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Can we "see" value? Spatiotopic "visual" adaptation to an imperceptible dimension

Sam Clarke [a,*], Sami R. Yousif [b]

[a] University of Southern California, United States of America
[b] Ohio State University, United States of America

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ABSTRACT

In much recent philosophy of mind and cognitive science, repulsive adaptation effects are considered a litmus test — a crucial marker, that distinguishes what is *perceived* from what is *judged* at the level of post-perceptual thought or cognition. Here, we provide evidence for a form of adaptation that challenges this contention. Across four experiments, we found consistent evidence of adaptation to a seemingly imperceptible dimension: arbitrarily assigned value. We show that this adaptation occurs across stimulus formats, is spatially indexed (i.e., spatiotopic) and otherwise analogous to putative cases of high-level visual adaptation in relevant respects. Combined, we suggest that our results force one of two conclusions: Either repulsive perceptual adaptation can be obtained for seemingly imperceptible dimensions, or — as we proceed to argue — adaptation fails to reliably demarcate perceptual content.

It has been recognized since antiquity that humans *adapt* to canonical visual features, like hue, motion, orientation, and brightness, resulting in *visible repulsive aftereffects*. As Aristotle noted, after staring at a flowing river, a stationary riverbank appears to move (Aristotle, cited in Ross, 1931, p. 459b). After staring at a bright red light, a neutral white surface can appear as if tinged green (and vice versa). Contemporary vision science considers these effects more than a mere curiosity. It deems them a "powerful tool for dissecting vision by exposing the mechanisms that are adapting" (Webster, 2015; p. 547), an "intrinsic feature of visual processing" which "reaches the status of a universal law" (p. 548). Correspondingly, repulsive adaptation effects are widely regarded as diagnostic of perceptual processing, on the proposed grounds that "All primary visual properties are susceptible to adaptation" (Burr & Ross, 2008; p. 425) and on the grounds that "No such phenomena [of conceptual or post-perceptual adaptation effects] have been reported" (Block, 2014; p. 8).

This has significant ramifications. The range of reported adaptation effects has recently expanded to include not only adaptation to canonical visual properties like color and motion but also higher-level, non-obviously perceptible features like number (Burr & Ross, 2008; but see Yousif, Clarke, & Brannon, 2024, Yousif & Clarke, 2025), causality (Rolfs, Dambacher, & Cavanagh, 2013), and variance (Maule & Franklin, 2020). Accordingly, many conclude that these non-obviously perceptible features must, in fact, be "primary visual attributes" — represented alongside color and shape in vision, rather than merely encoded in post-perceptual cognition.

But is adaptation uniquely perceptual, or does post-perceptual cognition also exhibit repulsive aftereffects? One problem for the view that adaptation is uniquely perceptual stems from anecdotal observations: After time spent thinking of mansions, a normal-sized apartment might be thought of as smaller than it otherwise would (Helton, 2016). Such suspicions are bolstered by empirical phenomena, such as prevalence-induced concept change (PICC), in which the repeated tokening of a concept like "violence" in thought shows a kind of repulsivity, increasing one's threshold for its attribution, thereby ensuring that middling-violent cases are less likely to be categorized as such (Levari et al., 2018). Or consider random number generation (Phillips & Firestone, 2023) in which subjects who are tasked with randomly picking successive numbers from a finite range find themselves disposed to avoid picking two or more successive numbers from one or other end of that range (e.g., Boger, Yousif, McDougle, & Rutledge, 2025). In cognitive neuroscience matters appear even starker: Neural adaptation, in the form of "repetition suppression" has been a cornerstone of the field for more than twenty years. Repetition suppression is thought to apply to the brain's representations quite generally and not simply to those produced by perceptual systems (Grill-Spector & Malach, 2001).

* Corresponding author.
E-mail addresses: sam.clarke@usc.edu (S. Clarke), yousif.36@osu.edu (S.R. Yousif).

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Despite these concerns, many continue to view adaptation as a definitive marker of perceptual processing on the grounds that only *perceptual* adaptation is indexed to retinotopic (Kominsky & Scholl, 2020; Rolfs et al., 2013) or spatiotopic (Burr & Ross, 2008) locations (but see Arrighi, Togoli, & Burr, 2014). By contrast, post-perceptual aftereffects of the above sort are widely assumed to be spatially unlocalized. As Block (2023) puts it, no cognitive aftereffect "has ever been shown to be retinotopic or spatiotopic" (p. 75).[1]

Here, we focus on *spatiotopic* adaptation, presenting evidence that runs contrary to Block's assessment. In four experiments, we found evidence of *spatiotopic* adaptation to a non-perceptual dimension: *arbitrarily assigned value*. In a first experiment, we demonstrate a canonical adaptation effect to arbitrarily assigned "coin" values. In a second experiment, we test whether this adaptation is bidirectional (as this has been a point of contention for other types of high-level adaptation; see Yousif et al., 2024, Yousif & Clarke, 2025). In a third experiment, we test value adaptation on displays of Arabic numerals (thus, ruling out certain low-level confounds). In a fourth experiment, we test whether these effects operate across formats, generalizing from Arabic numerals to coin displays. Finally, in a fifth experiment, we test the degree to which these effects are spatiotopic. To foreshadow: We argue that value adaptation occurs and exhibits the hallmarks of high-level visual adaptation, even though there exist compelling reasons to regard value as paradigmatically imperceptible.

