and spatial proximity more generally) is an important cue to item identity for the visual system and, hence, to an item's status as *old news*. Had such a result failed to materialize we accept that this would have strongly undermined our proposal.

At the same time, we do not claim these results come anywhere close to refuting the number adaptation hypothesis. Proponents of number adaptation can accommodate the observed effects of overlap by acknowledging that low-level effects of (e.g.,) contrast adaptation affect observers' sensitivity to dots, thereby influencing their perceived number. Thus, they might legitimately interpret these findings as reflecting a compound effect of both overlap and genuine number adaptation.

Even so, it is worth noting that the effects of overlap found in Experiment 1 already highlight a significant confound in existing studies of visual number adaptation. As far as we can tell, dot positions in prior number adaptation studies have always been fully randomized. The inevitable consequence is that adaptors containing large numbers of dots are more likely to have more dots overlap with those in their corresponding target displays. Indeed, this finding is important even if number adaptation genuinely obtains. For one, proponents of visual number adaptation regularly seek to quantify the strength of numerical adaptation effects — for instance, reporting that adaptation to a 400dot display can cause a 100dot display to appear equinumerous to just 30 dots in an un-adapted region (Burr & Ross, 2008; c.f., Aagten-Murphy &

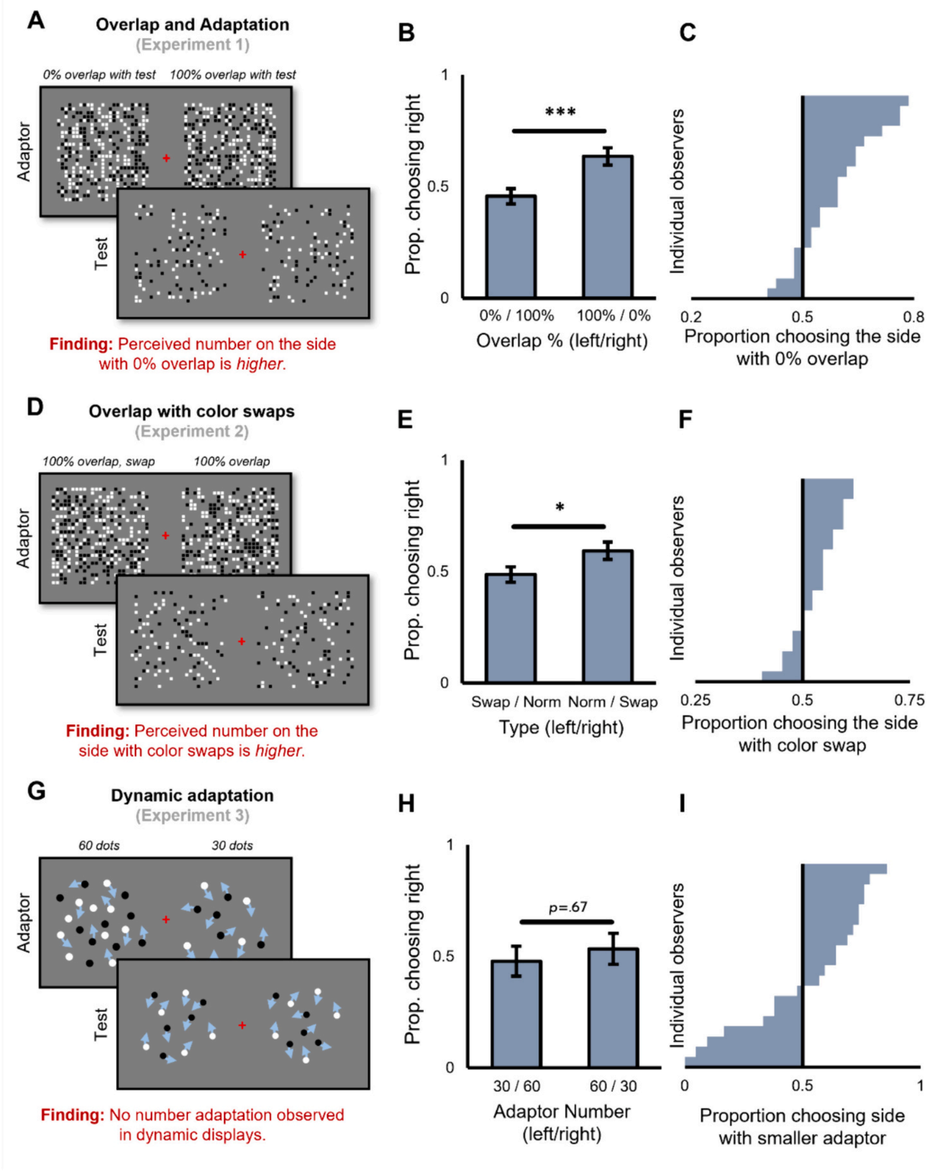


Fig. 3. Design and results of Experiments 1–3. (A, D, G) A visual depiction of a representative trial. (B, E, H) The proportion of time that observers chose the right side as a function of the trial type. (C, F, I) The magnitude of the relevant effect for each observer. Error bars represent +/− 1 SE.

Burr, 2016; c.f., Burr et al., 2018). But if it is true that low-level effects of overlap explain at least a portion of the observed effects — and it seems clear that they do — describing the magnitude of the effects in this way could be misleading.

5.2. Experiments 2 & 3 – Color and motion

Experiment 1 showed that spatial overlap (a cue to object identity and, thus, specific dots being *old news* for the visual system) significantly influences observer responses in number adaptation tasks. While this finding does not refute the existence of genuine number adaptation, it is consistent with, and motivates further consideration of, our old news hypothesis. Thus arises the question: Could cues to visual dot identity fully explain the documented reduction in perceived number, associated with adaptation to high-number collections?

Prima facie, it might seem not. After all, 'number adaptation' was not entirely eliminated when dots enjoyed 0% overlap across adaptor and test displays (as can be seen in the supplemental Demo #2.2 on the OSF page). Thus, dots in adaptor and test displays need not perfectly overlap to elicit the reduction in perceived number that is standardly associated with high-number adaptation. This does not settle the question, however. For a start, fully controlling for the effects of overlap, found in Experiment 1, is easier said than done. For even when there is 0% physical overlap among dots in an adaptor and test display, we cannot assume that the visual system does not treat dots as overlapping. This is because the receptive fields of adapted neurons are sufficiently large that low-level adaptation effects need not require perfect overlap among items. Indeed, the receptive fields of neurons are known to be larger in the periphery (Alonso & Chen, 2009), including those neurons in the lateral intraparietal sulcus (Ben Hamed, Duhamel, Bremmer, & Graf, 2001) which are hypothesized to implement the number adaptation effects under consideration (Anobile, Cicchini, & Burr, 2016; Roitman, Brannon, & Platt, 2007). As such, it is possible that this explains the otherwise puzzling fact that number adaptation (and particularly, the associated reduction in perceived number observed after adapting to a large-number display) is strongest when collections are presented in the periphery (Arrighi et al., 2014). In fact, we are not aware of any robust number adaptation effects that do *not* depend on the items being presented in the periphery. This point is worth a moment's reflection: There is no obvious reason why number adaptation should be stronger in the periphery, not least because this is (yet again) atypical of visual adaptation in general (e.g., Gao, Webster, & Jiang, 2019; but see, e.g., Zimmermann, 2023).

