Current Biology

Number adaptation survives spatial displacement

Highlights

- Adaptation to number travels with moving objects

- Adaptation to number is object specific, independent of hemifield or location

- Object-bound adaptation is equally strong in static and moving displays

Authors

Caroline Myers, Chaz Firestone, Justin Halberda

Correspondence

cmyers60@jhu.edu

In brief

Myers et al. show that number adaptation can be bound to objects: the aftereffect follows the same moving object, suggesting that numerosity can be encoded in an object-centered reference frame.

CellPress

Current Biology

⌘ CellPress

Report

Number adaptation survives spatial displacement

Caroline Myers,[1,2,*] Chaz Firestone,[1] and Justin Halberda[1]
[1]Department of Psychological and Brain Sciences, Johns Hopkins University, Ames Hall, 3400 N. Charles St., Baltimore, MD 21218, USA
[2]Lead contact
*Correspondence: cmyers60@jhu.edu
https://doi.org/10.1016/j.cub.2025.10.051

SUMMARY

Canonical visual adaptation effects, such as those observed for color or orientation, are spatially specific, consistent with their locus in early, retinotopically organized visual areas.[1,2] In contrast, number adaptation effects have been localized to the intraparietal sulcus (IPS), a higher-level region of the dorsal visual pathway involved in (among other things) tracking objects as they move across space and time.[3–5] This suggests that number may be a crucial test case for adaptation more generally, potentially revealing non-retinotopic adaptation effects. We predicted that number adaptation effects should persist even when the spatial positions of adapted and test stimuli are constantly changing. Six experiments measured adaptation when (1) adapted and tested dots were presented within constantly translating visible discs, (2) adapted and tested dots moved about constantly within the visibly translating discs, and (3) adapted and tested dots moved about constantly within bounded invisible translating discs. In all cases, we found object-specific number adaptation—as if adaptation travels with an object or bounding region. Additionally, we found that adaptation was specific to target objects—i.e., it did not transfer to other objects within the same hemifield—and that the size of the adaptation effect was equally large for moving and static stimuli. Unlike the retinotopic adaptation effects characteristic of other early visual features,[1,2] number adaptation can be bound to moving objects.

RESULTS

Our perceptual system automatically extracts certain features from visual scenes, including color, orientation, contrast, and spatial frequency.[1,2] Such attributes are considered fundamental to early visual processing and are often revealed by visual adaptation—a phenomenon whereby prolonged exposure to a specific stimulus attribute diminishes sensitivity to that attribute. Adaptation is typically thought to result from altered sensory representations in early visual areas such as V1.[2] On this view, such effects depend on the precise position of stimuli on the retina. Thus, adaptation is thought to occur before objects have been identified and tracked. Against this received view, it would be surprising to find that any form of adaptation *moved*, bound to an object.

Some of the strongest evidence that number is a genuine perceptual feature (like color or contrast) comes from studies demonstrating visual adaptation to number,[6–14] wherein prolonged exposure to a large number of dots decreases numerosity estimates of subsequent probe displays. These effects replicate across many display conditions, with controls for low-level visual features like brightness,[9] relative contrast,[15] total surface area,[7] and density.[8] Like canonical adaptation effects, number adaptation is phenomenologically striking (Figure 1A; see demonstration at https://carolinemyers.github.io/number-adaptation/) and difficult to override through task knowledge or goals.[2,6] Number may be a particularly strong candidate for adaptation effects that survive spatial shifts. Indeed, numerosity may be extracted from, and adapt within, non-retinotopic frames of reference, including duration,[16] temporal event structure,[17,18] and other
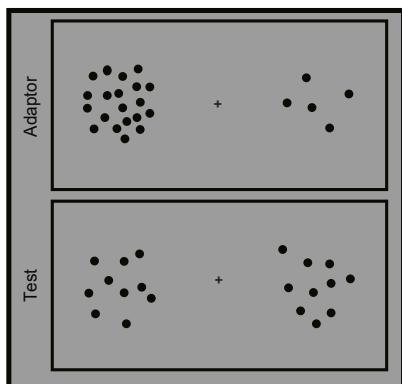
non-numerical features,[19,20] as well as across modalities[21–23] (although see Yousif et al.[24]).

Unlike early visual areas, the intraparietal sulcus (IPS), which supports number adaptation,[3] may not primarily be retinotopically organized[4,5] (although see Golomb and Kanwisher[25]), and it is involved in processing spatial relationships and tracking objects, supporting stable representations of multiple objects across shifting retinal coordinates.[26–33] Thus, IPS occupies a unique computational role: it encodes numerical information while simultaneously supporting the spatial updating of objects over time. On some accounts, the human number system may have co-opted spatial circuits in IPS through cortical recycling, whereby abstract numerical representations inherited functional properties from spatial attention and object-tracking systems.[34,35] If so, then number adaptation might reflect these origins, operating not over fixed retinal locations but over object-based representations that move through space.
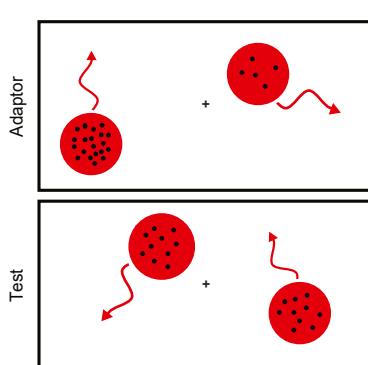
The present experiments