1. Experiment 1: Basic Value Adaptation

In a first experiment, observers were briefly introduced to displays of fake "coins" with arbitrarily assigned values ranging from one to five (see Fig. 1A). They were told that they would be completing a quantity discrimination task in which their goal was to select the side whose coins had a higher cumulative value given these assignments. Prior to making each judgment, however, participants *adapted* to separate displays of coins that were presented to the left or right of a central fixation point for 25 s. We wondered: Might observers adapt to *value* in the same way that they adapt to high-level dimensions like *number*?

1.1. Methods

1.1.1. Pre-registration and data availability

All experiments were pre-registered prior to data collection. Those pre-registrations, as well as raw data and materials, are available on our OSF page: https://osf.io/56umx/?view_only=9a1d89a019824c81a70336f583593c53.

1.1.2. Participants

Twenty undergraduate students participated in the study in exchange for course credit. All observers provided informed consent, and the study was approved by the university's Institutional Review Board.

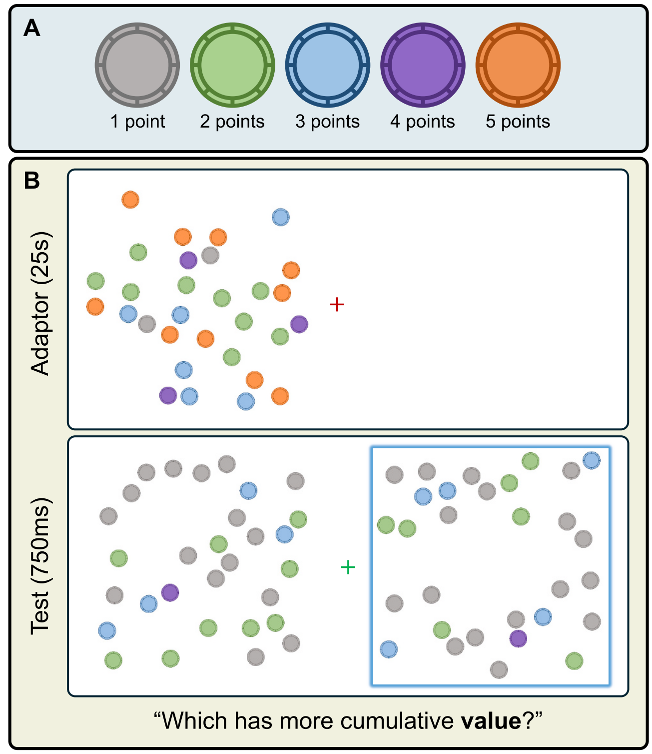

Fig. 1. (A) The coin stimuli. The coins were arbitrarily assigned the values one through five. Observers were told about the coin values immediately prior to beginning the experiment and then reminded about the coin values after completing the practice trials. (B) An example of a canonical value adaptation trial (as in Experiment 1). Observers would stare at a display with a single high-value adaptor on one side of the screen for 25 s before the test stimuli flashed for 750 milliseconds, at which time they were asked to indicate which display was greater in cumulative value. People tended to select the un-adapted stimulus (highlighted in blue), as if they perceived the adapted size as being less in value. The stimulus values were chosen to be comparable to those used in studies of number adaptation (e.g., Burr & Ross, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.1.3. Stimuli

Each trial consisted of displays of fake "coins" with arbitrarily assigned values from 1 to 5. The coins were grey, green, blue, purple, and orange, worth 1, 2, 3, 4, and 5 "points" respectively. These colors were chosen to ensure there was no stable mapping between the values and any specific color space. Each coin was assigned to a random location with the constraint that each coin had to be at least 5 pixels away from the nearest coin (from edge to edge) and the edge of the display. At a standard viewing distance, each coin would span about 1.1°. To arrive at the correct value for each display, algorithmically, each coin started with the minimum value (1) and one point was added iteratively to a random coin (not to exceed the maximum value of 5) until the desired cumulative value was reached. All stimuli were made up of exactly 30 coins. The test stimuli had an average value of 50 points. For twenty of the thirty-six total trials, both test stimuli were worth exactly 50 points; for eight additional trials one of the test stimuli was worth only 40 points (counterbalanced across sides); and the eight remaining trials, one of the test stimuli was worth 60 points (counterbalanced across sides). The adaptor stimuli either had a value of 50 points or a value of 100 points. Canonical stimuli can be seen in Fig. 1B/Fig. 2A.

1.1.4. Task design & procedure

Observers sat approximately 60 cm away from a 55° by 42° monitor.