To compound matters, overlap is not the only cue to object identity that must be considered when adjudicating the old news hypothesis. To illustrate, try flicking back and forth between the adaptor and test displays in Burr and Ross's original example; here, you will experience *apparent motion* of individual dots. That is, you will not perceive some dots disappearing and new dots popping into existence; you will perceive some individual dots as appearing to move from one location to another. Thus, it is demonstrably the case that individual dots *are* tracked by the visual system across adaptor and test displays, even when their positions change from one timepoint to another. The visual mechanisms involved in filtering out *old news* might filter out *old dots* when they move in predictable ways so as to prioritize visual discrimination of dots which are entirely new or otherwise novel — as plausibly occurs in cases of Troxler fading (see: 'Pacman illusion' or 'Lilac Chaser illusion') and cases of motion induced blindness, where slowly moving target items (akin to floaters in the eye) disappear from view (New & Scholl, 2008).

Indeed, prior work on number adaptation has already provided reason to believe that *old news* may explain numerical adaptation effects. Grasso et al. (2022) showed that simply switching the color of items from adaptors to targets fully eliminates number adaptation, perhaps, as they argue, because the perceptual system is sensitive to 'salient environmental features.' On our account, however, these findings are better explained by the fact that color changes render 'old dots' newsworthy again for the visual system.

To test this explicitly, Experiment 2 compared two key conditions: In one condition, dots in a test display had 100% spatial overlap with dots in their corresponding adaptor, just like the previous experiment. In another condition, dots in a test display also had 100% spatial overlap with dots in their corresponding adaptor but, unlike before, every dot changed color (i.e., every dot that was white turned black and vice versa). As expected (and consistent with the abovementioned prior work, conducted by proponents of number adaptation), a simple color swap significantly influenced the magnitude of the adaptation effect ($t(19) = 2.48$, $p = .023$, $d = 0.56$; see Fig. 3D-F). Note that this effect is more subtle, both statistically and phenomenologically (see Demo #3). Here, we intend to make no claims about what information (e.g., color vs. location changes) is meant to be more newsworthy; we are only observing that newsworthy differences between the adaptor and target do seem to affect the adaptation effect to some degree.

In many respects, the work of Grasso and colleagues makes our key point in an even more compelling way (i.e., they observe a complete elimination of adaptation when colors change). What is different here is that our effects cannot be explained by a global change in the color of the stimuli, as both adaptor and test displays were always composed of an equal proportion of black and white dots. In our experiment, what differed between the adaptor and test displays was merely the correspondence between the colors of the dots and their given locations. In other words, the result here hints at the fact that the relevant adaptation is occurring (at least in part) at the level of individual items rather than the entire ensemble.

Of course, this is only one piece of evidence. Perhaps color changes are unique in eliminating the number adaptation effect (though we struggle to discern a principled explanation for why this might be). However, if the old news hypothesis is correct, and a reduction in perceived number is *entirely* driven by the visual system's filtering out of old news, we would predict that making old dots newsworthy in other (seemingly unrelated) ways may, likewise, eliminate apparent cases of number adaptation. Simply put, unexpected changes to the dots may, again, constitute 'news' such that the visual system will make 'old' dots salient to the observer once again, thereby preventing these from disappearing.

Experiment 3 sought to test whether motion might influence number adaptation in this way. We constructed dynamic displays in which the dots moved around within fixed spatial envelopes on the screen in pseudo-random (and, hence, unpredictable) directions (see Demo #4). On the number adaptation hypothesis, there is no reason (that we can conceive of) why motion should eliminate the adaptation effect. After all, observers continue to readily discriminate the number of dots in the collections and all dots were bound to move around fixed spatial envelopes. However, if the effects of 'number adaptation' are instead driven by the newsworthiness of the dots (as the old news hypothesis predicts), the reduction in number that is associated with large-number adaptation may be eliminated in a dynamic display where the random motion of dots constantly provides newsworthy content for the visual system.[3]

With these dynamic stimuli, we ran a basic number adaptation study in which adaptors had either 60 dots or 30 dots and targets had 25, 30, or 35 dots (see Fig. 3G). For the entirety of the adaptation and test periods, the dots moved continuously around the display (at different trajectories and speeds). We used smaller numerical values than the previous experiments to accommodate the dynamic stimuli (i.e., to ensure that the dots were not constantly overlapping with one another throughout the animation). Prior work has shown that adaptation to 60 dots is sufficient to alter the perceived number of 30 dots (see DeSimone et al., 2020).

Crucially, the dynamic nature of the displays did not interfere with observers' ability to compare the numerical values of the arrays: Observers were able to successfully discriminate between 25, 30, and 35 dots in the target ($t(19) = 4.48$, $p < .001$, $d = 1.00$). Even so, we failed to observe any evidence of number adaptation (see Fig. 3 H—I). Observers were no more likely to choose the side on which they had adapted to 30 dots versus 60 ($t(19) = 0.32$, $p = .76$, $d = 0.07$, BF $= 0.24$). To help interpret this null effect (and other null effects in this paper), we also calculated Bayes factor for the critical effect. Bayes factors are reported as a measure of relative evidence for an alternative hypothesis (here, a difference from the chance value of 50%) relative to a null hypothesis (no difference from chance). Whereas Bayes factors >3 are considered substantial evidence in favor of the alternative hypothesis, Bayes factors $<1/3$ are considered substantial evidence in favor of the null hypothesis (see Wetzels et al., 2011). Here, therefore, there is substantial evidence in favor of the null hypothesis that there is no number adaptation for dynamic stimuli. Notably, however, this null effect is unusual in that many observers exhibited what looks like an effect of number adaptation; it just so happened that about as many observers exhibited an effect in the opposite direction (see Fig. 3I). This is unusual. It suggests to us that response biases may be influencing responses to some degree. For this reason, this latter result should be interpreted with caution.

The null effect, nevertheless, appears to be in tension with the 'number adaptation' hypothesis. It is difficult to see why moving dots should eliminate number adaptation effects, given that number adaptation is supposed to concern an ensemble percept that abstracts away from low-level properties of the display, and given that observers continued to perceive and discriminate the approximate number of dots that the moving collections contained. Indeed, this much is particularly perplexing when we remind ourselves that number adaptation is supposed to generalize across modalities. Why would "a perceptual system that transcends vision and audition to encode an abstract sense of

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[3] This prediction comes with the caveat that whether/how motion influences adaptation will almost certainly depend on the nature of that motion. Dots that move slowly may be easily recognized by the visual system as "old news" like static and unchanging dots. Likewise, the strength of the effect could depend on how the motion changes from one timepoint to another: A display in which dozens of dots move in random directions is different from a display in which all the dots suddenly move in different directions. These factors will intrinsically limit the generalizability of this experiment.

number in space and in time…" (Arrighi et al., 2014, p. 1) falter under the most basic of dynamic viewing conditions (even when participants continue to approximately enumerate the collections), or when dots enjoy a modest change of color (as in Experiment 2, as well as Grasso et al., 2022a)? By contrast, each of these results is naturally accommodated by the old news hypothesis.

5.3. Experiments 4a & 4b – Reverse adaptation

The findings from Experiments 1–3 place pressure on the claim that number adaptation accounts for the apparent reduction in number associated with adaptation to large collections. Even so, our alternative hypothesis — that the visual system is simply filtering out 'old news' — might seem to fare no better. This is because there are well-known findings that appear to be directly at odds with our proposal.

Take, for instance, reported cases of 'reverse number adaptation', where a low-number adaptor causes a middling number target to appear more numerous (e.g., Aulet & Lourenco, 2023; Burr & Ross, 2008). If 'old' items are causing similar items in the targets to be filtered out, how could this manifest an *increase* in perceived number? On the face of it, this evidence is more consistent with the number adaptation hypothesis.