To test whether number adaptation persists despite spatial translation, we investigated number adaptation for dot arrays with changing spatial properties (Figure 1B), asking whether adaptation occurs (1) when adapted and tested dots are presented within constantly moving visible discs, (2) when adapted and tested dots themselves move within moving visible discs, and (3) when adapted and tested dots move within bounded, invisible moving discs. We also tested whether adaptation transfers to an unadapted disc in the same hemifield. Across six experiments, number adaptation persisted despite drastic changes to spatiotopic and retinotopic position when probes

A Static, canonical number adaptation

B Dynamic, present task and stimuli

Figure 1. Static and dynamic adaptation displays

(A) Schematic of a static, canonical number adaptation task. Observers are exposed to a greater and lesser cloud of dots on the left and right (adaptation phase), followed by a probe with an equal middling number of dots (test phase). Observers typically experience the cloud previously containing fewer dots to contain more at test.

(B) The dynamic adaptation task design used in the present experiments, where adaptation and test stimuli are presented within constantly translating contexts.

appeared on previously adapted discs but did not transfer to unadapted discs in the same hemifield. A final set of experiments (5 and 6) confirmed that the magnitude of the adaptation effect is equally strong in both static and moving displays.

Experiment 1: Adaptation survives continuous translation

In experiment 1, observers viewed two randomly and independently moving discs on either side (left or right) of the display while fixating on a centrally placed cross (Figure 2). During adaptation, varying numbers of dots appeared and faded at 3-s intervals, reappearing at new locations within each continuously moving disc. After 12 s, the dots disappeared and the discs continued moving for an additional 1 s. Next, a tone signaled the appearance of a new number of probe dots, appearing for 500 ms in new locations within each disc; observers judged which disc contained more dots and gave responses (left vs. right) with a keypress. The 1-s delay, during which the empty discs continued to move, eliminated spatial overlap with the adaptor dots. Although the number of dots varied across trials, ratios between numerosities remained constant to control for the scalar variability of numerosity perception.[36,37] Because there was no effect of numerical scale across the adaptation effect (all $p > 0.1$), and because we used a constant display region size, this indicates that adaptation effects were consistent across different amounts of density, contour length, and filled region of the adapted dots.

We analyzed performance on critical trials in which observers adapted to different numbers of dots but were shown an equal number of dots at test (STAR Methods). The magnitude of the adaptation effect was computed as the proportion of critical trials in which observers judged that the side previously containing the smaller number of dots during adaptation now contained a larger number of dots at test (Figure 3A). Results revealed a significant adaptation effect, with observers more likely to judge the disc previously containing fewer dots during adaptation as having more dots at test ($\beta = 0.336$, SE = 0.08, $z = 4.22$, $p < 0.0001$).

Experiment 2: Adaptation persists despite additional random dot motion

Experiment 2 introduced additional individual dot motion, such that the black dots now moved randomly within the discs as they translated (Figure 3B). This was to further disrupt positional cues, while ensuring zero overlap between adapted and tested dots.

The predicted adaptation effect persisted, with observers again more likely to judge the disc containing fewer dots during adaptation as having more dots at test ($\beta = 0.586$, SE = 0.075, $z = 7.86$, $p < 0.0001$).
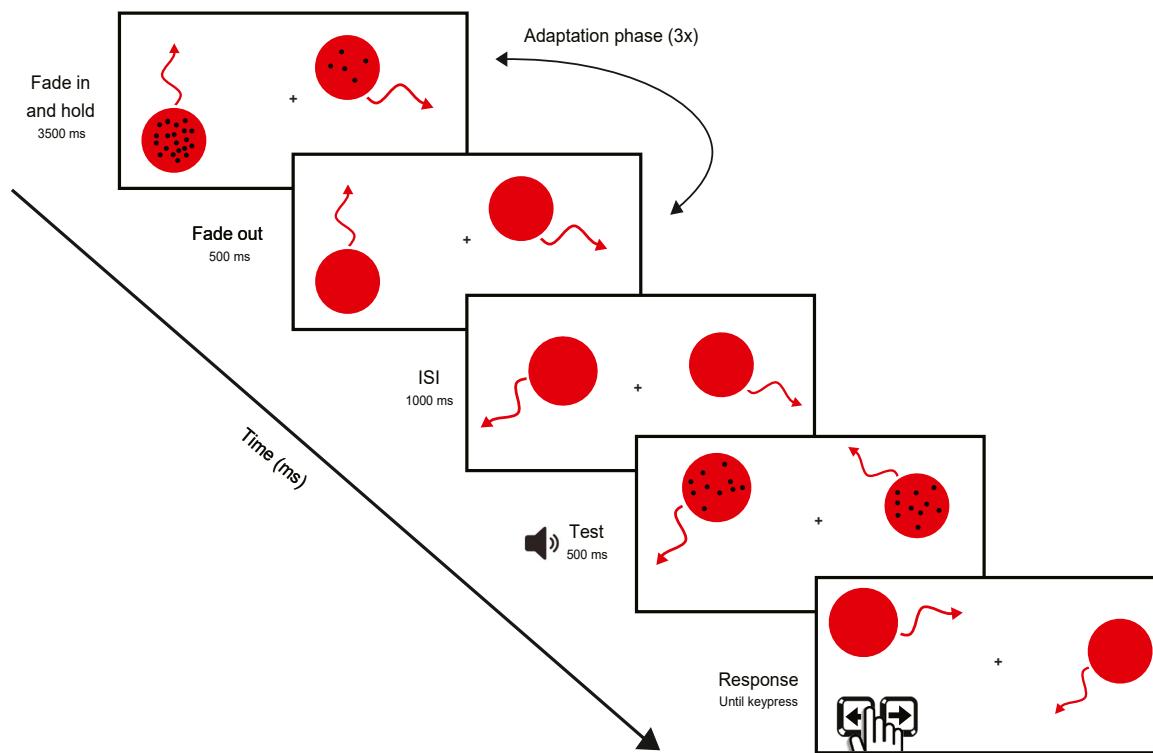
Experiment 3: Adaptation persists without visible object boundaries