[1] Note that Block is making a stronger claim than others. Kominsky and Scholl (2020) focus exclusively on retinotopic effects: "… we know of no type of higher-level judgment that yields any sort of retinotopically specific effect." (p. 3; see also Rolfs et al., 2013). Yet while there may be tacit agreement that retinotopic effects constitute *stronger* evidence than mere spatiotopic effects, many accept that spatiotopic effects are diagnostic of perceptual processing. Number adaptation, one of the best studied cases of 'higher-level' visual adaptation, occurs only in spatiotopic coordinates, for instance — but even that is taken to establish that it occurs in visual rather than cognitive processing (see, e.g., Arrighi et al., 2014). Indeed, few adaptation effects are demonstrably retinotopic (Anton-Erxleben et al., 2013; Maule & Franklin, 2020; Poorsmaeili et al., 2013; but see Afraz & Cavanagh, 2009; Knapen, Rolfs, & Cavanagh, 2009, Latimer, Curran, & Benton, 2014; Morgan, 2014; Wenderoth & Wiese, 2008). We return to this issue in the Discussion section.

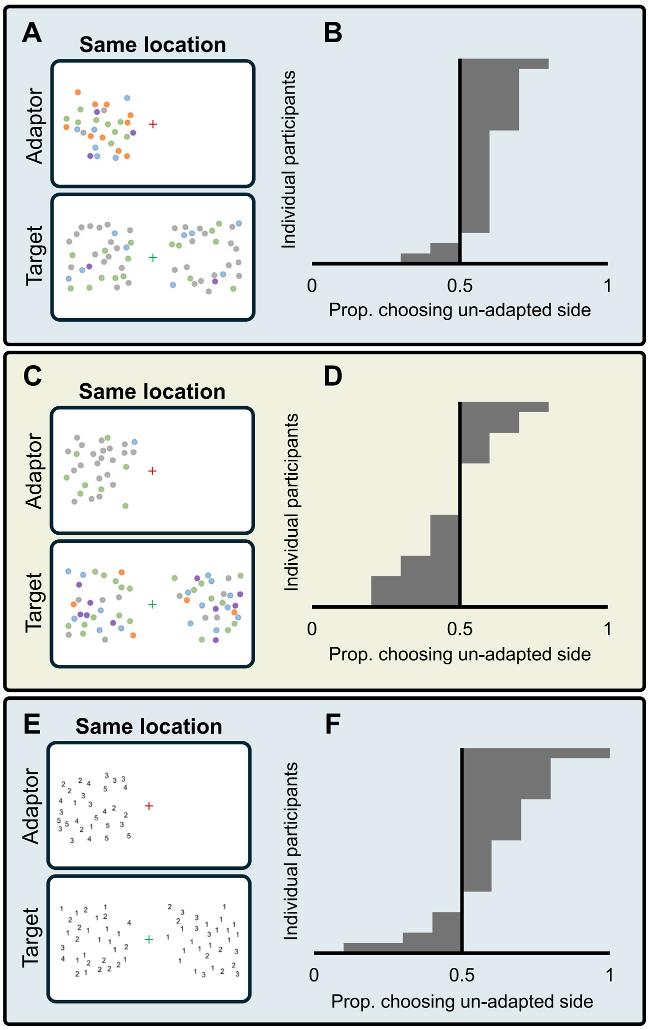

Fig. 2. (A) An example trial from Experiment 1. Here the adaptor has a value of 100 and each test stimulus has a value of 50. (B) Results from Experiment 1. Observers tended to choose the un-adapted side of the display. (C) An Example trial from Experiment 2. Here the adaptor has a value of 40 and each test stimulus has a value of 80. (D) Results from Experiment 2. Observers were no different from chance when the adaptor value was low. (E) An example trial from Experiment 3. Here the adaptor has a value of 100 and each test stimulus has a value of 50. (F) Results from Experiment 3. Observers tended to choose the un-adapted side of the display.

Observers were told about the coin values at the beginning of the instruction period and then reminded of them after an initial practice trial. They were told that their task would be to select which of the two displays was greater in cumulative value. Each trial began with a 25 s adaptation period: An "adaptor" stimulus appeared on either the left or right side of the screen (counterbalanced), positioned 11.5° away from the center and subtending a 14.4° by 14.4° space (see Fig. 1B). During this time, observers stared at a central, red fixation cross. After 25 s, two new "test" stimuli appeared for 750 ms, one on each side of the screen. The fixation cross turned green to indicate to observers that they should choose the stimulus of greater value. The order of the trials was randomized for each observer.

1.2. Results & discussion

The results of Experiment 1 can be seen in Fig. 2B. We found that adaptation to value resulted in a spatially indexed, repulsive aftereffect: When participants adapted to a display whose cumulative value was high (approximately double that of the target; see Fig. 2A), they were more likely to subsequently indicate that the contralateral side of the display was greater in value ($t[19] = 4.40$, $p < .001$, $d = 0.98$; see Fig. 2B). Per our pre-registered analysis plan, the reported analyses were conducted only on those trials for which the value of the two target stimuli was equated. The results are qualitatively identical for the overall test averaging across all trials.

