Number, Adaptation, & Perception

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According to an orthodox view, humans *adapt* to the number of items in seen collections, thereby demonstrating that number is a "primary visual attribute" (i.e., that number or numerical quantity is visually attributed to seen collections in much the way color and motion is visually attributed to seen objects; for review, see Anobile et al., 2016). This view has revolutionized the study of numerical cognition, shifting the field's focus from 'mind' to 'eyes' — from later stages of cognitive processing to early visual mechanisms. At the same time, the view that number adapts has transformed vision science: Adaptation, once thought to be restricted to a small number of canonical visual features (e.g., color, motion), has expanded to include higher-level properties like causality (Rolfs et al., 2013), size (Pooresmaeili et al., 2013; Tonelli et al., 2017; Tonelli et al., 2020; Yousif & Clarke, 2024), and variance (Maule & Franklin, 2020). This is due, in no small part, to the path paved by pioneering work on number adaptation.

Recently, we have questioned this orthodoxy (see Yousif, Clarke, & Brannon, 2024, 2025). We have highlighted various ways in which the evidence for number adaptation is less robust than typically assumed. We have also highlighted theoretical inconsistencies in how number adaptation is studied and described and provided an alternative explanation for extant results.

Proponents of number adaptation have responded, defending the phenomenon against some of our critiques (Burr et al., 2025; see also XXX in this volume). Yet our most substantive arguments remain unaddressed. As it stands, the existence of number adaptation seems dubious at best.

One recurring notion in our treatments of number adaptation is that understanding the phenomenon matters to more than just an understanding of number or numerical cognition. Number adaptation is perhaps the single best-studied instance of adaptation to a 'high-level' visual property. It has, thus, become a gold standard when it comes to understanding what high-level *visual* adaptation looks like and what distinguishes it from superficially related phenomena (see: Block, 2022, pp. 73-90). In this way, developing a complete understanding of *adaptation* requires first unpacking the problems with number adaptation.

Against this backdrop, the current chapter will review the status of the debate over number adaptation, with a specific focus on new empirical and theoretical frontiers. We'll start by explaining what adaptation is, before jumping into our varied skepticisms about the existence of number adaptation. Somewhat independently, we'll proceed to question the widely assumed link between *adaptation* and *perception*. We'll argue that, even if one sets aside our concerns with number adaptation, the existence of number adaptation would still provide poor evidence that number serves as a visual attribute. Finally, we'll conclude on a more positive note, discussing better reasons to believe that *number* is genuinely represented *in perception*, despite a dearth of evidence that genuine number adaptation obtains.

1. Adaptation: What is it?

Consider Figure 1. In Panel A you can see an oddly colored landscape. In Panel B you can see a grayscale version of the same image. Yet if you stare at Panel A for ~15 seconds or longer and then shift your gaze to Panel B, you'll see something remarkable: A vivid, colorful landscape. Your eyes just *adapted* to the colors in Panel A, yielding a *repulsive aftereffect* such that the neutral (colorless) Panel B appeared to possess Panel A's opponent color values. (Note: This demo does not work especially well in this format. Readers are encouraged to seek out an online demo if they are unfamiliar with the phenomenon. Demonstrations are readily available online.) This is, thus, an example of *color adaptation* — one instance of the broader phenomenon of *perceptual adaptation*. Intriguingly, repulsive adaptation effects of this sort can result in percepts that sound impossible yet seem phenomenologically indubitable (Crane, 1990; c.f., Bayne 2010).

Adaptation effects are more than just intriguing illusions, however. They have become a construct of great theoretical importance, for they are seen by many to be a key factor – perhaps *the* key factor – which distinguishes what is perceived, or perceptually represented (i.e., as when we visually perceive red), from that which is merely judged or conceived of in post-perceptual cognition (i.e., as when we think about Manzano bananas; see, e.g., Block, 2022). Concurrently, our understanding of what features exhibit adaptation has vastly expanded. What was once a phenomenon restricted to canonical visual features like color and motion has swollen to include higher-level visual properties like speed (Anton-Erxleben et al., 2013), size (Pooresmaeili et al., 2013; Tonelli et al., 2020; Yousif & Clarke, 2024), number (Burr & Ross, 2008; Yousif, Clarke, & Brannon, 2024), causality (Kominsky & Scholl, 2020; Rolfs et al., 2013), facial dimensions like race, sex, and emotional expression (Webster & MacLeod, 2011), as well as other abstract properties like variance (Maule & Franklin, 2020). See Figure 1C.

Webster, one of the leading experts on visual adaptation, thus describes adaptation as a "powerful tool for dissecting vision by exposing the mechanisms that are adapting" (2015; p. 547); adaptation, he argues, is an "intrinsic feature of visual processing" which "reaches the status of a universal law" (p. 548). Rolfs, Dambacher, and Cavanagh, responsible for the discovery of causal adaptation, agree; to them, adaptation is "a powerful tool [for uncovering] the neural populations that specialize in the analysis of visual features" (2013; p. 250). Kominsky and Scholl (2020) take an even stronger stance, arguing that adaptation offers "a largely unambiguous and uncontroversial way to identify visual processing" (p. 3). Block (2022) describes adaptation as a byproduct of the core function of vision – to highlight the newsworthy goings-on (roughly: *changes*) in one's visual environment – and takes this to distinguish vision from post-perceptual cognition. On this widespread view — espoused by Webster, Rolfs, Kominsky, Block, and countless others — adaptation is special: It reveals something meaningful about the systems doing the adapting. Namely, that they are perceptual rather than cognitive in nature.

Much of the intrigue surrounding adaptation traces back to the reported discovery of *number adaptation* by Burr and Ross (2008) almost two decades ago. Number adaptation captured scientific and theoretical interest because, unlike many subsequent instances of high-level adaptation, it could be *seen* — in a manner that seems just as compelling as the example of color adaptation you were invited to experience in Figure 1 (see Figure 2). This finding has been equally significant to the numerical cognition community. Adaptation is frequently touted as *the* reason to believe that number is special for featuring in the contents of perception, thereby serving as a "primary visual property" on a par with color, contrast, size, and speed (Burr & Ross, 2008). Number putatively bridges a gap between "core", foundational cognitive capacities (Feigenson et al., 2004; Halberda et al., 2008) and perceptual processing. Thus, by studying the latter, the hope has arisen that we will shed light on the former.