Experiment 3 replicated the setup of experiment 2 but removed the visible red discs, leaving the dots to translate while still constrained by a (now invisible) boundary (Figure 3C). This was done to test whether our effects required a visible bounding object. Despite removing the discs, we again found adaptation to number: on critical trials, subjects reported the side that contained fewer dots during adaptation as containing more dots at test ($\beta = 0.549$, SE = 0.093, $z = 5.93$, $p < 0.0001$).

Experiment 4: Adaptation is object specific, not retinotopic or hemifield based

Experiment 4 tested whether the adaptation effects observed in experiments 1–3 are object specific rather than hemifield specific (e.g., "painted" across the entire adapted hemifield). Test dots could appear on either the same discs that were previously adapted (same-object condition) or on other independently moving, unadapted discs within the same hemifield (different-object condition). If adaptation effects are object specific, we should expect adaptation effects only in the same-object condition. Indeed, subjects showed a robust adaptation effect when test dots appeared within the same disc as the adaptation stimuli ($\beta = 0.293$, SE = 0.082, $z = 3.56$, $p < 0.001$), but not when test dots appeared in different discs within the same hemifield ($\beta = -0.025$, SE = 0.039, $z = -0.66$, $p > 0.5$), ruling out a hemifield-wide explanation (Figure 3D). Further, to test whether retinotopic adaptation could explain these results, on each critical test trial, we computed whether or not the test disc fell entirely within the swept path of the adapted disc. This binary overlap measure did not predict adaptation ($\beta = -0.11$, SE = 0.08, $z = -1.40$, $p = 0.16$), the same-object advantage remained robust ($\beta = -0.36$, SE = 0.07, $z = -5.3$, $p < 0.0001$), and the interaction was not significant ($\beta = 0.13$, SE = 0.11, $z = 1.1$, $p > 0.1$). In another approach, we quantified overlap continuously as the percentage of the test disc that fell within the path of the adapted disc (0%–100%). Again, overlap did not predict adaptation ($\beta = -0.19$, SE = 0.18, $z = -1.07$, $p > 0.1$), the same-object effect remained strong

Current Biology
Report

CellPress

Example trial sequence (Experiment 1)

Figure 2. Representative experimental protocol and trial sequence for experiment 1
During the adaptation phase, observers viewed two large discs translating independently on either side of a central fixation cross. Dots within the discs gradually faded in over 500 ms, remained fully visible for 3,000 ms, and then gradually faded out over 500 ms. This cycle repeated three times during the 12-s adaptation phase, with dots reappearing at new locations each time. Following the adaptation phase, the empty discs continued to translate for an additional 1,000 ms, further ensuring zero overlap between adaptation and test stimuli. A tone signaled the onset of the test phase, with a new set of test dots appearing for 500 ms in different locations within the discs. Observers indicated which disc contained more dots at the time of the tone via a keypress.

($\beta = -0.61$, SE = 0.18, $z = -3.29$, $p < 0.001$), and the interaction was not significant ($\beta = 0.39$, SE = 0.22, $z = 1.725$, $p > 0.05$), indicating that spatial overlap between the test disc and adapted path did not account for the observed object-specific adaptation effect.

Experiment 5: Adaptation produces measurable perceptual shifts

To quantify the strength of the dynamic number adaptation effect, with the intention of comparing the effect size for dynamic adaptation to more canonical, static adaptation demonstrations, we ran a conceptual replication of experiment 1 with a broader range of test values (experiment 5 dynamic). During adaptation, observers viewed two translating discs containing 48 dots (test disc) and 24 dots (reference disc). At test, the reference disc always contained 24 dots, whereas the number of test dots on the adapted side varied across nine test numerosities (12–48; STAR Methods). All other parameters remained identical to experiment 1.