This result is unlikely to be explained by confounds with number or other spatial dimensions of the display, since those properties were equated by virtue of all the collections — both in the adaptors and test displays — containing exactly thirty equally sized dots. Thus, this experiment provides suggestive evidence that people may "adapt" to value.

An alternative possibility is that this putative "value" adaptation results from adaptation to the coins' colors, with these alterations to perceived color then having downstream effects on participants' judgements of value. While Experiment 1 cannot rule this possibility entirely, we're inclined to think it unlikely. For one thing, it isn't clear how exactly adaptation to color would result in the observed effects. If observers experience colorful aftereffects, and use color as a proxy for value, then the presence of an adaptor should tend to *increase* the overall amount of color and coins experienced by the observer on the adapted side of space. But participants in Experiment 1 were significantly more likely to choose the unadapted side of the display at test as higher in value. Alternatively, one might think that adapting to purple coins would cause subsequent purple coins to look less purple and thus be mistaken for lower-value coins. But the opposite is also true: If one adapts to lower-value green coins, those coins should likewise be perceived as less green, and thus be mistaken for higher-value purple coins (e.g., if adapting to green causes the observer to perceive more purple). Thus, while the results of Experiment 1 may not show that it is *impossible* to explain these results by appeal to color aftereffects, or other low-level confounds, doing so is far from straightforward. To be sure, however, we address this issue more thoroughly in Experiments 3 and 4, using colorless displays.

2. Experiment 2: 'Reverse' Value Adaptation

Adaptation is typically assumed to be bidirectional. Adapting to purple produces a green aftereffect, and adapting to green produces a purple aftereffect; adapting to the downward motion of a waterfall produces the appearance of upward motion, and adapting to upward motion produces the appearance of downward motion. Not all high-level adaptive aftereffects are bidirectional, however. Asymmetries between "high" and "low" value adaptors are common for cases of adaptation to putatively high-level visual attributes, such as number (Yousif et al., 2024), size (Pooresmaeili, Arrighi, Biagi, & Morrone, 2013; Yousif & Clarke, 2024), and speed (Anton-Erxleben, Herrmann, & Carrasco, 2013). To compare the adaptability of value to that observed for other attributes, we tested whether value adaptation is bidirectional.

2.1. Methods

Twenty new undergraduate students participated in the study in exchange for course credit. The design was like Experiment 1, except that the adaptors were designed to have equal or lesser value than the test stimuli. The test stimuli had an average value of 80 points. For twenty of the thirty-six total trials, both test stimuli were worth exactly 80 points; for eight additional trials one of the test stimuli was worth only 64 points (counterbalanced across sides); and the eight remaining trials, one of the test stimuli was worth 96 points (counterbalanced across sides). The adaptor stimuli either had a value of 40 points or a value of 80 points. All stimuli were made up of exactly 30 coins. A canonical trial can be seen in Fig. 2C.

2.2. Results & discussion

The results of Experiment 2 can be seen in Fig. 2D. In contrast with the prior experiment, when observers adapted to small-value displays (see Fig. 2C) their assessment of a middling-value collection in the adapted region went unaffected ($t[19] = 0.91$, $p = .38$, $d = 0.20$; see Fig. 2D). That is, participants were no more or less likely to select a test display located in the adapted region of the display, versus one positioned on the display's contralateral side. The asymmetry between Experiments 1 and 2 is important for two reasons. Firstly, it shows that the results of Experiment 1 cannot simply be explained by a general tendency to select test collections that occupy un-adapted regions of the display. Rather, the selection of an unadapted test collection is disposed only by adaptation to high-value collections. Second, the asymmetry between Experiments 1 and 2 is notable insofar as most canonical cases of adaptation, like color and motion adaptation, are bidirectional. But while this renders value adaptation unlike certain canonical forms of visual adaptation, it resembles "visual" adaptation to features such as number (Yousif et al., 2024, Yousif & Clarke, 2025), size (Pooresmaeili et al., 2013; Yousif & Clarke, 2024), and speed (Anton-Erxleben et al., 2013). One possibility is that this may ultimately reflect the nature of these representations' contents (see Webster & MacLeod, 2011): unlike color or motion — which do exhibit bidirectional adaptation effects and vary along multiple dimensions — number, size, speed and value are one-dimensional magnitudes, each spanning from zero to infinity.