Recent work of our own calls into question this way of thinking by critically investigating the evidence for number adaptation. In a first paper (Yousif, Clarke, & Brannon, 2024), we provided a range of theoretical and empirical reasons to doubt the existence of genuine number adaptation. Our work received two critical replies (Burr et al., 2025; Durgin, 2025), which we then had a chance to address (Yousif, Clarke, & Brannon, 2025). In the following sections, we'll review some critical takeaways from that dialogue. We'll then discuss some new evidence that casts independent doubt on the specific link between adaptation and perceptual processing that is routinely presupposed in these discussions. To foreshadow: We conclude that evidence for number adaptation continues to be lacking but that, even if it were genuine, there would be little reason to think that this adaptation serves as a useful marker of perceptual encoding.

2. Number adaptation: A critical look

If you haven't already, take a moment to consider Figure 2. This is a famous demonstration of number adaptation, popularized by Burr and Ross (2008). If you stare at the fixation cross in the first panel for about 30 seconds and then switch to the second, you will experience a powerful illusion: You will seem to see the left-hand test display as containing a smaller number of dots. Consequently, if you are asked to choose which of the latter test displays contains a larger *number of dots* you will be likely to choose the contralateral display, despite the verifiable fact that both collections are – in fact – equinumerous.[1]

This simple demonstration is often taken as *de facto* proof that number adaptation is genuine; that just as one can adapt to color or motion, yielding visibly repulsive aftereffects, one can likewise adapt to the number of items in a collection, resulting in obvious and phenomenologically striking visual aftereffects. Specifically, demonstrations of this sort are taken to show that when one adapts to a large number of dots this can cause a middling number of dots, presented shortly thereafter in a spatially overlapping region, to be perceived as *smaller in number*; likewise, they are taken to show that when one adapts to a small number of dots at a given region, this can cause a middling number of dots in that same region to be perceived as *larger in number*. The claim is that: "although the total apparent number of dots is greatly reduced after adaptation, no particular dots seem to be missing" (Burr & Ross 2008; p. 426). We continue to *see* all the dots in the collections, it's just that the numerical content that our visual system attributes to the collections (as a whole) gets altered. Indeed, this is key, for it is the alleged fact that the visual aftereffect occurs on *a representation of number*, as opposed to representations of the individual

[1] Note, that these demonstrations work much better when observers are not required to move their eyes. To see clearer versions of demonstrations like this, we refer readers here: https://www.cogdevlab.org/number-adaptation/demos.

dots or their low-level properties, that motivates the bold assertion that *number* features in the contents of human vision. Below, we summarize some of the many reasons to be skeptical of this assessment.

2.1 Number adaptation can be explained by more general perceptual mechanisms. One reason why the above demonstration is less convincing than standardly assumed, stems from a smorgasbord of well-known visual phenomena, in which 'old news' is filtered out from visual awareness.

Consider the "lilac chaser illusion": As you stare at a central fixation point, a collection of peripheral, but unchanging, magenta dots fade from awareness. This is an example of a broader phenomenon, known as Troxler Fading, which has been known about for more than two-centuries. Perhaps even more striking is "motion-induced blindness": here a high-contrast shape (e.g., a bright yellow circle), that is salient and seemingly impossible to miss, is deleted from visual awareness entirely when it remains stationary against a backdrop of moving items (see New & Scholl, 2008). In these and many other cases, 'old news' in the form of unchanging magenta dots or bright yellow circles gets filtered from visual awareness, right before our very eyes, plausibly because the visual system functions to prioritize newsworthy content at the expense of the old (Block, 2023).

Without positing any further quirks of human vision, this already provides a simple, deflationary explanation for many claimed demonstrations of number adaptation (Yousif et al., 2024). In canonical demonstrations of number adaptation — like the demonstration described above — the dots in both the adaptor and test stimuli are randomly distributed within two fixed spatial envelopes. In practice, this means that the spatial relationship *between* individual dots in the adaptor and those in the test stimuli (i.e., how close adaptor dots are positioned in relation to subsequent test dots) is uncontrolled. But, as we can now appreciate, this poses a challenge to the number adaptation enterprise, for adapted collections that are greater in number will be statistically more likely to contain dots that overlap or sit adjacent to those found in corresponding test displays. Since spatial overlap or proximity is a particularly strong cue to dot identity for the visual system, the visual system will tend to treat more of the dots in a test display as 'old' dots, identical to those present in an original adaptor, when it is positioned in the location previously occupied by a large-number adaptor. And since we have just seen that the visual system seems to filter out peripheral dots and objects when it deems these 'old news' and there is more newsworthy content to make salient to the observer, the result is that we should expect to end up seeing less of the dots in a test display when we have just adapted to a large number collection in that location. This is not because we have adapted to their *number*, however. It is simply because more of the individual dots fade from awareness and, hence, go *unseen*.

Proponents of number adaptation may wish to incorporate our "old news" idea into their conception of number adaptation. We think this is a mistake. While the *number adaptation hypothesis* and the *old news hypothesis* sometimes make congruent predictions, they often make opposing ones. For example, the old news hypothesis predicts that the adaptation effects are likely to be unidirectional, as observed by Yousif and colleagues (2024). The old news hypothesis also makes more specific predictions, like the fact that overlap should influence the magnitude of the adaptation (Yousif et al., 2024) or the fact that the adaptation effects should be strongest in the periphery (Yousif et al., 2025). All three of these facts are naturally explained by *old news* and left unexplained by proposed adaptation to number.

Defenders of number adaptation have brushed these concerns aside. In response to the demonstration that the reduction in perceived number is significantly stronger when the dots from test displays occupy locations that overlap with those found in corresponding adaptors they claim that, insofar as displays with non-overlapping dots still exhibit some degree of "number" adaptation, the effects of "old news" cannot fully explain observed number adaptation effects. Specifically, they suggest that while overlap among dots can influence the strength of the adaptation effect, these effects are not strong enough to fully explain reported cases of number adaptation (Burr et al., 2025; Burr et al. this volume). This reflects a significant misunderstanding of our hypothesis. As we have emphasized in each and every one of our papers on this topic, including our original paper that introduced our hypothesis (Yousif et al. 2024) and one which corrects Burr et al.'s misunderstanding on this point and many others (Yousif et al. 2025), overlap is *one* particularly strong cue to dot identity and, thus, a dot's status as 'old news' for the visual system. But it is not the only cue to dot identity. As readers can freely appreciate, non-overlapping dots are tracked across adaptors and test displays when one flicks back and forth between images of the adaptors and test displays in demos of visual number adaptation. This is perceived in the form of *apparent motion* and shows that when two dots are sat at slightly different spatial locations they can and will often be treated by the visual system as identical. Hence, creating a test display with *no* functional overlap or perceived identity between dots in the adaptors and the corresponding test displays is effectively impossible.[2]

2.2 The "old news" hypothesis makes bold predictions. Beyond offering a simple and elegant explanation for classic demonstrations of "number" adaptation, our "old news" hypothesis also predicts and explains numerous findings that the number adaptation hypothesis leaves puzzling.