We fit observers' responses with cumulative Gaussian functions, plotting the probability of choosing the test disc as "more numerous" as a function of test numerosity (Figure 4A). The point of subjective equality (PSE) defined the test numerosity at which participants were equally likely to judge either disc as

containing more dots (e.g., Castaldi et al.,[3] Harvey et al.,[4] Fairhall et al.,[5] Burr and Ross,[6] Ross and Burr,[7] DeSimone et al.,[8] and Burr et al.[9]). In the adaptation condition, the PSE shifted significantly rightward relative to a baseline (no adaptation) condition ($t(29) = 5.39$, $p < 0.0001$), corresponding to a ≈10% increase in the number of dots needed to match the perceived numerosity of the 24-dot reference following adaptation.
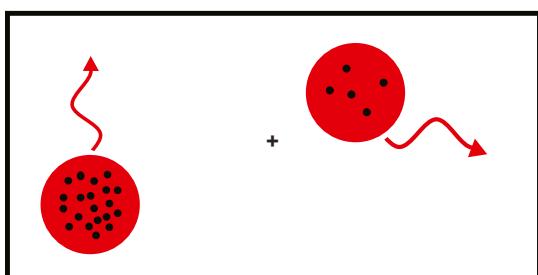
Experiment 6: Dynamic and static adaptation yield comparable effects

In experiment 6, a new group of participants completed our numerical decision task using the exact same displays as in experiment 5 (dynamic), but now the stimuli remained entirely static—fixed at ±480 px from fixation.
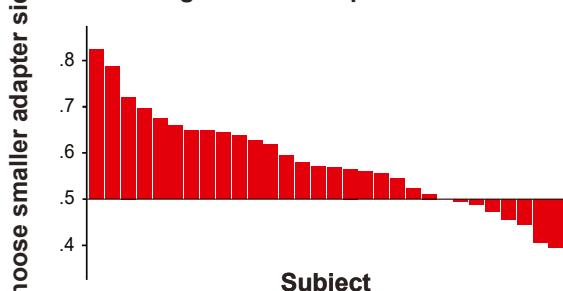
We note that adaptation effect sizes vary widely across the number adaptation literature and are influenced by many task, stimulus, and observer parameters—including delay duration between adapt and test[6,24]; test-to-adapt ratio[6,9,14,24]; numerosity range[14,38]; and item shape,[39] color,[12,13,39] and luminance[39]—making direct comparisons across studies challenging. Thus, it is of central importance that stimulus parameters be kept constant across comparisons.

Static adaptation to a large numerosity produced a significant shift in PSE relative to a baseline (no adaptation) condition
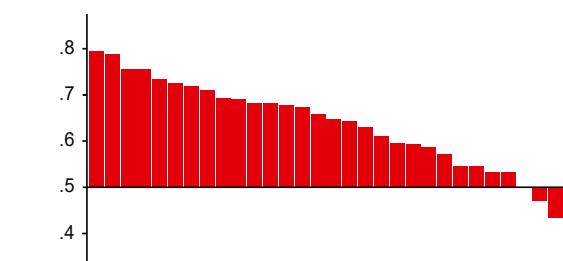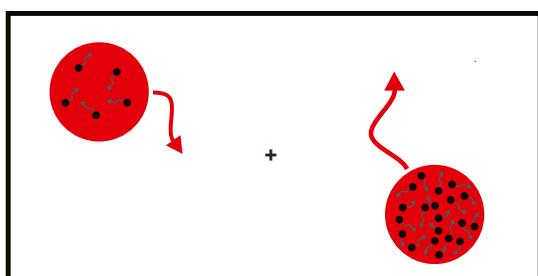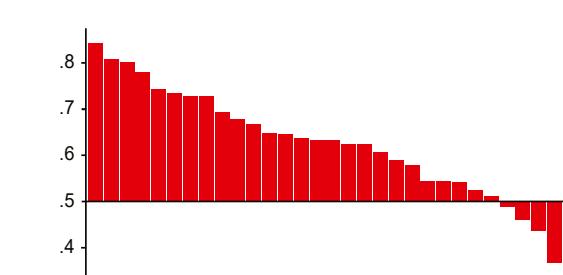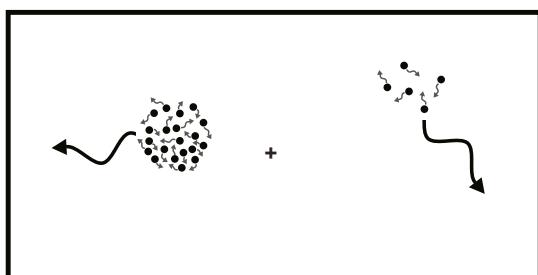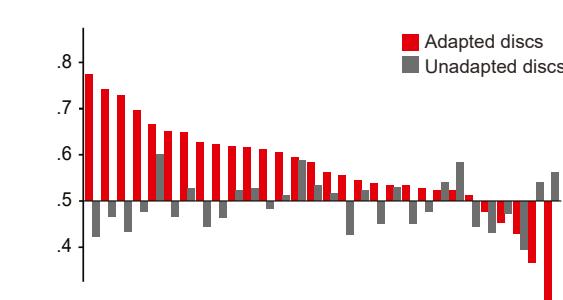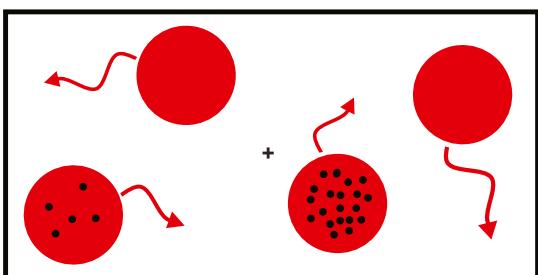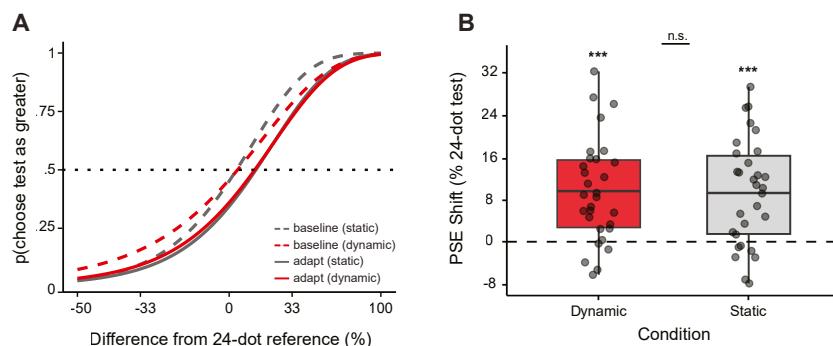
Figure 3. Observers demonstrate the predicted adaptation effect across three experiments, demonstrating that number adaptation is not constrained to retinotopic coordinates