Finally, it is important to note that these results rule out the possibility that the results of Experiment 1 are explained by "neutral" number adaptation. Traditionally number has been assumed to exert downward adaptive pressure only when the adaptor is higher than the target stimulus (see, e.g., Grasso, Anobile, Caponi, & Arrighi, 2021). However, recent work has shown that equinumerous adaptors can also exert downward adaptive pressure (see Yousif et al., 2024; though there is disagreement about why this happens; see Burr, Anobile, & Arrighi, 2025; Durgin, 2025). If the results of Experiment 1 were caused solely by adaptation to number, then we should have observed the same pattern in Experiment 2 since the collections in both the adaptors and test display each contained an identical number of coins (30). As it stands, there are two possibilities: Either (A) Number adaptation is not a factor in these experiments, and there is clear evidence of "downward" but not "reverse" value adaptation, or (B) Number is a factor in these experiments, and the reason we fail to observe "reverse" value adaptation is because the "reverse" effect is competing against a "downward" number effect. Either way, value adaptation occurs.

3. Experiment 3: Arabic numerals

While we think that the results of Experiment 1 are unlikely to be explained by adaptation to color, we wanted to rule out this possibility decisively. Thus, we tested value adaptation without using color as a cue, by having observers adapt to sets of Arabic numerals (see Fig. 2E). We reasoned that such adaptation would be unlikely to be explained by any visual confound, since Arabic numerals are composed of the same basic visual features (i.e., simple lines) and the composition or quantity of these features is arbitrarily related to the numerical values they represent.

3.1. Methods

Twenty new undergraduate students participated in the study in exchange for course credit. Experiment 3 was identical to Experiment 1 except that coins were substituted for Arabic numerals between 1 and 5.

3.2. Results & discussion

The results of Experiment 3 can be seen in Fig. 2F. As with Experiment 1, we found that, after adaptation to a collection of numerals with a high-cumulative-value, participants were more likely to subsequently indicate that the contralateral side of the display was greater in value when presented with two middling-value adaptors ($t[19] = 2.40$, $p = .027$, $d = 0.54$; see Fig. 2F). This result strongly undermines the possibility that the previously observed value adaptation, found in Experiment 1, is due to confounds with color. That said, it is possible that the use of digits introduced some other unique visual confounds. One salient fact about the digit displays is that the digit "1" has less curvature than the other digits, leaving open the possibility that the patterns we observe are somehow caused by a sort of curvature adaptation (see, e.g., Coltheart, 1971; Vernoy, 1976). While intriguing, this possibility seems unlikely to explain our results for two reasons: (1) Curvature adaptation might cause a curved stimulus to look less curved, or it might cause an uncurved stimulus to appear curved in the opposite direction of the adaptor stimulus. In the latter case, adaptation to a "2" would make "1" seem more curved — but this should only increase the perceived value of the stimulus since the less-curved "1" is already the least valuable item in the display. And (2) While it is true that the "1 s" in the display appear to stand out, the "4 s" also contain no curvature. In this way it isn't clear that there's a reliable mapping between curvature and value that would be sufficient to explain our results.

4. Experiment 4: Cross-format value adaptation

We believe that the results of both the coin experiments (Experiments 1 and 2) and the Arabic numeral experiment (Experiment 3) are unlikely to be explained by lower-level visual confounds with features like color or curvature. But how can we know for sure? The 'gold standard' in adaptation studies is to show that adaptation persists *across formats* — i.e., on stimuli that have totally different visual properties (e.g., curvature, color), but share the same abstract property (value). Cross-format demonstrations are often considered the strongest evidence in support of number adaptation, for instance (Arrighi et al., 2014; Clarke & Beck, 2021), and have also been used in the study of variance adaptation (Maule & Franklin, 2020). Here, we simply combined the two stimulus sets from the previous studies to ask whether people adapt to abstract value, independent of the visual medium: Observers adapted either to coins or to Arabic numerals but were tested on the other dimension (see Fig. 3A). If we observe adaptation even in these cases, then we think that all questions about lower-level confounds may be laid to rest.[2]

4.1. Methods

Twenty new undergraduate students participated in the study in exchange for course credit. Experiment 4 was identical to Experiment 1 except that all the adaptors were of a high value (100) and each trial began with an adaptor made up of *either* coins *or* Arabic numerals. The test stimuli were always of the opposite kind. The initial stimulus type was counterbalanced.

4.2. Results & discussion

The results of Experiment 4 can be seen in Fig. 3B. We found reliable value adaptation when observers adapted to numerals but were tested on coins ($t[19] = 3.52$, $p = .002$, $d = 0.79$; see Fig. 3B), but only a marginal effect in the opposite condition ($t[19] = 1.97$, $p = .06$, $d = 0.44$; see Fig. 3B). Overall (averaged across the two conditions) the effect was robust, ($t[19] = 3.36$, $p = .003$, $d = 0.75$). These results indicate

[2] Every once and awhile, a colleague suggests an idea so good that you can only be angry you did not think of it yourself. For the inspiration for this experiment, we (angrily) thank Chaz Firestone, who suggested such a design following a talk about this work at the 2025 meeting of the Society for Philosophy and Psychology.