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[2] It is frustrating that Burr et al. have continued to misrepresent our view in this and other ways. For instance, in the entry in this volume they reiterate the claim that, according to our old news hypothesis, moving dots should not be filtered out from visual awareness and that our view is thereby refuted if adaptation is observed in dynamic displays. This is a blatant mis-construal. Once again, in every single one of our papers on this topic, we've explicitly argued for completely the opposite: Since objects are manifestly tracked by visual systems as they move and change location, we predict that our visual system will occasionally treat moving dots as 'old news', apt to be filtered out from awareness, when there are other items that it deems novel and interesting to make salient to the observer. Indeed, everyone in vision science should already accept that this much is so. In cases of motion induced blindness, predictably moving dots disappear from awareness when they are presented against a more visibly salient backdrop (New & Scholl 2018). Indeed, you are experiencing this very phenomenon for yourself *right now*, at least insofar as you are not visually aware of floaters moving around on your eyeballs – these moving items need to be deleted from visual awareness precisely because there is more newsworthy stuff for your visual system to make salient to you. Our observation is simply that these well-known mechanisms of visual filtering already suffice to explain most reported cases of visual number adaptation.

For example: Why is it that number adaptation is dramatically reduced when the color of the dots changes from blue in an adaptor to green in a test display (Grasso et al., 2022)? According to proponents of number adaptation, this is because number perception is somehow tuned to collections whose identity is demarcated by "salient environmental features". Thus, changing the color of the dots, changes the collection for the visual system, largely eliminating the adaptation effect. In contrast, the "old news" hypothesis offers an alternative explanation for this results: Changes of color increase the newsworthiness of 'old' items in the test stimulus, rendering them newsworthy again, and thus reducing the extent to which these would be filtered from awareness. Consistent with our proposal, and inconsistent with the alternative, we've shown that this true not only when the entire ensemble of dots changes color, but also when individual dots switch colors (i.e., when black dots in a specific location change to white and white dots change to black, such that the overall distribution of black and white dots is unchanged; see Yousif et al., 2024). This latter finding indicates that the effect of overlap is occurring at the level of individual items rather than merely at the level of the ensemble, precisely as the "old news" hypothesis predicts.

This is not all. The "old news" hypothesis also explains why number adaptation, unlike canonical instances of adaptation, is stronger in the periphery (and virtually non-existent in focal vision). Because the receptive fields of adapted neurons are relatively large in the periphery, dots in the periphery need not overlap to the same degree to be treated as numerically identical by the visual system, and hence regarded as 'old news', such that they are filtered from awareness. It also explains why the presence of supposedly irrelevant "neutral" adaptors, which match the number of items in a spatially overlapping test display, appears to reduce the strength of the adaptation pertaining to high-number adaptors located elsewhere in the visual field (Grasso et al. 2021). On the old news hypothesis, this should be expected; since neutral adaptors provide *some* dots for the visual system to treat as old news in a corresponding test display, the contrast between the number of seen dots found in *this* display and those in a test display that corresponds to a previous high-number adaptor, will be less marked. Once again, this is striking, since analogous effects of neutral adaptors are not found in other, better understood cases of adaptation, like adaptation to orientation or tilt; they are thus regarded as surprising or unexpected on the number adaptation hypothesis, even among its most enthusiastic proponents (ibid.).

There are many other isolated effects that our "old news" hypothesis explains. We will not review these here (but see Yousif et al., 2024, 2025). Yet we hope that readers can appreciate that we are not talking about one or two unexplained anomalies of number adaptation, but potentially *dozens*, all of which seem to be straightforwardly predicted by our alternative hypothesis.

2.3 Most putative effects of number adaptation are not phenomenologically appreciable. That is: Unlike canonical demonstrations of number adaptation, many published effects of number adaptation are not ones that an observer can experience for themselves. Regardless of the empirical state of the debate, such lacking phenomenology is critical: Without visible demonstrations, proponents of number adaptation face a dilemma. One option is to accept that the absence of such demonstrations tells of the fact that the phenomena in question do not exist. This is surely unpalatable, not least because hard-to-appreciate effects like cross-modal adaptation are touted as the strongest evidence that number adaptation effects pertain to *number* and not just low-level confounds (Block 2022: 87-90; Clarke & Beck 2021). The other option is to accept that these effects are not visually appreciable, but to maintain that they are actual. Yet herein lies a different concern: Insofar as these phenomena cannot be readily appreciated in a demonstration, what reasons do we have for thinking that the alleged effects are of the same basic kind as the classic demonstrations of the phenomena that convinced so many of number adaptation's existence? Indeed, without visually appreciable alterations of phenomenology, what reason have we for even thinking these effects perceptual in nature? This is a particularly thorny issue since reported cases of cross-modal number adaptation typically lack other alleged indicators of perceptual processing, such as spatiotopy (Arrighi et al. 2014; but see Section 4).

Based on evidence from several failed replications, we have argued that, despite seemingly robust evidence of their existence, both reverse number adaptation (wherein adaptation to a small number collection yields a visible increase in a middling test display's number; see Burr & Ross, 2008) and cross-modal number adaptation (wherein adaptation in the visual modality, e.g., influences perceived number in the auditory modality; see Arrighi et al., 2014) are unlikely to be genuine (Yousif et al., 2024). These matters are now the subject of an ongoing, multi-site, registered, adversarial collaboration (Yousif et al., under review). But in our recent response to critics (Yousif et al., 2025), we also laid out a clear challenge to proponents of number adaptation: Show us a single visible demonstration of either reverse adaptation or cross-modal adaptation. This should be easy, if such adaptation is as robust as advertised. To date, no party has taken us up on that challenge.

Ironically, however, you don't need to take our word for any of this. Perhaps the most significant problem with the existence of cross-modal number adaptation concerns inconsistencies that proponents of the phenomenon have freely embraced and documented. To wit: Proponents of number adaptation claim that number adaptation is highly general, manifesting even when numerical stimuli are presented in different forms (e.g., sequentially vs. simultaneously; Arrighi et al., 2014) and different modalities (e.g., vision vs. audition, vision vs. action; Arrighi et al., 2014; Anobile et al., 2016). These cross-format and cross-modal effects are supposed to have decisively ruled out non-numerical confounds as the drivers of other proposed number related aftereffects.

Yet, aside from the abovementioned problems of replication, and the lack of any perceptually appreciable demonstrations, it is striking that these authors elsewhere claim that number adaptation is-shockingly brittle — eliminated almost entirely when the adapted objects and test displays differ even modestly in color (Grasso et al., 2022). In fact, we noted above that we have confirmed these latter results, finding that changing the color of even individual dots, while holding the distribution of black to white dots in the ensemble constant, significantly reduces the apparent adaptation effect in much the same way (Yousif et al., 2024). These findings are hard to reconcile: How could a sense of number be so abstract as to transcend sensory modalities in cross-modal paradigms, yet falter under even modest changes of color? In fact, this is one point that our critics seem to accept, calling for future work to explore this apparent contradiction further (see Burr et al., 2025).