(A) Experiment 1: adaptor and test stimuli are presented within two independently translating discs, with no spatial overlap between adaptation and test phases. Adaptation is measured on critical trials as the increased likelihood of reporting the disc previously containing fewer dots during adaptation as having more dots at test.

(legend continued on next page)

Current Biology
Report

CellPress

A

B

Figure 4. No difference between static and dynamic adaptation

(A) Group-level psychometric functions from experiments 5 (dynamic) and 6 (static), showing the probability of choosing the test disc as more numerous than a fixed 24-dot reference across a range of test numerosities (12–48). Each curve reflects cumulative Gaussian fits to participants' responses in adaptation and baseline conditions. Adaptation produced a clear rightward shift in both dynamic (red) and static (gray) conditions, indicating underestimation of the test disc. Baseline curves are plotted with dashed lines; adaptation curves with solid lines.

(B) Point of subjective equality (PSE) shifts for dynamic and static displays, computed as the difference in PSE between adaptation and baseline for each subject. Both conditions yielded significant PSE shifts (***$p < 0.001$), and the size of the shift did not differ between conditions (n.s.). Boxplots show mean and interquartile range; individual subject data are overlaid.

($t(29) = 5.15$, $p < 0.0001$). Critically, the magnitude of this adaptation effect did not differ between dynamic (experiment 5) and static (experiment 6) displays ($t(57.93) = -0.04$, $p > 0.5$; Figure 4B). That is, number adaptation is robust to spatial translation, with an effect size comparable to canonical (static) adaptation effects with matched stimulus parameters.

DISCUSSION

Across six experiments, number adaptation effects survived drastic changes to the spatial properties of adaptor and test stimuli. Adaptation persisted when dots appeared in new locations (experiment 1), when individual dot motion was added (experiment 2), and when visible disc boundaries were removed (experiment 3). Adaptation occurred only for previously adapted discs, even when visually similar objects were present within the same hemifield (experiment 4).

This pattern suggests that number adaptation is neither spatially diffuse nor hemifield wide but object bound. That is, observers track and adapt to the numerosity of specific entities in the visual field rather than regions of space per se. This aligns with evidence that number adaptation is implemented in mid-level areas like IPS, implicated in both numerosity encoding and object-based tracking. Experiments 5 and 6 support this interpretation: dynamic adaptation effects were preserved and statistically indistinguishable from matched static conditions despite stimuli occupying entirely different retinotopic positions and undergoing continuous object motion.

Although these effects resemble classic adaptation phenomena, their underlying mechanisms may diverge from those supporting early visual adaptation in important ways. Unlike canonical (retinotopic) adaptation effects localized to early visual areas, Castaldi et al. found that number adaptation attenuates responses in IPS but not in early visual cortex.[3] Using multivariate pattern analysis, they could decode adaptation states from IPS (but not V1), marking a striking reversal of the typical pattern observed in low-level adaptation, where early visual areas carry the adaptation signal, and parietal cortex does not.

This divergence suggests a broader functional distinction. Although IPS encodes numerosity, it is also involved in a very different class of computations required to track objects as they move across the visual field.[27,30] In multiple-object tracking (MOT), IPS activity scales proportionally with tracking load.[28,29] Causally, inhibiting IPS via transcranial magnetic stimulation (TMS) impairs tracking performance and reduces sensitivity to object-specific trajectories,[31] whereas stimulation enhances tracking accuracy.[33] Beyond tracking, IPS supports spatial updating across eye movements by encoding saccade targets in a gaze-invariant format, despite differences in retinal input.[5,40] TMS to IPS also impairs performance on double-saccade tasks requiring cross-saccadic updating.[41] Together, these findings establish IPS as a locus for object-centered updating across object motion and eye movements.

This duality is striking: a single region encodes abstract properties like number while solving the dynamic correspondence problem. This suggests that successful numerical representation may require selecting items prior to enumeration—something afforded by object-bound collections, like those studied here. This also aligns with cortical recycling accounts, wherein symbolic systems like number co-opt older spatial attention and tracking circuits.[34,35] If so, number adaptation may inherit this object-based, spatially flexible format. Consistent with this view, our effects persisted, even when spatial alignment between adaptor and test was disrupted, yet remained object specific. This profile distinguishes number adaptation from canonical effects that are typically spatially specific and fail to generalize across changes in location or context.[2]

This object specificity also directly challenges a recent account proposing that number adaptation reflects spatiotopic attenuation to unchanging information rather than true adaptation to numerosity.[24] On this view, adaptation effects depend on spatial overlap between the adaptor and test, and should be eliminated when stimuli no longer occupy the same region.