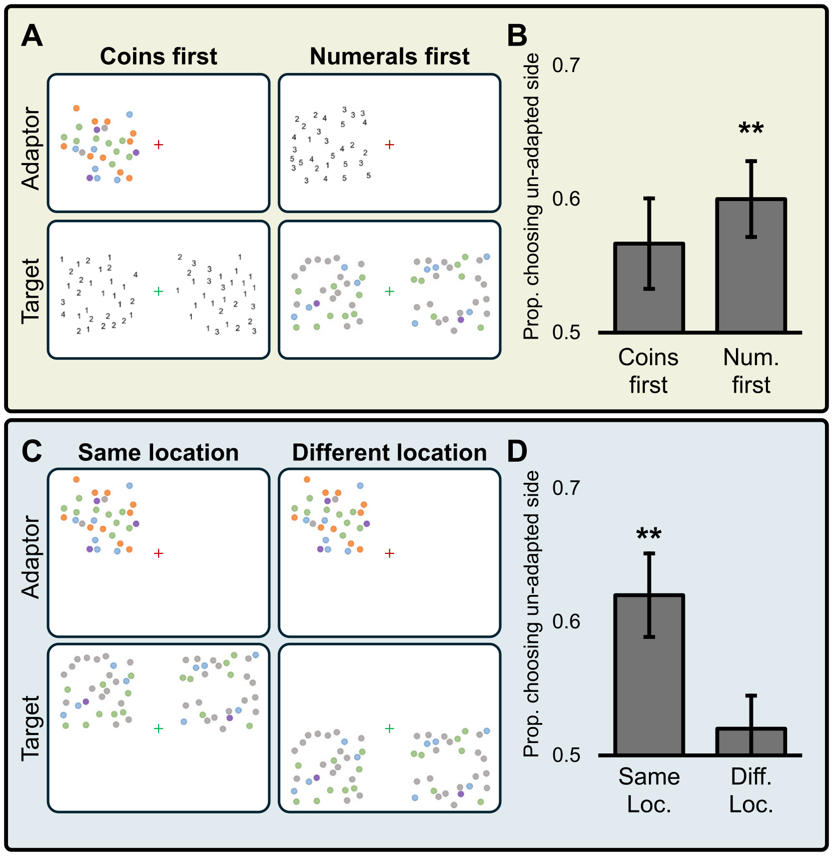

Fig. 3. (A) An example trial from Experiment 4. Here the adaptor has a value of 100 and each test stimulus has a value of 50. (B) Results from Experiment 4. Observers tended to choose the un-adapted side of the display. (C) Example trials from Experiment 5. Adaptors were always in the upper quadrants. For half the trials, the targets were in the same quadrant as their corresponding adaptor. For the other half of the trials, the targets were in the lower quadrant. (D) Results from Experiment 5. Observers tended to choose the un-adapted side, but only when the adaptors and targets were presented in the same location, indicating spatial selectivity. Error bars represent +/− 1 SEM.

that value adaptation occurs on *abstract* value, in such a way that it cannot be readily explained by mere adaptation to lower-level features like color or curvature.

5. Experiment 5: Spatiotopy?

The previous experiments demonstrate that value adaptation is spatially selective: When observers adapt to high-value collections on one side of a screen, they are significantly more likely to select a test display on the screen's contralateral side. But how spatially selective are these effects, exactly? To understand the respect in which these effects are spatially selective, we conducted a stronger test of spatiotopy, asking whether value adaptation is simply indexed to the left or right hemifield (or screen-region), or if it is instead indexed to a specific location within that hemifield. Hence, in Experiment 5, the adaptors were always shown in the upper quadrants of the screen, whereas the to-be-judged target stimuli appeared either in its upper quadrants or the lower quadrants (equally often; counterbalanced; see Fig. 3C). If adaptation is truly spatiotopic, then we should expect that adaptation would only occur when the adaptors and targets appear in the same quadrant. In contrast, if adaptation is selective only to a given hemifield, but *not* selective to an exact region of space, then we should expect adaptation in both conditions (i.e., same location and different location).

5.1. Methods

Twenty new undergraduate students participated in the study in exchange for course credit. Experiment 5 was identical to Experiment 1 except that all the adaptors were of a high value (100) and the screen was divided into quadrants. Adaptors always appeared in the upper quadrants, whereas targets appeared equally often in both the upper and lower quadrants (counterbalanced).

5.2. Results & discussion

The results of Experiment 5 can be seen in Fig. 3D. We observed robust value adaptation when the adaptor and target stimuli appeared in the same location ($t[19] = 3.84$, $p = .001$, $d = 0.86$; see Fig. 3D), but not otherwise ($t[19] = 0.81$, $p = .43$, $d = 0.18$; see Fig. 3D). These results suggest that the adaptation observed here is not merely selective to broad spatial regions, but is instead indexed to specific locations in space. Of course, our findings do not rule out a stronger interpretation of these results — namely, that the effects in question are *retinotopic* and, in fact, indexed to specific locations on the retina. However, most commentators proceed as if retinotopy is even stronger evidence of perceptual encoding than spatiotopy (e.g., Kominsky & Scholl, 2020, p.3; Rolfs et al., 2013). For this reason, we proceed cautiously, on the conservative assumption that our effects are *at least* spatiotopic, though we encourage future work which tests this more thoroughly.