We could go on. The preceding remarks offer a brief glimpse into the many puzzles, mysteries, and challenges facing proponents of number adaptation. Beyond the fact that there is an alternative explanation for readily appreciable, classic "demonstrations" of number adaptation – one which simply appeals to well-known principles of visual filtering (which all parties should already accept as actual), and one which straightforwardly predicts many of the myriad quirks which render number adaptation effects unlike canonical forms of adaptation (for more evidence, see Yousif et al., 2024, 2025) – the only studies which are not readily accommodated by our rival "old news" hypothesis (e.g., Arrighi et al., 2024; Fornaciai et al., 2016) seem to be plagued by failures of replication (ibid.; Shepherd & Durgin, 2016) and seem not to yield any appreciable demonstrations. For these reasons, we encourage caution: The default hypothesis moving forward should be that number adaptation is probably *not* genuine. We do not claim to have proved a negative, but if one means to show that number adaptation is genuine, they should take a diagnostic rather than confirmatory approach. We should carefully consider the nitty-gritty psychophysical details that have been brushed aside for much too long.

3. Adaptation as a litmus test

Let us suppose that everything we have argued until this point is false — that, contrary to the arguments above (and the many additional arguments we provided in Yousif et al. 2024; 2025), number adaptation is actual. What follows from this conclusion?

A standard answer has been that number adaptation's existence matters because it provides ironclad evidence that number is a perceptual attribute (Burr & Ross, 2008; Anobile et al., 2016). Thus, one might think that if proponents of number adaptation could defend the existence of number adaptation against the above critiques, this would be significant for revealing that number is a perceptual dimension. We will now argue that this is not so: Even if number adaptation survives our critiques, this would only provide poor reason to think that number is a perceptual attribute in any interesting or substantive sense of the term.

In our original work, we made our stance on this matter explicit: "Number may well be a perceptual attribute," we wrote, "but whether number adaptation is genuine need not bear on that question" (Yousif et al., 2024; p. 13). In more recent work, we've brought data to bear on this assertion. We've demonstrated spatiotopic "perceptual" adaptation — of the same sort that is documented in dozens of papers about number adaptation — to a dimension that is not plausibly perceived: arbitrarily assigned value (Clarke & Yousif, under review).

In our experiments, observers considered displays of fake "coins" with arbitrary values ranging from one to five (see Figure 3A). Observers were simply told that coins of one color were worth five points, coins of another color were worth four points, and so on, and that their task would be to identify which of two 30-coin collections had a greater cumulative value given these assignments. There was, however, a twist: In a paradigm reminiscent of our original number adaptation experiments, observers first adapted to 30-coin collections of varying value in the location of one or other of the subsequent test collections to be discriminated (see Figure 3B).

Remarkably, this produced an analogous pattern of results to that found in our studies probing number adaptation. In a straightforward value-adaptation experiment, in which observers adapted to a single high-value collection on one side of a central fixation point, we found a robust spatiotopic adaptation effect: Observers were significantly above chance in selecting that the test collection on the contralateral side of the display was greater in value. In a "reverse" adaptation experiment (in which observers adapted to a low- or medium-value item) we found that observers were no more or less likely to choose the side with a low-value adaptor, but they were less likely to choose the side with a medium-value adaptor. This pattern of results shows that subjects were not simply disposed to pick or attend to contralateral sides of the display. Notably, however, all of these results mirrored exactly what we previously observed when studying number adaptation, where adaptation to a high-number adaptors yields an appreciable reduction in apparent number while "reverse" adaptation to small-number collections has no effect (just as our old-new hypothesis predicts: Yousif et al., 2024). But in the current value-experiments, the collections each contained an identical number of coins, with identical cumulative surface areas and spatial densities; thus, orthogonal dimensions, such as number, surface area, and density were controlled. Moreover, follow up experiments showed that these effects are, indeed, both spatiotopic (indexed to a specific spatial location in the display; rather than, say, a specific hemifield) and obtain for other, uncolored stimuli, such as collections of Arabic numerals (thereby ruling out color adaptation as a possible confound). It therefore seems that it was the arbitrarily assigned values of the coins (rather than number or continuous confounds) which drove the repulsive aftereffects we observed.

We see three ways that proponents of the view that *number adaptation is diagnostic of number's status as a perceptual attribute* might respond. The first (and simplest) response would involve them concluding from our results that arbitrarily assigned value is, indeed, a perceptual dimension. Viewed this way, value adaptation is a monumental discovery. But we think this is an extravagant conclusion. After all, researchers often consider value assignments paradigmatically non-perceptual; monetary value is often touted as a property that is plainly only going to be represented in post-perceptual thought (see Butterfill, 2011). Indeed, when clarifying what it would mean for numbers or numerical contents to be visually represented, Block contrasts number with monetary value, writing "we can often tell visually whether something is expensive but I doubt that expensiveness is visually represented" (2022; p. 11).

A second and more plausible response would involve proponents of *number adaptation as diagnostic of number perception* identifying some principled difference between the evidence we described for value adaptation and evidence that is routinely marshalled in favor of number adaptation. However, it isn't clear what this would be. While it is true that, as of writing, number adaptation has been much more exhaustively studied, much of that additional work has only yielded contradictory evidence. All that we can really say about number adaptation, conclusively, is that there are sometimes repulsive behavioral aftereffects in one direction following adaptation to certain collections of seen dots. Considering our recent results, we can now say the same of value. In both cases, *why* adaptation is observed is somewhat mysterious. More positively, it might be claimed that number adaptation results are distinctively perceptual since they are spatiotopic and many find it hard to imagine spatiotopic effects in thought (Block, 2022; p. 75). But aside from the aforementioned fact that key results from the number adaptation literature are, themselves, not spatiotopic (Anobile et al., 2016) nor even spatially indexed (Arrighi et al., 2014), the results of our value experiments were.

For these reasons we are partial to a third path forward: We believe that our results reveal that spatiotopic adaptation is not diagnostic of perceptual processing after all. Even if one brackets our concerns that number adaptation is unlikely to be genuine (c.f. Burr, Anobile, & Arrighi, 2025; Yousif et al., 2024, 2025), the existence of number adaptation simply wouldn't do the work of distinguishing a *perceptual* number sense from a *non-perceptual* one (see also Phillips & Firestone, 2023). This path forward also strikes us as the most empirically fruitful: If it is true that spatiotopic adaptation occurs for non-perceptual dimensions, then many new questions arise from this revelation. What other phenomena, previously designated as "cognitive" phenomena and hence not prone to adaptation, might be explained by adaptive mechanisms? For instance: Could something like *random number generation* (see Boger et al., 2025) be explained by a kind of adaptation (see Phillips & Firestone, 2023)?