(B) Experiment 2: adaptor and test stimuli include additional individual dot motion within the translating discs, further disrupting positional cues. Adaptation effects persist, with observers more likely to judge the disc containing fewer dots during adaptation as having more dots at test.

(C) Experiment 3: adaptor and test stimuli move within invisible bounded regions.

(D) Experiment 4: adaptor and test stimuli either appeared on the same discs (red bars) or different discs (gray bars), yet they were always within the same hemifield as the adaptor stimuli. The adapted disc replicated our adaptation result, whereas no effect was observed on the unadapted disc.

In experiments 1–6, we eliminated spatial overlap (novel dot configurations and new locations following delay) and still observed robust adaptation, provided test dots reappeared on the adapted disc. This contradicts the core prediction of the "old news" hypothesis,[24] which requires continuity of low-level input across space and time. Instead, our results support an account in which the relevant unit of number adaptation is neither location nor spatial repetition but object identity.

This emphasis on objecthood further distinguishes our findings from earlier reports of aftereffects that may generalize across retinotopic coordinates—e.g., spatiotopic adaptation to duration,[16] motion aftereffects across saccades,[19] and cross-modal number adaptation.[20–22] Our results differ in an important way: we show that number adaptation is not only spatially flexible but also tied to discrete moving objects within a purely visual, within-modality context. Number adaptation may be functionally flexible: capable of operating over multiple reference frames depending on context. In this way, number adaptation may resemble other perceptual phenomena (e.g., motion processing) that flexibly recruit multiple reference frames in accordance with task demands.[42]

Nevertheless, our findings converge with a core motivation behind recent critiques: if number adaptation reflects genuine recalibration of perceived numerosity, it must be driven by number itself—not by spatial overlap, repetition, or other low-level confounds. Our results satisfy this demand, offering a demonstration of number adaptation that is unconfounded by spatial overlap or stimulus repetition—yet still robust and perceptual in nature.

In sum, because adaptor and test stimuli were presented in different locations, and with intervening motion, these effects cannot be explained solely by reduced sensitivity to repeated spatial information, whether retinotopic or spatiotopic. Unlike traditional adaptation phenomena anchored to early retinotopy, number adaptation is free to move.

RESOURCE AVAILABILITY

Lead contact
Requests for further information and resources should be directed to, and will be fulfilled by, the lead contact, Caroline Myers (cmyers60@jhu.edu).

Materials availability
This study did not generate new, unique reagents.

Data and code availability
- The original experimental data are freely available via the OSF open-access repository (database: https://osf.io/6exy9/).
- All analyses were conducted using the open-source statistical environment R[43] and are freely available via the OSF open-access repository (database: https://osf.io/6exy9/).
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

AUTHOR CONTRIBUTIONS

Conceptualization, J.H. and C.M.; methodology, J.H. and C.M.; software, C.M.; data collection, C.M.; formal analysis, C.M.; writing – original draft, C.M.; writing – reviewing and editing, J.H., C.F., and C.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- **KEY RESOURCES TABLE**
- **EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS**
- **METHOD DETAILS**
  - Apparatus and setup
  - Stimuli
  - Procedure
- **QUANTIFICATION AND STATISTICAL ANALYSIS**
  - Data cleaning and analysis
  - Proximity and overlap analyses
  - Comparing the magnitude of the adaptation effect for static and dynamic displays
  - Controls and performance analyses

REFERENCES

1. Block, N. (2023). The Border between Seeing and Thinking (Oxford University Press). https://doi.org/10.1093/oso/9780197622223.001.0001.

2. Kohn, A. (2007). Visual adaptation: physiology, mechanisms, and functional benefits. J. Neurophysiol. 97, 3155–3164. https://doi.org/10.1152/jn.00086.2007.

3. Castaldi, E., Aagten-Murphy, D., Tosetti, M., Burr, D., and Morrone, M.C. (2016). Effects of adaptation on numerosity decoding in the human brain. NeuroImage 143, 364–377. https://doi.org/10.1016/j.neuroimage.2016.09.020.

4. Harvey, B.M., Klein, B.P., Petridou, N., and Dumoulin, S.O. (2013). Topographic representation of numerosity in the human parietal cortex. Science 341, 1123–1126. https://doi.org/10.1126/science.1239052.

5. Fairhall, S.L., Schwarzbach, J., Lingnau, A., Van Koningsbruggen, M.G., and Melcher, D. (2017). Spatiotopic updating across saccades revealed by spatially-specific fMRI adaptation. Neuroimage 147, 339–345. https://doi.org/10.1016/j.neuroimage.2016.11.071.

6. Burr, D., and Ross, J. (2008). A visual sense of number. Curr. Biol. 18, 425–428. https://doi.org/10.1016/j.cub.2008.02.052.

7. Ross, J., and Burr, D.C. (2010). Vision senses number directly. J. Vision 10, 1–8. https://doi.org/10.1167/10.2.10.

8. DeSimone, K., Kim, M., and Murray, R.F. (2020). Number adaptation can be dissociated from density adaptation. Psychol. Sci. 31, 1470–1474. https://doi.org/10.1177/0956797620956986.