6. General discussion

Here we have shown that observers "adapt" to arbitrarily assigned value (Experiments 1, 3, 4, and 5). Like some other high-level features, this adaptation does not appear to be bidirectional (Experiment 2). However, this adaptation does generalize across distinct stimulus types (c.f., Experiments 1, 3, and 4), is abstract in the sense that it operates across stimulus formats (Experiment 4) and is highly spatially selective, seemingly indexed to spatiotopic locations (Experiment 5).

A critic might point out that we have not — and perhaps could not — isolate value from all possible visual confounds, since value will always need to be indicated via some other visual feature. That may be true. Yet, taken to its extreme, this argument would undermine not only the evidence presented here for value adaptation, but virtually all other evidence in support of high-level visual processing. Number cannot be presented independently of low-level visual features (DeWind, Adams, Platt, & Brannon, 2015; Leibovich, Katzin, Harel, & Henik, 2017). Nor can causality (Rolfs et al., 2013), nor variance (Maule & Franklin, 2020), nor facial dimensions (Webster & MacLeod, 2011). This opens the door to critiques, according to which apparent cases of high-level adaptation result entirely from adaptation to less exotic, low-level features (see Durgin, 2008; Yousif et al., 2024, Yousif & Clarke, 2025). But it is also why cross-modal and cross-format effects have been seen as crucial evidence, particularly in the case of number adaptation: such effects separate the high-level content that exists across modalities from its lower-level, modality-specific components (see Arrighi et al., 2014). The reliability of that evidence has been questioned in the case of perceptual number adaptation, however, meaning that it is unclear whether there is any robust evidence for cross-modal adaptation to a high-level property (Yousif et al., 2024). In any case, the challenge that we have presented would-be-critics is this: If you do not believe that adaptation to *value* is occurring in our experiments, you need to tell us what adapted feature *is* driving the reported effects. And we have provided reasons to doubt several simple stories along these lines. For instance, we have argued that our results are unable to be explained by mere adaptation to color, number or curvature, especially in light of the cross-format findings from Experiment 4.

Evidence of value adaptation would typically be taken as a demonstration that the adapted feature (value) exhibits *perceptual* adaptation. That is: On a conventional view, motivated by well-established work on adaptation to number (Arrighi et al., 2014; Burr & Ross, 2008), spatially indexed adaptation to cumulative value indicates that arbitrarily assigned value is a perceptual attribute: Value is not merely 'judged' at the level of thought but can, also, feature in the content of observers' visual experience. After all, the displays used in our experiments needed to be *visually* discerned, and the repulsive effects elicited by adaptation to high-value adaptors were *at least* spatiotopic, indexed not only to a specific hemifield of the display, but to a specific region of that hemifield.

There is, however, another possible interpretation of our results. On this more heterodox view, what our results show is that spatiotopic, or otherwise spatially indexed, adaptation is not uniquely indicative of perceptual processing after all. Instead, it can occur at the level of post-perceptual judgment. If true, these results would constitute the first documented instance of a distinctively non-perceptual, yet spatially indexed, repulsive adaptation effect — a finding that would significantly alter our understanding of the phenomenon.

One reason we prefer this latter interpretation is that properties like economic value are typically regarded as paradigmatically imperceptible. For instance, when clarifying longstanding debates over which features and properties get represented in vision, Butterfill (2009) writes that "It is fairly uncontroversial that we can see the shapes of things and their movements. It is also reasonably uncontroversial that we cannot see properties like *market value* or processes like radioactive decay" (p. 405, *our emphasis*). He then proceeds to consider intermediary cases, like that of causality, where interested parties have sincerely drawn diverging conclusions (Hume, 1739; Michotte, 1946). Block reaches a similar conclusion when clarifying what it would mean for numbers or numerical contents to be visually represented, contrasting this with the case of monetary value: "we can often tell visually whether something is expensive but I doubt that expensiveness is visually represented" (2023; p. 11). We recognize there may be some that are happy to consider value a perceptual attribute, at least under certain conditions. Nevertheless, these quotes, from researchers who are otherwise in the business of positing high-level contents in human vision, are indicative of a widely shared intuition — that there are certain properties that simply seem to be paradigmatically imperceptible, at least insofar as any sense can be made of a straightforward distinction between perception and thought. That so many researchers share the intuition that value is some such feature is thus suggestive: We should be skeptical that value is a visual attribute, pending extraordinary evidence to the contrary.

With this in view, it is important to reflect on the conditions under which repulsive adaptation effects were observed in our "coin" experiments. Observers were simply told which of five arbitrarily colored coins corresponded to one of five possible values. This was learnt in under a minute. While some have claimed that learning can alter or enrich the range of attributes that vision attributes to objects and collections (Siegel, 2006; but see Green, 2021 for critique), proponents of this suggestion typically distance themselves from the claim that such learning could alter perceptual attribution *synchronically*, instead altering perceptual attribution on a time course of weeks, months, and years. Indeed, this seems critical to the plausibility of such views, given recalcitrant visual illusions which persist repeatedly in the face of subjects' knowledge that they are being tricked (Fodor, 1983). If 'perception' is used in a literal and non-metaphorical way, it simply seems very far-fetched that the adaptation we observed is or could be genuinely perceptual in nature.