Given the significance of 'reverse' number adaptation, we investigated this phenomenon in two additional experiments. In Experiment 4a, we replicated the basic effect (see Fig. 4A).[4] We demonstrated that in a double-adaptor trial (where observers adapt to a low-number on one side of a screen and a middling number on the other) observers are indeed more likely to choose the side where they had adapted to a low number as *more numerous* when subsequently tested on two middling collections (78% of the time; $t(19) = 19.6$, $p < .001$, $d = 4.38$; see Fig. 4C). On the number adaptation account, these findings are easily explained: The low-number adaptor causes the corresponding target to appear more numerous due to a repulsive aftereffect. Meanwhile, the middling-number adaptor has no effect on observers' perception of a middling test display since there is no change in number (this is akin to the way that adapting to a red surface and then being presented with *more red* fails to yield a discernable, repulsive aftereffect).

Crucially, the old news hypothesis offers an alternative explanation for this result. On the view that 'old' information is being filtered out in favor of the 'new', we predicted that adaptation to the middling-number adaptor caused less of the dots in an equinumerous test display to be seen, since a middling number adaptor enables more dots to be erroneously identified with those from the adaptor. Thus, where the number adaptation hypothesis explains the results of Experiment 4 by appealing to a perceived *increase* in number caused by adaptation to a low-number display (and adaptation to the middling-number adaptor having no effect on the perceived quantity of a middling-number test display), the old news hypothesis explains this result in terms of a *decrease* in perceived number brought about by the middling-number adaptor. In other words, the number adaptation hypothesis and the old news hypothesis explain the above case of reverse adaptation by positing effects that primarily occur on opposite sides of the display.

To test these divergent explanations, Experiment 4b 'split' the adaptors used in Experiment 4a in half (see Fig. 4B). We used identical stimuli to those described above but separated adaptor displays such that each trial consisted of only one adaptor at a time. Thus, observers *either* adapted to a single low-number adaptor on one side of the screen (with this expected to elicit an increase in perceived number on the number adaptation hypothesis and little to no effect on the old news hypothesis) *or* a single middle-number adaptor on the other (with this expected to elicit a decrease in perceived number on the old news hypothesis and little to no effect on the number adaptation hypothesis). Consistent with the old news hypothesis, we found that responses were driven not by the low-number adaptors but by the middling-number adaptors (see Fig. 4D). On the trials where observers adapted to a single middling-number adaptor, observers chose the contralateral side 73% of the time ($t(19) = 6.35$, $p < .001$, $d = 1.42$, BF = 4707). In contrast, on trials where observers adapted to a single low-number adaptor, observers chose that same side only 54% of the time, no different from chance ($t(19) = 1.01$, $p = .33$, $d = 0.23$, BF = 0.37). The Bayes factor for this latter comparison indicates moderate evidence in favor of the null hypothesis in the latter comparison.

These results suggest that reverse number adaptation does not genuinely obtain. While there was no discernible effect elicited by adaptation to a low number display, there was a pronounced effect of adaptation to a middling number display. You can see as much for yourself (see Demo #5). In both cases, the findings from Experiment 4b run contrary to the predictions of the number adaptation hypothesis. They are, however, predicted by the old news hypothesis which holds that apparent cases of number adaptation are *entirely driven* by visual mechanisms filtering out *old news* (and thus, reducing the number of items that observers see). Since adaptation to a middling-number adaptor provides more opportunities for dots in the test display to be identified as *old dots,* already adapted to, the old news hypothesis predicts that less dots will be seen in a test display when that test display occupies a region of space that overlaps with a middling number adaptor.

5.4. Interim summary and discussion

Experiments 1–4 introduce four novel results that problematize received formulations of the 'number adaptation' hypothesis — the effect of overlap in Experiment 1, the elimination of an adaptation effect following simple color changes at the level of individual items in Experiment 2, the fact that motion eliminated number adaptation entirely in Experiment 3, and the fact that apparent cases of 'reverse adaptation' failed to obtain in Experiment 4b.

Meanwhile, all of these results bear out the predictions of an independently motivated alternative explanation for purported cases of the phenomena: each is consistent with, and predicted by, the view that the visual system is simply 'filtering out old information' in apparent cases of number adaptation. On this view, it makes sense that overlap would increase the effects of adaptation: Items of the same color and in the same location are 'old news'. It also makes sense that a change in color, or the introduction of random motion, could eliminate any sign of adaptation: A color change, or an unpredicted change in position, is newsworthy to the visual system. Finally, it makes sense why a middling-number adaptor would cause a middling-number target to appear less numerous (insofar as there are opportunities for overlap, or item identity to be tracked, there are opportunities for new dots in a test display to be erroneously deemed '*old news*', familiar from an adaptor, and thus filtered out). Thus, Experiments 1–4 reveal that canonical illustrations of visual number adaptation – such as the illustration provided in Burr and Ross (2008) supplementary materials, described above, and seen by many — provide little reason to posit the existence of number adaptation at all. On inspection, they are more consistent with our proposal.

Nevertheless, proponents of number adaptation might dismiss this suggestion for independent reasons. They may argue that we have so far

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[4] There is some ambiguity about whether we directly replicated the methods of Burr and Ross (2008). We have received conflicting information about whether the original studies used a double adaptor or a single adaptor design, and the materials in the original paper are, in our opinion, ambiguous. However, one reviewer felt strongly that it was misleading to say that Experiment 4a is a direct replication of Burr and Ross because they interpreted the original paper as having used a single adaptor in contrast to our double adaptor. They felt it would therefore be more appropriate to say that Experiment 4b is the direct replication. If framed this way, then our results constitute a straightforward failure to replicate the original results (setting aside the methodological choice we made not to include a 400 ms delay between the presentation of the adaptors and targets).

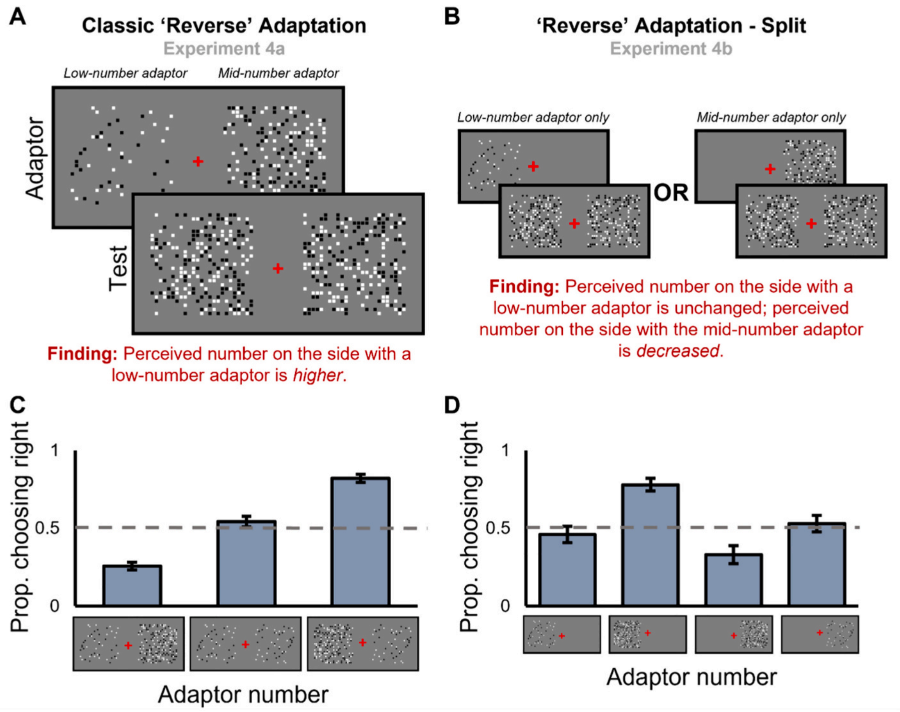

Fig. 4. Design and results of Experiments 4a and 4b. (A) A visual depiction of a representative trial in Experiment 4a. (B) A visual depiction of representative trials in Experiment 4b. (C) Results of Experiment 4a. (D) Results of Experiment 4b. Error bars represent +/− 1 SE.

failed to accommodate two remaining elephants in the room — the fact that 'number' adaptation is affected by connectedness, wherein the visual system adapts to the number of whole bounded objects in an array, independently of those objects' low-level confounds (Fornaciai et al., 2016), and the fact that there are *cross-modal* number adaptation effects. Cross-modal effects, in particular, are considered a 'gold standard' in the sense that they cannot be explained by low-level confounds like density or area or overlap (see Barth, La Mont, Lipton, & Spelke, 2005). Indeed, the existence of cross-modal effects is often described as the strongest evidence in favor of number adaptation (Block, 2022; Burr, 2017). Buoyed by the results of Experiments 1–4, Experiment 5, 6a, and 6b were designed to examine these reported effects more closely.