4. Number as a perceptual attribute

Available evidence suggests that number adaptation is unlikely to be genuine. But even if number adaptation is genuine, we should avoid assuming that this renders number a visual attribute (see Section 3). Does this mean that number is only ever represented in post-perceptual cognition? We think not. There are other reasons for thinking that number features in perceptual content (for a review of concrete alternatives, see Clarke & Beck, 2023). For one, number is processed *quickly*, is represented in *early stages of visual cortex* (DeWind et al., 2019; Fornaciai et al., 2017), and is encoded in an analog format that's characteristic of magnitude perception more generally (Beck 2019; Clarke 2022; 2023; see also [CLARKE & BECK CHAPTER – THIS VOLUME)). Number is also processed relatively *automatically*, interfering in task-irrelevant ways with judgements about orthogonal magnitude types (Cicchini et al., 2016; Savelkouls & Cordes, 2020; Yousif & Keil, 2019, 2020). This is to say nothing of the fact that the perception of number *interacts in rich ways with other visual processes* like object-based attention (Franconeri et al., 2009).

The trouble here is that none of these criteria are individually diagnostic. There's no established threshold for how quickly something must be perceived to be truly visual in nature. Making inferences from localizations in the brain is more *art* than *science.* Replication issues notwithstanding, automaticity is discussed as often in the cognitive realm as it is in the perceptual (Bargh & Chartrand, 1999). This is why adaptation as a criterion was valuable: The discovery of Burr and Ross (2008) was exciting because it purported to make an intractable debate trivial. Adaptation promised to make the boundary between *perception* and *cognition* an objective one.

If adaptation cannot mark the dividing line, then are there other characteristics of visual features that would suffice? We think that one characteristic may come close: the fact that *number is subject to recalcitrant illusion* (for a relevant architectural proposal, see Clarke, 2021). There are many distinct illusions of number, including the regular-random illusion (Ginsburg, 1976), the coherence illusion (DeWind et al., 2020), the connectedness illusion (Franconeri et al., 2009; He et al., 2009; Qu et al. 2024; Clarke et al. 2025), and the crowd size illusion (Waterhouse & Yousif, under review). In these cases, the observer experiences compelling, often substantial, distortions of perceived number — and they continue to experience these distortions even when they are made aware of them (as readers can appreciate for themselves by inspecting Figure 4). The recalcitrance of perceived number indicates an imperviousness of perceptual systems to cognitive ones (Firestone & Scholl, 2016) and seems to demonstrate a unique signature of perceptual processes that cannot be straightforwardly explained by appeal to post-perceptual thought (because such illusions persist *despite* thoughts to the contrary).

For these reasons, we're inclined to believe that number *is* a perceptual attribute after all — but not because it exhibits adaptation. Of course, it might be noted that adaptation effects sometimes yield readily appreciable and recalcitrant illusions of their own. But given the preceding remarks we should now appreciate that even if such effects were to operate over higher-level contents, like number, it would be the recalcitrance (and other perceptual signatures) of the effects that would now be doing the heavy lifting in convincing us of their status as perceptual (see also Philliips & Firestone, 2023; for concrete examples, consider how the recalcitrance of agential attributions [Gao & Scholl 2013] of certain cases of pareidolia might convince us that high-level social content is attributed in perception). Adaptation is neither here nor there.

5. Conclusion

This chapter has provided a whistlestop tour of recent developments in the debate surrounding number adaptation (and adaptation more broadly). Building on prior work, we have rehearsed several reasons why we find the evidence for number adaptation unpersuasive. We have also charted new territory, introducing reasons to think number adaptation would lack the significance it is typically taken to possess, regardless of our skepticism about the phenomenon. We say this because spatiotopic adaptation effects, of the sort that number adaptation is meant to exemplify, seem to be poor markers of perceptual attribution. They obtain for arbitrarily assigned coin values which seem to only be encoded outside of perception. On reflection, it then seems that the best reasons we have for thinking number a perceptual attribute will likely have nothing to do with adaptation whatsoever. But while this could all sound rather negative, we believe that these results raise many productive questions of their own: They challenge us to pay closer attention to the question of what adaptation is and what would enable it to play the roles that are expected of it in vision science and the philosophy thereof. So, however the chips fall with respect to the varied controversies discussed in this chapter, we believe that further engagement with number adaptation and its alternatives is likely to prove immensely productive.