Others have entertained similar suggestions. In a sophisticated discussion of the problems with using repulsive adaptation effects to delineate what is and is not perceptually representable, Phillips and Firestone (2023) speculate that "Certainly, it would seem that a committed psychophysicist could produce a spatiotopic criterion effect" that is repulsive in nature yet occurs outside of perception. Consider us committed psychophysicists, then: Our results seem to confirm this speculation. Such a discovery is significant given a paucity of alternative proposals for how to reliably distinguish perceptual from post-perceptual forms of repulsive adaptation. For instance, while it is true that canonical forms of visual adaptation often yield readily appreciable alterations to *visual* phenomenology, these phenomenological alterations have been found to dissociate from their measured effects on behavior (see Yousif & Clarke, 2024). Moreover, such phenomenological alterations seem to be entirely lacking in key cases of adaptation to high-level visual properties which actually set out to control for low-level confounds (a point that their proponents freely acknowledge: Burr et al., 2025). This is to say nothing of the fact that few vision scientists would be happy to fall back on an introspectionist methodology when distinguishing visual adaptation from post-perceptual effects.

Our results stop short of fully addressing *retinotopic* adaptation, leaving open the possibility that retinotopic effects but not spatiotopic effects are uniquely perceptual. While we noted in our discussion of Experiment 5 that it remains an open possibility that our results are, indeed, retinotopic, one way of understanding the present results is that they provide empirical support for the claim that retinotopy is the critical criterion for distinguishing between perceptual and non-perceptual processes. This would be significant insofar as many documented cases of putative visual adaptation fail to decisively meet this higher standard (Anton-Erxleben et al., 2013; Arrighi et al., 2014; Burr & Ross, 2008; Jeong & Chong, 2020; Kreutzer, Fink, & Weidner, 2015; Maule & Franklin, 2020; Pooresmaeili et al., 2013; Zeng, Kreutzer, Fink, & Weidner, 2017). However, it would also be challenging insofar as many paradigmatically visual effects abstract away from retinotopically indexed positions (e.g., trans-saccadic memory representations), thereby undermining the view that adaptation can cleanly distinguish what is and isn't perceptual. Worse still, this proposal raises a further, and more insidious, concern. For insofar as it is the retinotopy of certain effects that is used mark out the definitively perceptual effects, one might wonder what role repulsive adaptation plays in our assessment of these cases (Phillips & Firestone, 2023). On such a view, it is retinotopy, not adaptation, that is distinctive of perceptual processing.

One might dismiss this as a matter of wordplay — as a matter of what we decide to call 'perceptual'. We think this would be a mistake. It is central to the enterprise of cognitive science that we identify and distinguish the distinct and interesting kinds of psychological process that permit inductive generalization between cases. If spatiotopic or even retinotopic repulsive adaptation can be observed for dimensions like arbitrarily assigned value, this suggests that these sorts of adaptation are unlikely to play the roles expected of it in much recent philosophy and cognitive science, where it is used to motivate grand claims about the content and function of an interesting perceptual kind. Future work might now consider the possibility that other, related phenomena, such as PICC, can be indexed to spatial or even retinotopic locations in analogous ways — and thus, whether the same cognitive and neural mechanisms might support these disparate phenomena.

There might still be many legitimate ways to draw a distinction between perception and post-perceptual cognition, such that there is no single answer as to whether a given feature is or can be represented in vision (Clarke & Beck, 2023; Phillips, 2017). Even so, adaptation has achieved a special status — such that, in many cases, the presence of spatially indexed adaptation alone leads to strong conclusions about the involvement of perceptual processing. At the very least, our results suggest that these conclusions, and the premise of the argument on which they are based, should be reexamined.

7. Conclusion

By questioning the sufficiency of spatiotopic evidence for making claims about perceptual processing, the present work undermines widely held views regarding perceptual adaptation. Maybe more attention should be paid to the need for retinotopic effects, as some have argued (Kominsky & Scholl, 2020; Rolfs et al., 2013). This is only one of many issues facing the adaptation enterprise, however; in actual fact, we believe that the questions posed by the current work hardly scratch the surface (see Yousif et al., 2024, Yousif & Clarke, 2025; Yousif & Clarke, 2024; forthcoming). For the reasons discussed here and many others, we wager that a critical revision to our understanding of adaptation is in order if it is to be of use when adjudicating vexed theoretical issues in cognitive science and philosophy of mind, especially those concerning a joint between perception and thought.

CRediT authorship contribution statement

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

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Data availability

I have shared the link to my data within the manuscript, via an OSF view only link.

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