5.5. Experiment 5 & 6 – Connectedness and cross-modal effects

Broadly speaking, cues to objecthood influence perceived number. For instance, connecting pairs of dots with thin lines effectively turns pairs of dots into bounded dumbbell shaped objects, and this is known to significantly reduce the perceived number of dots in a collection (Franconeri et al., 2009; Yu, Gunn, Osherson, & Zhao, 2018). Indeed, such results persist even though observers are instructed to ignore the lines and attend only to the dots. Thus, it is as if observers cannot help but visually enumerate the bounded objects in a seen collection, even when this is detrimental to task performance and even though the addition of connecting lines increases items' continuous properties (e.g., their total surface area) while reducing their number (see He et al., 2009).

Previous research has found that connectedness also influences 'number adaptation'. Fornaciai and colleagues found that after adapting to 20 unconnected dots, perceived number is reduced for 10 unconnected dots as well as 20 paired dots, but *not* 20 unconnected dots (Fornaciai et al., 2016). Thus, it appears that 'number' adaptation is influenced by the visual system's enumeration of whole bounded objects, and that it is not simply operating over continuous properties of the stimulus. After all, the introduction of additional connecting lines *increases* the total surface area of the items while reducing their perceived number.

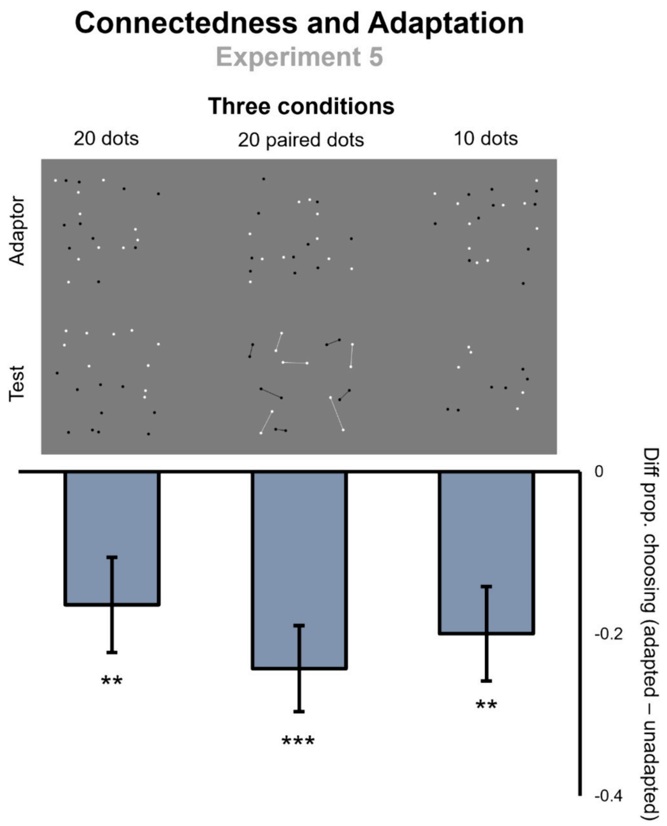

Fig. 5. Design and results of Experiment 5. Each bar represents the magnitude of the key effect in each condition. Error bars represent +/− 1 SE. The key finding here is a significant result in the 20-dot condition, where Fornaciai et al. (2016) found a null effect.

However, when we ran a version of Fornaciai et al.'s experiment ourselves, we found a different pattern of results (see Fig. 5). Whereas Fornaciai and colleagues only found number adaptation when observers, who had adapted to 20 items, were tested on 20 connected dots (i.e., 10 bounded dumbbells) or 10 unconnected dots, we found adaptation in *all three* conditions, including when observers adapted to 20 unconnected dots and were subsequently tested on a new collection of 20 unconnected dots (20 unconnected dots: $t(19) = 3.09$, $p = .006$, $d = 0.69$; 20 paired dots: $t(19) = 4.14$, $p < .001$, $d = 0.93$: stats; 10 unconnected dots: $t(19) = 3.44$, $p = .003$, $d = 0.77$). None of these effects was significantly different from any other ($ps > 0.30$).

Such results reflect more than a failed replication. We found a *positive result* where a null result was originally reported. This positive result is at odds with received formulations of the number adaptation hypothesis, since adapting to 20 unconnected items should not influence one's subsequent perception of 20 unconnected items on this account. Indeed, the lack of an adaptation effect in this condition was a direct prediction of Fornaciai et al.'s study. Much as adaptation to a red surface does not affect one's perception of a separate red surface, adaptation to a middling number should not influence one's subsequent perception of another middling collection. It is, however, what we should expect if the visual system were filtering out unchanging content. Having adapted to 20 unbounded items, we should expect that some of the 20 dots in a test display might (rightly or wrongly) be identified as old news and therefore filtered out from view.

In two further experiments — Experiments 6a and 6b — we investigated cross-modal adaptation (see Demo #6). Experiment 6a was a first attempt at a replication, based on our reading of the method used by Arrighi et al. (2014). It was not intended to be a direct replication, but rather a close approximation of the original design. In pre-registering Experiment 6a, we noted that, if we should fail to replicate the original findings, we would reach out to the original authors and run an updated version of the task based on their feedback. Experiment 6b is the result of modifying the design after corresponding with the original authors.

In Experiment 6a, there were two key trial types: Visual-to-auditory trials (see Fig. 6A) and auditory-to-visual trials (see Fig. 6B). Within each trial type, there were two possible rates at which the adaptor could be presented (8hz vs. 2hz). In this task, all sounds were played in both ears (via headphones) and all visual stimuli were presented centrally. The key prediction of the number adaptation view is that number estimates should be lower after observers adapt to an 8hz adaptor and higher when they adapt to a 2hz adaptor.

We failed to find any evidence of number adaptation. For visual-to-auditory trials, there was a significant effect of adaptor number, but in the opposite direction of what the number adaptation view would predict. Adapting to the 8hz adaptor *increased* estimated number ($t(19) = 2.61$, $p = .017$, $d = 0.59$, BF = 3.32; see Fig. 6A). For auditory-to-visual trials, there was a marginal effect of adaptor number in the expected direction ($t(19) = 1.97$, $p = .063$, $d = 0.44$, BF = 1.16; see Fig. 6B). Combined across both trial types, then, there was no meaningful effect of the adaptors on number estimation ($t(19) = 0.17$, $p = .87$, $d = 0.04$, BF = 0.24).

We want to emphasize that Experiment 6a was not a direct replication of the original cross-modal adaptation effect reported in Arrighi et al. (2014; see methods for details on how they differed). However, if cross-modal number adaptation is genuine, we see no reason why a significant result should not have been observed. This was still a fair test of the broader theory.