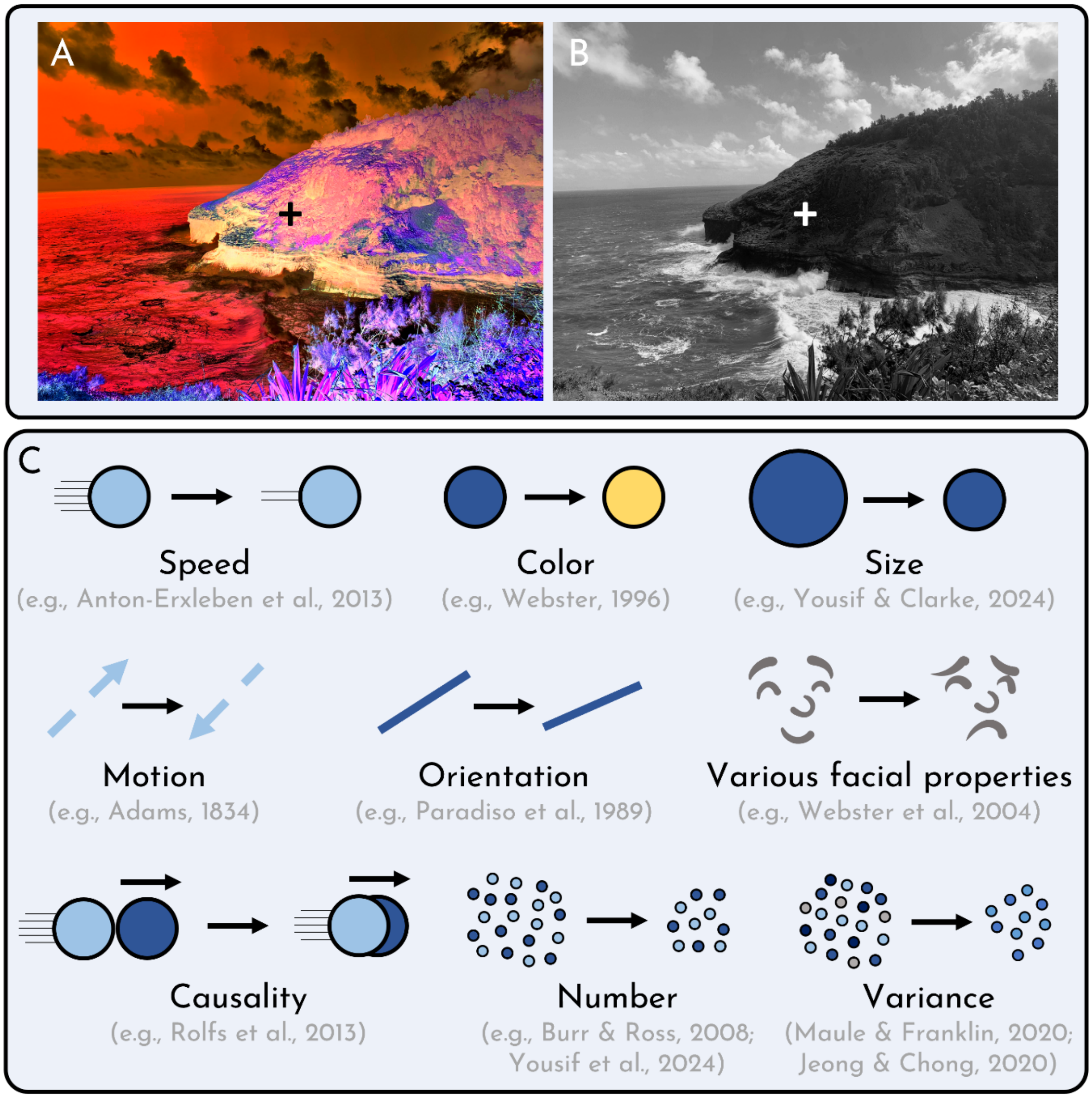

Figure 1. You can experience color adaptation by staring at (A) and then rapidly shifting your eyes to (B). (C) Various other kinds of "high-level" visual adaptation.

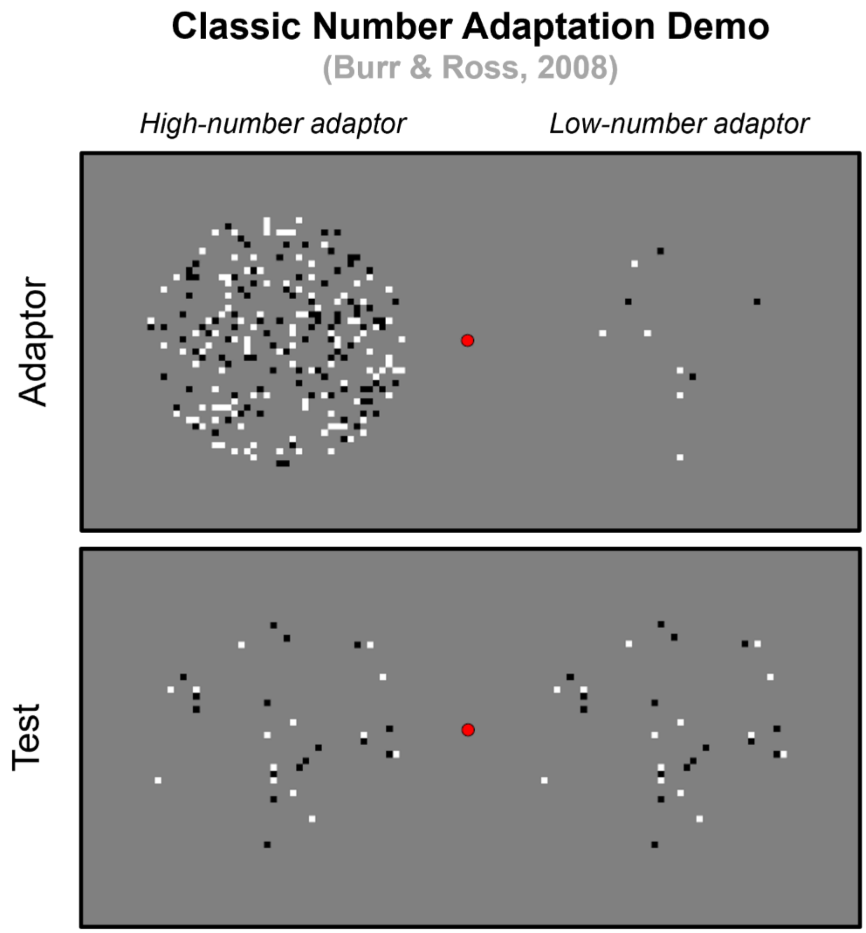

Figure 2. A classic example of number adaptation, popularized by Burr & Ross (2008).