9. Burr, D.C., Anobile, G., and Arrighi, R. (2017). Psychophysical evidence for the number sense. Philos. Trans. R. Soc. Lond. B Biol. Sci. 373, 20170045. https://doi.org/10.1098/rstb.2017.0045.

10. Fornaciai, M., Cicchini, G.M., and Burr, D.C. (2016). Adaptation to number operates on perceived rather than physical numerosity. Cognition 151, 63–67. https://doi.org/10.1016/j.cognition.2016.03.006.

Current Biology
Report

🔹 CellPress

11. Aagten-Murphy, D., and Burr, D. (2016). Adaptation to numerosity requires only brief exposures, and is determined by number of events, not exposure duration. J. Vis. *16*, 22. https://doi.org/10.1167/16.10.22.

12. Grasso, P.A., Anobile, G., Gurioli, M., Cicchini, G.M., and Arrighi, R. (2025). Color-selective numerosity adaptation depends on the automatic categorization of colored information. iScience *28*, 112572. https://doi.org/10.1016/j.isci.2025.112572.

13. Grasso, P.A., Anobile, G., Arrighi, R., Burr, D.C., and Cicchini, G.M. (2022). Numerosity perception is tuned to salient environmental features. iScience *25*, 104104. https://doi.org/10.1016/j.isci.2022.104104.

14. Burr, D.C., Anobile, G., and Turi, M. (2011). Adaptation affects both high and low (subitized) numbers under conditions of high attentional load. Seeing Perceiving *24*, 141–150. https://doi.org/10.1163/187847511X570097.

15. Tibber, M.S., Greenwood, J.A., and Dakin, S.C. (2012). Number and density discrimination rely on a common metric: Similar psychophysical effects of size, contrast, and divided attention. J. Vision *12*, 8. https://doi.org/10.1167/12.6.8.

16. Burr, D., Tozzi, A., and Morrone, M.C. (2007). Neural mechanisms for timing visual events are spatially selective in real-world coordinates. Nat. Neurosci. *10*, 423–425. https://doi.org/10.1038/nn1874.

17. Arrighi, R., Togoli, I., and Burr, D.C. (2014). A generalized sense of number. Proc. Biol. Sci. *281*, 20141791. https://doi.org/10.1098/rspb.2014.1791.

18. Grasso, P.A., Petrizzo, I., Coniglio, F., and Arrighi, R. (2024). Electrophysiological correlates of temporal numerosity adaptation. Front. Neurosci. *18*, 1349540. https://doi.org/10.3389/fnins.2024.1349540.

19. Schwiedrzik, C.M., Bernstein, B., and Melloni, L. (2016). Motion along the mental number line reveals shared representations for numerosity and space. eLife *5*, e10806. https://doi.org/10.7554/eLife.10806.

20. Turi, M., and Burr, D. (2012). Spatiotopic perceptual maps in humans: evidence from motion adaptation. Proc. Biol. Sci. *279*, 3091–3097. https://doi.org/10.1098/rspb.2012.0637.

21. Anobile, G., Arrighi, R., Togoli, I., and Burr, D.C. (2016). A shared numerical representation for action and perception. eLife *5*, e16161. https://doi.org/10.7554/eLife.16161.

22. Moscoso, P.A.M., Cicchini, G.M., Arrighi, R., and Burr, D.C. (2020). Adaptation to hand-tapping affects sensory processing of numerosity directly: evidence from reaction times and confidence. Proc. Biol. Sci. *287*, 20200801. https://doi.org/10.1098/rspb.2020.0801.

23. Yang, H., Jia, L., Zhu, J., Zhang, J., Li, M., Li, C., and Pan, Y. (2024). The interplay of motor adaptation and groupitizing in numerosity perception: Insights from visual motion adaptation and proprioceptive motor adaptation. PeerJ *12*, e16887. https://doi.org/10.7717/peerj.16887.

24. Yousif, S.R., Clarke, S., and Brannon, E.M. (2024). Number adaptation: A critical look. Cognition *249*, 105813. https://doi.org/10.1016/j.cognition.2024.105813.

25. Golomb, J.D., and Kanwisher, N. (2012). Higher level visual cortex represents retinotopic, not spatiotopic, object location. Cereb. Cortex *22*, 2794–2810. https://doi.org/10.1093/cercor/bhr357.

26. Goodale, M.A., and Milner, A.D. (1992). Separate visual pathways for perception and action. Trends Neurosci. *15*, 20–25. https://doi.org/10.1016/0166-2236(92)90344-8.

27. Howe, P.D., Horowitz, T.S., Morocz, I.A., Wolfe, J., and Livingstone, M.S. (2009). Using fMRI to distinguish components of the multiple object tracking task. J. Vis. *9*, 10.1–1011. https://doi.org/10.1167/9.4.10.

28. Culham, J.C., Cavanagh, P., and Kanwisher, N.G. (2001). Attention response functions: characterizing brain areas using fMRI activation during parametric variations of attentional load. Neuron *32*, 737–745. https://doi.org/10.1016/s0896-6273(01)00499-8.

29. Jovicich, J., Peters, R.J., Koch, C., Braun, J., Chang, L., and Ernst, T. (2001). Brain areas specific for attentional load in a motion-tracking task. J. Cogn. Neurosci. *13*, 1048–1058. https://doi.org/10.1162/089892901753294347.