Nevertheless, we conducted a modified version of the task based on feedback from the original authors (Experiment 6b). These modifications included adding a familiarization period, blocking the trials, adding a lengthier adaptor at the beginning of each block, and presenting the stimuli on different sides of space (rather than centrally, or in both ears). For more details, see *Methods*. One important detail is that, in this version, the adaptors were always presented on the left side. This is relevant for the analyses below.

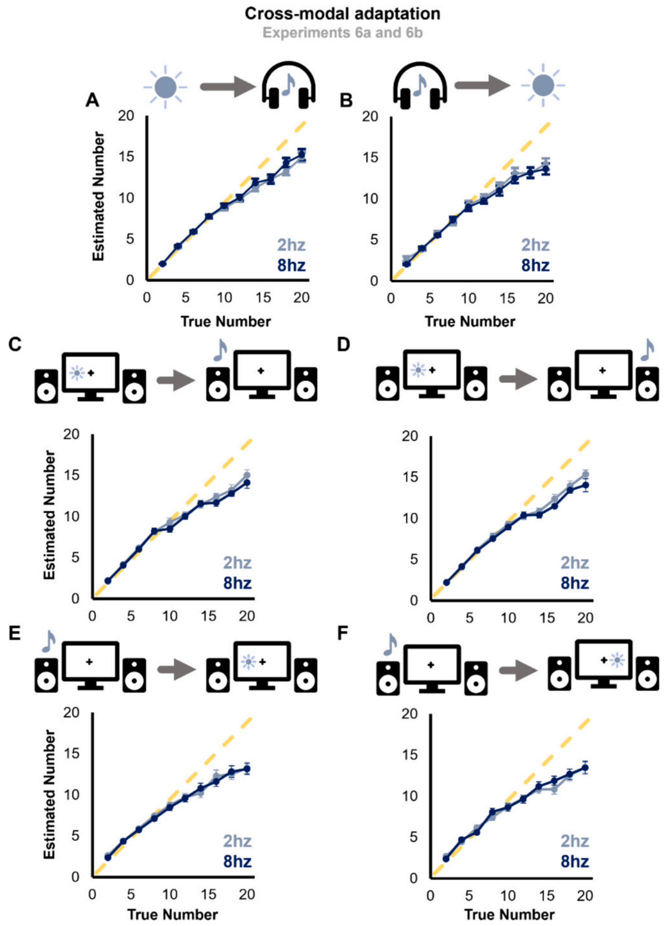

Fig. 6. Results of Experiment 6a and 6b. (A, B) Results of Experiment 6a, for each type of cross-modal adaptation. (C, D) Visual-to-auditory adaptation results of Experiment 6b, for spatiotopic and non-spatiotopic adaptation trials. (E, F) Auditory-to-visual adaptation results of Experiment 6b, for spatiotopic and non-spatiotopic adaptation trials. Error bars represent +/− 1 SE. There is no evidence of cross-modal adaptation.

For the visual-to-auditory trials (see Fig. 6C-D), there was a small, non-significant adaptation effect, both when the target stimuli were presented on the left ($t(19) = 1.51$, $p = .15$, $d = 0.34$, BF = 0.62) and the right ($t(19) = 1.69$, $p = .11$, $d = 0.38$, BF = 0.78), such that observers produced lower number estimates following a higher frequency adaptor. Even if this non-significant effect is taken seriously because it is in the predicted direction, it is not spatiotopic (replicating the original findings; Arrighi et al., 2014).

For the auditory-to-visual trials (see Fig. *E*-F), there was a small, non-significant adaptation effect, when the target stimuli were presented on the left ($t(19) = 0.17$, $p = .87$, $d = 0.04$, BF = 0.24) and an equally small non-significant effect in the opposite direction when the target stimuli were presented on the right ($t(19) = 0.49$, $p = .63$, $d = 0.11$, BF = 0.26).

As in Experiment 6a, we again observed inconsistent, marginal-at-best effects of number adaptation in a cross-modal paradigm. Moreover, as in the original work, we found no evidence of spatiotopic effects. Put simply, the results here undermine grand claims about the generality of number adaptation.

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. We further propose that, if such a replication is to occur, all raw data should be made available in full, as we have done for these experiments, so that research groups can more easily compare their findings.

6. Discussion

Collectively, the eight experiments reported here pose problems for the number adaptation hypothesis. We contend that many of these results are more parsimoniously explained by the alternative hypothesis that we have advanced — the notion that the visual system is merely filtering out 'old news.' In addition to all the empirical support provided here, this alternative hypothesis is motivated by well-known phenomena (e.g., Troxler Fading and Motion Induced Blindness), explains otherwise puzzling results (e.g., that color changes eliminate number adaptation entirely), and follows from well-established principles of visual perception (e.g., that unchanging information, especially in the periphery, will disappear from awareness).

First, we demonstrated that the spatial correspondence between adaptors and targets influences adaptation: Dots that overlap more in space are more likely to fade from awareness at test (Experiment 1). Second, we showed that this effect of overlap is reduced when the individual items in the display change colors (Experiment 2). Whereas others have argued that such effects reflect the visual system's sensitivity to "salient environmental features" (Grasso et al., 2022), we contend that the color change is 'newsworthy' to the visual system and therefore prevents it from filtering out otherwise 'old' items. Moreover, the fact that color changes eliminate the adaptation effect, even when individual black dots turn white (and vice versa) in collections containing an even number of black and white dots (see Experiment 2) indicates that these 'old news' effects occur at the level of individual items, rather than the collection as a whole, in line with the predictions of our account. Third, we showed that number adaptation is eliminated in dynamic displays (Experiment 3). When dots move around the display area, no adaptation was observed. The lack of adaptation in dynamic displays is predicted by our hypothesis insofar as unpredicted changes in direction/motion trajectory could plausibly render 'old' dots newsworthy. But these findings do not seem to be predicted or accommodated by the number adaptation hypothesis. How is it possible that number adaptation is sufficiently abstract to transcend modalities (e.g., Arrighi et al., 2014), but not sufficiently abstract to survive motion or a simple color change? If number adaptation is truly general, in the way its proponents have suggested, adaptation should surely persist across changes of color and motion.

In additional studies, we addressed some of the strongest evidence that has been cited in support of number adaptation. For instance, we considered 'reverse adaptation', where a low-number adaptor causes a middling-number target to appear more numerous. We found an apparent reverse adaptation effect (Experiment 4a) but went on to show that it is explained not by adaptation to a small number adaptor yielding an *increase* in perceived number, but instead by a reduction in apparent number elicited by adaptation to a middling number adaptor (Experiment 4b). This is precisely what the old-news hypothesis predicts, since it predicts that the visual system would filter out more old items on this middling-number side of the display. However, this is precisely the opposite of what's predicted by the number adaptation account: On this view, adaptation to a middling ('neutral') number adaptor should not alter the perceived number of items in a middling number display, just as adapting to green should not cause a green surface to appear otherwise.

Next, we investigated the claim that number adaptation is influenced by 'connections' between items in a display. While our experiment (Experiment 5) replicated some aspects of the prior work supporting these claims, we found a broader pattern of results that was at odds with number adaptation. In particular: Adapting to a display of 20 dots caused a subsequent target display of 20 dots to appear less numerous (contrary to the original reported effects but in line with the predictions of our old news hypothesis; c.f. Fornaciai et al., 2016).

Finally, we considered what is perhaps the strongest evidence for the existence of genuine number adaptation: cross-modal number adaptation. Previous studies report that adapting to sequences of tones can alter the perceived number of seen dots in a sequence of flashes or collection of dots and vice versa. Yet, despite multiple efforts to replicate these effects, we were unable to do so (Experiments 6a and 6b). The one significant effect we found in both experiments went in the opposite direction from what is predicted by the number adaptation hypothesis.