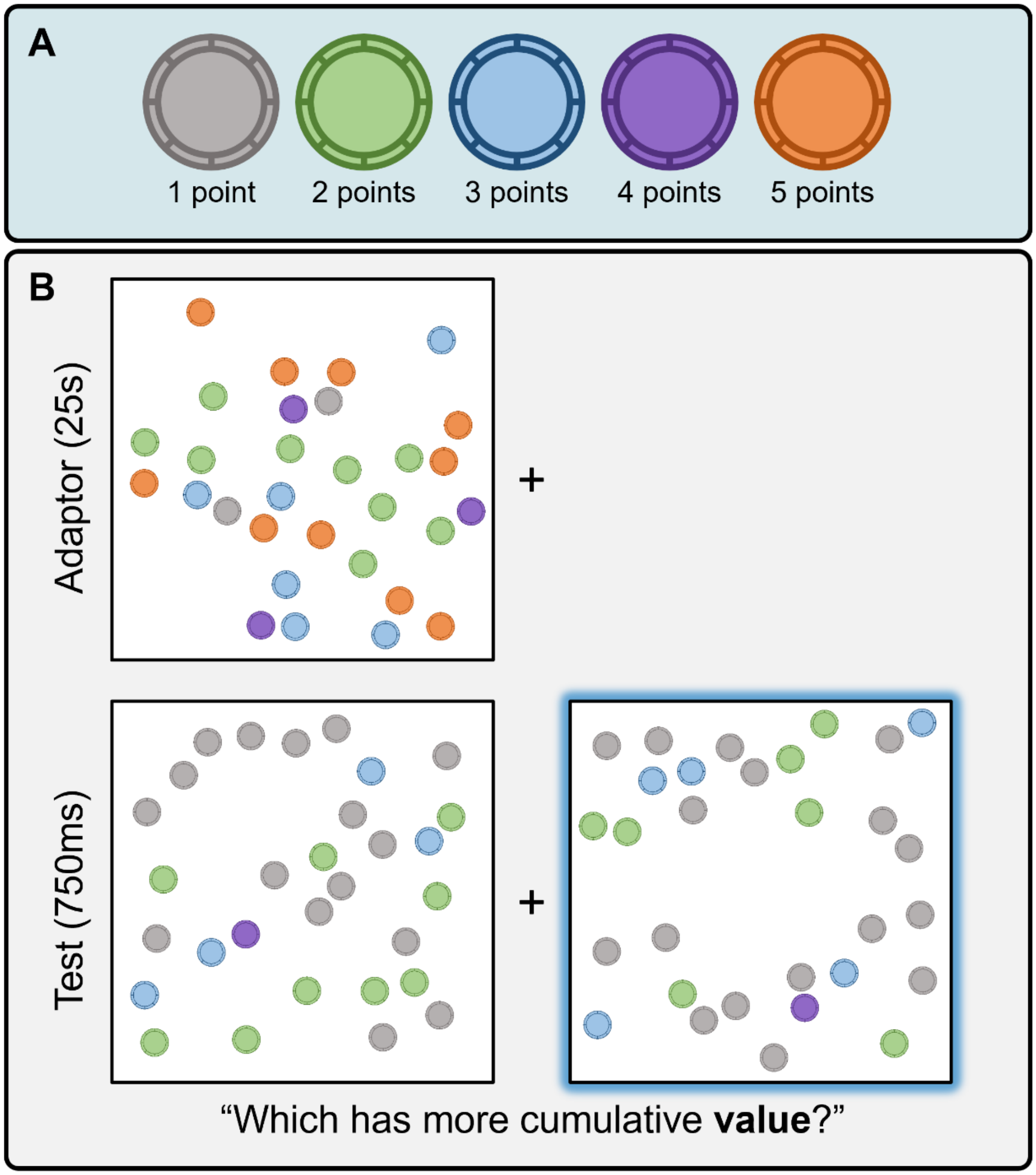

Figure 3. (A) The coin stimuli used in the present experiment. The coins were arbitrarily assigned the values one through five. Observers were told about the coin values immediately prior to beginning the experiment and then reminded about the coin values after completing the practice trials. (B) An example of a canonical value adaptation trial (as in Experiment 1). Observers would stare at a display with a single high-value adaptor on one side of the screen (counterbalanced) for 25 seconds before the test stimuli flashed for 750 milliseconds, at which time they were asked to indicate which display was greater in cumulative value. In a situation like this one, people tended to select the un-adapted stimulus (highlighted in blue), as if they perceived the adapted size as being lesser in value. The stimuli always contained thirty coins. The stimulus values were chosen to be comparable to those used in studies of number adaptation (e.g., Burr & Ross, 2008).

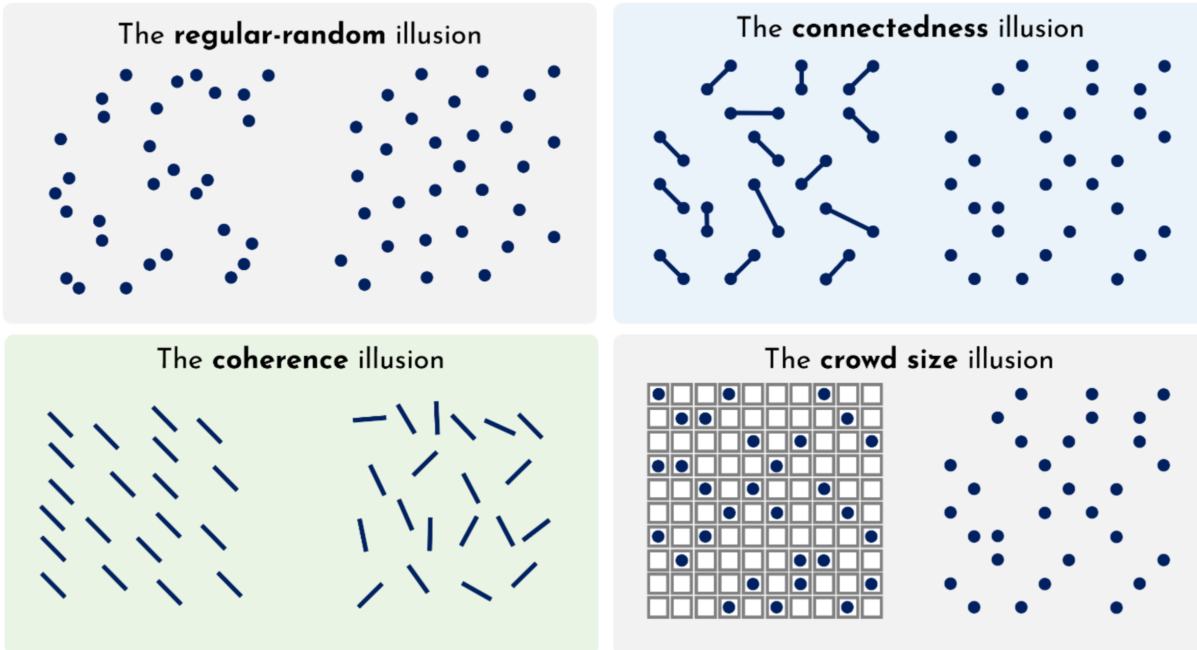

Figure 4. Various illusions of number.

References

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

Anobile, G., Cicchini, G. M., & Burr, D. C. (2016). Number as a primary perceptual attribute: A review. *Perception*, *45*(1-2), 5-31.

Anton-Erxleben, K., Herrmann, K., & Carrasco, M. (2013). Independent effects of adaptation and attention on perceived speed. *Psychological Science*, *24*, 150–159.

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

Bargh, J. A., & Chartrand, T. L. (1999). The unbearable automaticity of being. *American Psychologist*, *54*(7), 462-479.

Bayne, T. (2010). *The unity of consciousness.* Oxford University Press.

Beck, J. (2019). Perception is analog: The argument from Weber's Law. *Journal of Philosophy* 116(6): 319-349.

Block, N. (2023). *The border between seeing and thinking*. Oxford University Press.

Boger, T., Yousif, S. R., McDougle, S., & Rutledge, R. (2025). Random behavior is stable across tasks and time.

Burr, D., Anobile, G., & Arrighi, R. (2025). Number adaptation: reply. *Cognition*, *254*, 105870.

Burr, D., & Ross, J. (2008). A visual sense of number. *Current Biology*, *18*(6), 425-428.

Burr, D. C., Anobile, G., & Arrighi, R. Number Adaptation: Reply. *Available at SSRN 4839798*.

Butterfill, S. (2011). Seeing causings and hearing gestures. In Fiona Macpherson & Katherine Hawley (eds.), *The admissible contents of experience*, Blackwell, 36-59.