Most of the experiments in this paper were conducted without any delay between adaptors and targets (as is customary in many number adaptation studies). A reviewer questioned whether this allows that some of our critical results might be explained away by this methodological choice. There are several reasons why we think this is unlikely to be the case. First, in the one experiment in which we did include a delay (Experiment 1), we still observed an effect of overlap (albeit to a lesser extent). Furthermore, it is hard to see how any of our subsequent results could be explained by the lack of a delay. For instance, in Experiment 3 we observed a null effect of number. We do not believe that any proponent of number adaptation would argue that a delay should strengthen the effect. Likewise, in Experiment 4b, we once again showed a null effect of number. Perhaps here one could argue that there were counteracting effects of number and overlap, and that a 400 ms delay eliminates the latter but the former. Then we would ask: Why? What reason do we have to believe that this very specific threshold would eliminate one effect (adaptation to the objects themselves) but not the other (adaptation to the number of objects)? After all, other forms of adaptation seem not to depend on such fickle delays. Color adaptation, for instance, seems to occur naturally with delays as short as 0 ms and as long as 2040 *h* (Jones & Holding, 1975). And even in the case of number there seem to be no principled or agreed upon standards for how long the delay should be, or how it should influence adaptation. There is not, to our knowledge, any justification for such specific delays.

In Experiment 5, we did observe a critical effect predicted by proponents of number adaptation. However, we also observed an effect where the number adaptation hypothesis predicts that there should be none. Furthermore, none of these effects were significantly different from one another. If the lack of a 400 ms delay explains the unexpected positive effects that we observed, why wouldn't it also explain our replication of the original results, championed by proponents of number adaptation? Lastly, and perhaps most critically, the introduction of a delay surely would not explain our failure to observe cross-modal adaptation, since those experiments naturally involve temporal delays. Our latter cross-modal study replicated the original design of these experiments as closely as possible, yet we still observed no effect. All of this is to say that it seems implausible to attribute the collective pattern of results documented here to our failure to include 400 ms delays between the adaptors and test displays used in our studies. Looking ahead, clarification is needed regarding when/how delays influence different types of adaptation, so that concerns like these may be adjudicated in a more principled manner.

6.1. Is there hope for number adaptation?

Our findings undermine many prominent claims about number adaptation. For instance, it is unlikely there are genuine cases of 'reverse adaptation' wherein adaptation to a small-number adaptor causes a middling test display to appear *more* numerous than it otherwise would. While Experiment 4 A replicated a canonical example of what has traditionally been interpreted as reverse adaptation, Experiment 4B demonstrated that the effect was ultimately driven by adaptation to a 'neutral adaptor' in the contralateral side of the display *reducing* the number of seen dots in its target location. This pattern of results is precisely what the old news hypothesis predicts.

Our concerns with the existence of reverse adaptation are amplified by the fact that we have never seen nor been able to create a phenomenologically compelling demonstration of the phenomenon (see Demo #5 in our supplemental materials). For certain phenomena, phenomenological demonstrations are a bonus, not a requirement. But for number adaptation, demonstrations arguably *are* the phenomenon. It is hard to imagine that this research program would have had the impact it has had if it were not the case that people can so readily appreciate the effects for themselves. If not for the phenomenology, after all, how would one argue that this is a perceptual phenomenon? Independently of our experimental results, a lack of phenomenologically compelling demonstrations should be a cause for concern (but see Yousif & Clarke, 2024).

Another critical claim made by proponents of the number adaptation hypothesis is that the effects are cross-modal. We have, however, failed to find cross-modal number effects, despite repeated efforts to match Arrighi et al.'s (2014) design as closely as possible. These failures persisted when we sought external advice on our design from proponents of the phenomenon. While we are more than willing to attempt additional replications of this basic finding, we find it hard to identify any principled reason why the design we employed should not have been effective under the basic assumptions of the number adaptation hypothesis.

Yet perhaps the strongest reason to doubt the existence of cross-modal number adaptation exists may come from data reported by proponents of number adaptation. Grasso et al. (2022) reported that the effect is eliminated when dots change in color. In Experiment 2 we found that this breakdown occurs even if the cumulative color distribution remains unchanged (i.e., swapping black for white and white for black in black and white dot displays). We have also shown that number adaptation breaks down for dynamic stimuli (i.e., when dots move continuously around a display in pseudo-random ways — Experiment 3), though we have also suggested that this latter result should be interpreted with caution. In each case, such findings are hard to square with the number adaptation hypothesis. In principle, it seems possible that number adaptation operates at a sufficiently abstract level for cross-modal adaptation to occur. Yet it seems hard to see how number adaptation might generalize across modalities given that it does not generalize across more subtle changes to visual input such as color. Of course, it is not *impossible* that number adaptation may operate in this way. In that case, though, proponents of number adaptation would need to be more specific about the mechanisms underlying the adaptation, so that the number adaptation hypothesis can make meaningful predictions. We need to understand why exactly one should expect that number adaptation effects occur in one direction but not the other, why they occur in static but not dynamic displays, why they supposedly reach across modalities but not across colors, and so on. Answering these questions may also require elaboration on the mechanisms underlying number perception itself (see, e.g., Odic et al., 2024). But without clear answers to these questions, the number adaptation hypothesis is both incomplete and in tension with extant results.

We admit that none of our arguments provide definitive proof that number adaptation does not exist. It might. We have only argued that there is an alternative explanation for the results currently documented. Though our recommended old-news hypothesis is independently motivated, appealing only to well-known mechanisms and processes of visual perception that all parties should accept as genuine, we do not claim to have proved a negative.

This raises the question: What would it take to demonstrate that number adaptation is genuine?

It would not be enough to simply show that there are cross-modal effects. One would also have to show that these cross-modal effects are genuinely perceptual (rather than a consequence of some higher-level response bias). That is no trivial task, not least because the canonical design of cross-modal number adaptation experiments naturally prevents any possible comparison that one could experience for themselves.

It might be enough to show that there are effects of number adaptation that cannot be explained by our 'old news' account. However, it is unclear what these effects might look like. It is virtually impossible to eliminate any correspondence between the adaptor and test displays. Indeed, in cases where we have tried to eliminate the correspondence as much as possible (by changing the colors of dots or introducing motion to the displays) adaptation effects have been eliminated.

It may also be enough to show that there are genuine effects of 'reverse adaptation' that could not be explained by our old news hypothesis. Assuming that it was not the result from a higher-level response bias or another deflationary explanation, such a result would be intriguing. However, Experiments 4a and 4b provided strong reason to doubt the existence of reverse adaptation. We are not aware of any compelling evidence to support its existence, and we have not yet seen a compelling demonstration of it.

6.2. *Is number a primary perceptual attribute?*

One of the reasons that number adaptation has garnered the interest it has is for its theoretical implications — specifically, from the idea that adaptation is a marker of perceptual content (Burr & Ross, 2008; Block, 2022; c.f. Smortchkova, 2020; Phillips & Firestone, 2022). It is a provocative idea, to say the least, that number may be akin to color, size, and speed in being a 'primary perceptual attribute'.

But does evidence against number adaptation provide reason to think number is *not* a 'primary perceptual attribute'? We think not. Number may well be a perceptual attribute, but whether number adaptation is genuine need not bear on that question.

For a start, there appear to be various properties and happenings which can be visually represented, yet for which no known adaptation effects occur. For instance, Phillips & Firestone, 2022 propose that we can visually represent objects as *to the left* or *to the right*. However, they deny that there is compelling evidence of adaptation to these properties, criticizing recent arguments to the contrary (e.g., Block [2022, 67–8] who appeals to Finke [1989] in this connection). Similar points are raised with respect to other properties: Does seeing several objects as nearby make subsequent objects look far away? Does seeing multiple objects as connected make subsequent examples look disconnected? What about symmetry: Does seeing lots of symmetrical objects make subsequent objects look asymmetrical? It seems not, despite the properties in question naturally being seen to feature among the contents of visual perception.

If these criticisms succeed, then adaptability is a non-necessary feature of perceptual content. Thus, the non-existence of number adaptation need not preclude the possibility that number is computed by the visual system, not least because there may be independent reasons to posit number as a genuine content of human vision (see Clarke & Beck, 2023). For one, number sensitive neurons have been found in early visual areas of the brain (Castaldi, Piazza, Dehaene, Vignaud, & Eger, 2019; DeWind, Park, Woldorff, & Brannon, 2019; c.f., Fornaciai & Park, 2021). In addition, number is susceptible to many well-known *recalcitrant* illusions. For instance, beyond the connectedness effects described in this paper (Franconeri et al., 2009; He et al., 2009) the arrangement of dots in an array can alter their apparent number, causing one subset of the array to appear significantly more or less numerous than an equinumerous subset (Frith & Frith, 1972). The entropy of items in a collection also alters apparent number, such that homogenously colored or homogenously oriented items appear more numerous than their otherwise identical yet heterogenous counterparts (DeWind, Bonner, & Brannon, 2020; Qu, DeWind, & Brannon, 2022). Crucially, all these results persist even when participants know the effects to be illusory: Even when participants know two collections to be equinumerous, and reflect on this fact, the collections will continue to *appear* quite different in number under the above conditions. This suggests an important dissociation between putatively visual representations of number and their cognitive counterparts, indicating that there is a legitimate sense in which number features in the contents of visual perception and not just post-perceptual judgement, irrespective of whether number adaptation obtains.

6.3. Perceptual adaptation beyond number

Bracketing these concerns, we think our discussion raises broader questions about the notion of adaptation that is at issue in various disputes in contemporary vision science.

Suppose, for instance, that future research provides more definitive evidence for the number adaptation hypothesis and against the old-news hypothesis. We suggest that our discussion should nevertheless serve to highlight a range of problems concerning our current understanding of number adaptation. It may be overly simplistic, for instance to say that a feature simply *does* or *does not* exhibit adaptation (Smortchkova, 2020). For a start, there are likely to be different *ways* that one can adapt to some property or happening.

Consider the issue of retinotopy as one example. Careful work has been done to show that certain kinds of high-level adaptation, like adaptation to causality, are retinotopic (see Kominsky & Scholl, 2020; Rolfs, Dambacher, & Cavanagh, 2013). This retinotopic specificity helps to support claims that the observed effects are genuinely perceptual in nature. It is hard (but not impossible) to imagine why non-perceptual effects would occur in specific locations on the retina (c.f. Phillips & Firestone, 2022). Number adaptation, in contrast, is normally considered to be spatiotopic, although there are documented number adaptation effects that are neither retinotopic nor spatiotopic (see Arrighi et al., 2014). This raises the question: Is retinotopic adaptation different from spatiotopic adaptation? Are both different from adaptation that is neither retinotopic nor spatiotopic? In what ways — and how would we know?

It is worth noting that retinotopy is important not just for how we interpret the phenomenon of number adaptation, but also for how we study it. In an effort to rule out certain spatial confounds (e.g., area, density) in number adaptation displays, some experimenters have carefully manipulated the spatial envelopes in which dots appear (see Anobile et al., 2014; DeSimone et al., 2020). That is, the adaptor stimulus might occupy a larger area on the retina than the target stimulus, or vice versa. This design choice makes sense if you think that the adaptation is merely spatiotopic. However, it is quite easy to see that the retinotopic size of the spatial envelope *does* matter. In Demo #7 in our supplemental materials, for instance, we show that adapting to a central clump of dots vs. a ring of dots influences not only the apparent number of dots in a test display, but also the shape of the collection. This simple demonstration, thereby, undermines the central assumption behind previous work (see Anobile et al., 2014; DeSimone et al., 2020) that has manipulated area/density by varying the size of the spatial envelope that collections occupy. This leaves open the possibility that, even if all our arguments fall short of target, certain number adaptation effects may still be explained (either in part or entirely) by confounds with density and area. However, it bears emphasizing that a simple appeal to density adaptation (e.g., Durgin, 2008) does not accommodate the full range of results documented here. For instance, it is hard to see why an appeal to density adaptation would predict or explain the fact that color changes eliminate 'number' adaptation effects entirely.

There are other aspects of 'adaptation' that are similarly ambiguous. In this paper, for instance, we have taken issue with the notion of 'reverse number adaptation'. We have argued that previous reports of reverse number adaptation were spurious and that a lack of reverse number adaptation undermines the grounds for positing number adaptation in the first place. It is important to acknowledge, however, that certain better-understood forms of adaptation, most notably speed adaptation, are thought to be similarly unidirectional. In this domain, a fast adaptor can cause a subsequent stimulus to look as if it is moving slower, but a slow adaptor does not influence perceived speed in the reverse direction (e.g., Anton-Erxleben, Herrmann, & Carrasco, 2013). This is not an isolated example. While bidirectional effects are the norm, even forms of adaptation that do exhibit bidirectional effects, like size adaptation, nevertheless exhibit important asymmetries (e.g., a large adaptor causes greater adaptation on a middling stimulus than a small adaptor will; see Pooresmaeili, Arrighi, Biagi, & Morrone, 2013; but see Yousif & Clarke, 2024).

These modest observations raise a host of unanswered questions: Must adaptation effects be retinotopic to be considered perceptual? Must adaptation effects be bidirectional to be considered genuine? And how much of an asymmetry in this bidirectionality is important? Just as there may be no agreed-upon standards for what constitutes adaptation (Phillips & Firestone, 2022), there are no agreed-upon standards for what aspects of adaptation are meaningful or necessary when generalizing from one domain to another (e.g., Smortchkova, 2020; but see Webster, 2015).

These are not merely semantic concerns. We are not simply raising a concern over what deserves to be *called* adaptation. Rather, we are highlighting a more foundational problem, which lies at the heart of various theoretical debates in which adaptation effects feature prominently. For insofar as phenomena like number adaptation are to support theoretical claims, such as the claim that number is a "primary visual attribute" (Burr & Ross, 2008), or insofar as the phenomenon of perceptual adaptation (in general) is to support claims over the function of perceptual processing *more broadly* (Block, 2022; Webster, 2015), we must assume that adaptation constitutes a unified natural kind — that there is a genuine joint in nature that distinguishes genuine adaptation effects from other related phenomena, and which thereby licenses inductive inferences from one case of 'adaptation' to another. Indeed, this point seems pressing given the findings discussed in this paper. For whether we are correct to deny the existence of number adaptation, it seems all but inevitable that 'number adaptation' will end up differing in important ways from better understood cases of adaptation (after all, this point is conceded by proponents of the phenomenon; see Grasso et al., 2021), leaving an awkward question: Is number adaptation still of the same fundamental kind as (e.g.) brightness or color adaptation? What about intermediate cases like size adaptation (see Yousif & Clarke, 2024)? And if number and size adaptation are not like other canonical forms of adaptation, why should the status of these other well-established phenomena as decisively perceptual license the conclusion that number, size, or any other feature is a 'primary visual attribute' in the same way?

7. Conclusion

In some respects, number adaptation is among the best-documented phenomena in psychophysics. There have been dozens of papers in the last fifteen years purporting to document cases of number adaptation in a variety of compelling ways. And you can *see* this phenomenon for yourself. In canonical cases, collections of dots quite literally change in perceived quantity. Yet we argue that there is a simpler and more parsimonious explanation for many, if not all, of these findings: The visual system is simply responding differentially to new versus old information. The view presented here offers a new foundation from which to understand documented effects of putative number adaptation and raises questions about the nature and meaning of adaptation itself.