Cicchini, G. M., Anobile, G., & Burr, D. C. (2016). Spontaneous perception of numerosity in humans. *Nature Communications*, *7*(1), 12536.

Clarke, S. (2021). Cognitive penetration and informational encapsulation: Have we been failing the module? *Philosophical Studies* 178 (8): 2599-2620.

Clarke, S. (2022). Beyond the Icon: Core cognition and the bounds of perception. *Mind & Language* 37(1): 94-113.

Clarke, S. (2023). Compositionality and constituent structure in the analogue mind. *Philosophical Perspectives* 37(1): 90-118.

Clarke, S. & Beck, (2021). The number sense represents (rational) numbers. *Behavioral & Brain Sciences* 44: 1-57.

Clarke, S., & Beck, J. (2023). Border Disputes: Recent Debates along the Perception–Cognition Border. *Philosophy Compass* 18 (8): e12936.

Clarke, S. & Yousif, S.R. (2025). Can you *see* value? Spatiotopic "visual" adaptation to an imperceptible dimension.

Crane, T. (1988). The Waterfall Illusion. *Analysis* 48:142-47.

DeSimone, K., Kim, M., & Murray, R. F. (2020). Number adaptation can be dissociated from density adaptation. *Psychological Science*, *31*(11), 1470-1474.

DeWind, N. K., Bonner, M. F., & Brannon, E. M. (2020). Similarly oriented objects appear more numerous. *Journal of Vision*, *20*(4), 1-11.

DeWind, N. K., Park, J., Woldorff, M. G., & Brannon, E. M. (2019). Numerical encoding in early visual cortex. *Cortex*, *114*, 76-89.

Durgin, F. H. (2025). Refreshing the conversation about adaptation and perceived numerosity: A reply to Yousif, Clarke and Brannon. *Cognition*, *254*, 105883.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in cognitive sciences*, *8*(7), 307-314.

Fornaciai, M., Cicchini, G. M., & Burr, D. C. (2016). Adaptation to number operates on perceived rather than physical numerosity. *Cognition*, *151*, 63–67.

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

Franconeri, S. L., Bemis, D. K., & Alvarez, G. A. (2009). Number estimation relies on a set of segmented objects. *Cognition*, *113*(1), 1-13.

Ginsburg, N. (1976). Effect of item arrangement on perceived numerosity: Randomness vs regularity. *Perceptual and Motor Skills*, *43*(2), 663-668.

Grasso, P. A., Anobile, G., Caponi, C., & Arrighi, R. (2021). Implicit visuospatial attention shapes numerosity adaptation and perception. *Journal of Vision*, *21*(8), 1-12.

Grasso, P. A., Anobile, G., Arrighi, R., Burr, D. C., & Cicchini, G. M. (2022). Numerosity perception is tuned to salient environmental features. *IScience*, *25*(4), 104104.

Green, E. J. (2021). The Perception-Cognition Border: A Case for Architectural Division. *Philosophical Review* 129 (3):323-393.

Hafri, A., & Firestone, C. (2021). The perception of relations. *Trends in Cognitive Sciences*, *25*(6), 475-492.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*(7213), 665-668.

He, L., Zhang, J., Zhou, T., & Chen, L. (2009). Connectedness affects dot numerosity judgment: Implications for configural processing. *Psychonomic Bulletin & Review*, *16*(3), 509-517.

Kominsky, J. F., & Scholl, B. J. (2020). Retinotopic adaptation reveals distinct categories of causal perception. *Cognition*, *203*, Article 104339.

Maule, J., & Franklin, A. (2020). Adaptation to variance generalizes across visual domains. *Journal of Experimental Psychology: General*, *149*(4), 662-675.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*(5109), 1519-1520.

Phillips, I., & Firestone, C. (2023). Visual adaptation and the purpose of perception. *Analysis*, *83*, 555–575.

Pooresmaeili, A., Arrighi, R., Biagi, L., & Morrone, M. C. (2013). Blood oxygen level-dependent activation of the primary visual cortex predicts size adaptation illusion. *Journal of Neuroscience*, *33*, 15999–16008.

Qu, C., Clarke, S., Luzzi, F., & Brannon, E. (2024). Rational number representation by the approximate number system. *Cognition*, *250*, 105839.

Rolfs, M., Dambacher, M., & Cavanagh, P. (2013). Visual adaptation of the perception of causality. *Current Biology*, *23*(3), 250-254.

Savelkouls, S., & Cordes, S. (2020). The impact of set size on cumulative area judgments. *Acta Psychologica*, *210*, 103163.

Scholl, B. J., & Gao, T. (2013). Perceiving animacy and intentionality: Visual processing or higher-level judgment. *Social perception: Detection and interpretation of animacy, agency, and intention*, *4629*, 197-229.

Shepherd, E., & Durgin, F. (2016). No effect of unitization (connectedness) on the adaptation of perceived number. *Journal of Vision, 16*, 815.

Siegel, S. (2006). Which Properties Are Represented in Perception. In Tamar Szabo Gendler & John Hawthorne (eds.), *Perceptual experience*. New York: Oxford University Press. pp. 481-503.

Tonelli, A., Cuturi, L. F., & Gori, M. (2017). The infuence of auditory information on visual size adaptation. *Frontiers in Neuroscience*, *11*, 1–8.

Tonelli, A., Pooresmaeili, A., & Arrighi, R. (2020). The role of temporal and spatial attention in size adaptation. *Frontiers in Neuroscience*, *14*, 1–9.

Waterhouse, G.C.L. & Yousif, S.R. (under review). The "crowd size illusion" and the relativity of number perception.

Webster, M. A. (2015). Visual adaptation. *Annual Review of Vision Science*, *1*(1), 547-567.

Webster, M. A., & MacLeod, D. I. (2011). Visual adaptation and face perception. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*(1571), 1702-1725.

Yousif, S.R., Arrighi, R., Brannon, E.M, Clarke, S., Tologi, I., et al. (Under review). Registered report: A multi-site replication of audiovisual cross-modal number adaptation.

Yousif, S. R., & Clarke, S. (2024). Size adaptation: Do you know it when you see it? *Attention, Perception, & Psychophysics*, *86*(6), 1923-1937.

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

Yousif, S. R., Clarke, S., & Brannon, E. M. (2025). Seven reasons to (still) doubt the existence of number adaptation: A rebuttal to Burr et al. and Durgin. *Cognition*, *254*, Article 105939.

Yousif, S. R., & Keil, F. C. (2019). The additive-area heuristic: An efficient but illusory means of visual area approximation. *Psychological Science*, *30*(4), 495-503.

Yousif, S. R., & Keil, F. C. (2020). Area, not number, dominates estimates of visual quantities. *Scientific Reports*, *10*(1), 13407.