8. Methods

For all experiments, the sample size, primary dependent variables, and key statistical tests were all pre-registered. Pre-registrations, as well as demos, raw data, and materials, are available on our OSF page, here: https://osf.io/eh3ws/

In each experiment, 20 individuals (after exclusions; see below) participated (in lab) in exchange for course credit or monetary compensation. While many adaptation studies rely on 'expert' participants (for discussion on the challenges of adaptation experiments, see Kominsky & Scholl, 2020), we specifically opted to use naive participants. All participants were unaware of the design as well as the hypotheses. Because of this, we thought it important 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. Across all of the experiments, only two participants were excluded for this reason. Three additional participants were excluded because of unreasonably high and/or erratic response times.

For all but two experiments (6a and 6b; explained below), participants sat approximately 60 cm from a 20in by 11.25in monitor. All subsequent calculations of visual size are based on these values.

In **Experiment 1**, Stimuli were composed of square dots arranged in a grid shape (see Fig. 3A). 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 25 × 25 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 ensure the dots did not touch neighboring dots and could thus be individuated. An individual dot was approximately 0.30° 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 one side of the display, 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 the other side of the display, the adaptor and the test stimulus had 0% spatial 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.

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. Adaptor number, target number, and overlap percentage were all counterbalanced with respect to one another. 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.

Experiment 2 was designed to be as similar as possible to Experiment 1, with one exception. Rather than one side having 0% overlap and the other having 100% overlap, *both* sides had 100% spatial overlap. In other words, all the dots in the target stimuli were in the same location as a dot in the corresponding adaptor. The one difference is that one side would also have identical colors, and the other would have all the colors swap (i.e., any dot that was white became black, and vice versa).

In **Experiment 3**, we tested number adaptation for dynamic stimuli (i.e., dots moving around). As with the other experiments, displays were made up of both black and white dots, adaptors were presented for 25 s, and targets appeared for 750 ms. One of the adaptors always had 60 dots; the other always had 30 dots. For 3/7 of the trials, both targets had 30 dots. For 4/7 of the trials, the number of dots on one side of the screen was equal to 30 +/− 5 (and the other side had 30 dots). In total, there were 42 trials (7 target number conditions × 2 adaptor number conditions × 3 repetitions).

Experiment 4a was designed to be as similar as possible to Experiment 1. Only a few changes were made to the design, as explained below. This experiment was designed to test 'reverse adaptation' — cases where an adaptor of lower number causes a test stimulus of higher number to appear more numerous (see Burr & Ross, 2008). The numbers for the test stimuli were identical to Experiment 1, 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.

Experiment 4b was modeled on Experiment 4a. But where Experiment 4a involved 'double adaptor' trials (i.e., trials in which adaptors appeared on both sides of the screen at once), Experiment 4b 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 4a. The difference here is that trials from Experiment 2a were effectively 'split in half'. We showed participants the same test stimuli as in Experiment 4a, 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 4a.

Experiment 5 was modeled after the study by Fornaciai et al. (2016) but used the same stimulus/task parameters as Experiment 1. Here, the dots in the target stimuli were sometimes connected via thin lines (to create an illusion of a change in number). On all trials, there was a single adaptor with 20 unconnected dots. The targets varied in three distinct trial types. For one-third of the trials, the target stimulus had ∼20 unconnected dots; for another third of trials, the target stimulus had ∼20 dots connected in pairs; for a final third of trials, the target stimulus had ∼10 unconnected dots. Independently, for three-sevenths of the trials, both targets had an equal number of dots (20 in two of the conditions, or 10 in the third condition). For the remaining trials, one target had 16 (8) dots and the other had 20 (10). This was counterbalanced across sides. There were a total of 42 trials (3 trial types × 7 number/side combinations × 2 sides of the display).

In **Experiment 6a**, we attempted to replicate the cross-modal adaptation effects documented by Arrighi et al. (2014). This initial replication attempt was conducted based on our impression of the design having read the original paper.

Per the design of Arrighi et al., the trials consisted of an adaptor stimulus as well as a test stimulus. The adaptor stimulus consisted of items presented at either 2hz or 8hz for 6 s. The target stimulus consisted of either 2, 4, 6, 8, 10, 12, 14, 16, 18, or 20 items, always presented within a 2 s period. There were 2 conditions (audio/visual) x 2 adaptor frequencies (2hz/8hz) x 10 numbers (2–20, increments of 2) x 3 unique instance of each trial, for a total of 120 trials. These 120 trials were randomly intermixed with no constraints. (At the time of this preregistration, it was unclear to us how the trials were ordered.)

Unlike the design of Arrighi et al., we did *not* have neutral non-adaptation trials (other than the 20 practice trials). We also did not have the initial 40s adaptation period.

In the Arrighi et al. study, stimuli were constrained so that no items appeared within 40 ms of one another. We extended this window to 50 ms, ensuring that we could still fit the maximum number of items within a 2 s period, but allowing for slightly more space between the items.

Prior to beginning the cross-modal trials, participants completed twenty practice trials, during which they witnessed *either* dots flashing *or* tones playing (10 of each trial type). The sequences contained 2, 4, 6, 8, 10, 12, 14, 16, 18, or 20 items. For these trials only, they were given feedback about the correct answer after each response.

The task was *not* intended to be a perfect, direct replication. Instead, we designed a task that we thought, in principle, should reveal cross-modal adaptation effects (based on our understanding of the original findings). Because we had considerable difficulty discerning the exact experimental design based on the original materials, we specifically preregistered that we would contact the authors about these results to get their feedback should we fail to replicate the key effects.

In **Experiment 6b**, we attempted another replication of cross-modal number adaptation after having consulted with the authors of the original study. This resulted in numerous substantive changes to the design.

First, we added in a ‘familiarization phase’ after the practice trials. This consisted of twenty additional practice trials without adaptation, but also without any feedback. Second, we divided the task into four blocks. These blocks were the product of a 2 × 2 design, with two relevant factors. One relevant factor was the rate of the adaptor (2hz vs. 8hz) and the other was the type of adaptation (auditory vs. visual). The blocks were presented in four unique orders, following a Latin square design. Third, at the beginning of each block, there was a 40s adaptation phase (followed by the usual 6 s adaptation phase on each trial). Each block itself consisted of 40 trials, with 10 numbers (2–20, increments of 2) x 2 sides for the target (left/right) x 2 instances. Fourth, the adaptor was always presented on the left side. Fifth, the auditory stimuli played from either a left speaker or a right speaker that sat adjacent to the monitor, and the visual stimuli (dots 1.42° in diameter) were presented in the periphery (17.0° offset horizontally), close to the speakers (as the original authors emphasized this aspect of the design in our correspondences). The 40 trials were randomly intermixed with no constraints.

This design was still not a perfect replication of the original paper. It was designed to be as close as possible, given the information available in the paper, the information we were able to glean from our correspondence with the original authors, as well as our desire to be consistent with other aspects of our designs across the rest of our studies (in terms of experiment length, number of participants tested, etc.).

Experiments 6a and 6b were run on a separate computer/monitor, to ensure that we could run the task at the appropriate framerate. The display was 21.4in x 11.9in, running at 200hz.

Author note

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CRediT authorship contribution statement

Sami R. Yousif: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sam Clarke:** Writing – review & editing, Writing – original draft, Conceptualization. **Elizabeth M. Brannon:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization.

Declaration of competing interest

None.

Data availability

All of our data are available on an OSF page linked in the article

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