30. Alnæs, D., Sneve, M.H., Richard, G., Skåtun, K.C., Kaufmann, T., Nordvik, J.E., Andreassen, O.A., Endestad, T., Laeng, B., and Westlye, L.T. (2015). Functional connectivity indicates differential roles for the intraparietal sulcus and the superior parietal lobule in multiple object tracking. Neuroimage *123*, 129–137. https://doi.org/10.1016/j.neuroimage.2015.08.029.

31. Battelli, L., Alvarez, G.A., Carlson, T., and Pascual-Leone, A. (2009). The role of the parietal lobe in visual extinction studied with transcranial magnetic stimulation. J. Cogn. Neurosci. *21*, 1946–1955. https://doi.org/10.1162/jocn.2008.21149.

32. Castelli, F., Glaser, D.E., and Butterworth, B. (2006). Discrete and analogue quantity processing in the parietal lobe: A functional MRI study. Proc. Natl. Acad. Sci. USA *103*, 4693–4698. https://doi.org/10.1073/pnas.0600444103.

33. Blumberg, E.J., Peterson, M.S., and Parasuraman, R. (2015). Enhancing multiple object tracking performance with noninvasive brain stimulation: a causal role for the anterior intraparietal sulcus. Front. Syst. Neurosci. *9*, 3. https://doi.org/10.3389/fnsys.2015.00003.

34. Dehaene, S., and Cohen, L. (2007). Cultural recycling of cortical maps. Neuron *56*, 384–398. https://doi.org/10.1016/j.neuron.2007.10.004.

35. Hubbard, E.M., Piazza, M., Pinel, P., and Dehaene, S. (2005). Interactions between number and space in parietal cortex. Nat. Rev. Neurosci. *6*, 435–448. https://doi.org/10.1038/nrn1684.

36. Gallistel, C.R., and Gelman, R. (1992). Preverbal and verbal counting and computation. Cognition *44*, 43–74. https://doi.org/10.1016/0010-0277(92)90050-r.

37. Dehaene, S. (2011). The Number Sense: How the Mind Creates Mathematics (Oxford University Press).

38. Anobile, G., Cicchini, G.M., and Burr, D.C. (2014). Separate mechanisms for perception of numerosity and density. Psychol. Sci. *25*, 265–270. https://doi.org/10.1177/0956797613501520.

39. Caponi, C., Castaldi, E., Grasso, P.A., and Arrighi, R. (2025). Feature-selective adaptation of numerosity perception. Proc. Biol. Sci. *292*, 20241841. https://doi.org/10.1098/rspb.2024.1841.

40. Pertzov, Y., Avidan, G., and Zohary, E. (2011). Multiple reference frames for saccadic planning in the human parietal cortex. J. Neurosci. *31*, 1059–1068. https://doi.org/10.1523/JNEUROSCI.3721-10.2011.

41. Morris, A.P., Chambers, C.D., and Mattingley, J.B. (2007). Parietal stimulation destabilizes spatial updating across saccadic eye movements. Proc. Natl. Acad. Sci. USA *104*, 9069–9074. https://doi.org/10.1073/pnas.0610508104.

42. Sasaki, R., Anzai, A., Angelaki, D.E., and DeAngelis, G.C. (2020). Flexible coding of object motion in multiple reference frames by parietal cortex neurons. Nat. Neurosci. *23*, 1004–1015. https://doi.org/10.1038/s41593-020-0656-0.

43. R Core Team (2021). R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing). https://www.R-project.org.

44. de Leeuw, J.R., Gilbert, R.A., and Luchterhandt, B. (2023). jsPsych: Enabling an open-source collaborative ecosystem of behavioral experiments. J. Open Source Softw. *8*, 5351. https://doi.org/10.21105/joss.05351.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Psychophysical data	This paper	https://osf.io/6exy9/
Software and algorithms		
MATLAB R2020b	Mathworks, Natick, MA, USA	http://www.mathworks.com/products/matlab/; RRID: SCR_001622
JsPsych	de Leeuw et al.[44]	https://www.jspsych.org/7.3/; RRID: SCR_023508
R (version 4)	R Core Team[43]	https://www.r-project.org; RRID: SCR_001905

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Each experiment recruited 30 college-age undergraduate and graduate students from the Johns Hopkins University SONA Subject Pool to participate in exchange for one hour of course credit. All subjects were over the age of 18 and reported normal or corrected-to-normal vision.

All experimental procedures and documents were approved by the Institutional Review Board at Johns Hopkins University in accordance with the Declaration of Helsinki. All participants were naive to the experimental hypotheses and provided informed consent and prior to and throughout their participation.

METHOD DETAILS

Apparatus and setup

Stimuli were generated and presented using custom Javascript code in conjunction with the JsPsych framework[44] on an Apple iMac desktop computer projecting to a 1920×1080px display with a 100 Hz refresh rate. The display was calibrated and linearized using a vPixx i1Display Pro Spectra-Colorimeter photometer. Centrally-fixating observers were tested in a dimly lit, sound-attenuated room, maintained with a forehead and chinrest.

Stimuli

In Experiments 1-4, the number of dots during adaptation and test phases were structured around a fixed ratio of 1:2:4 with varying numerical magnitudes. This ratio was instantiated using dot values of 7:14:28, 5:10:20, and 10:20:40, ensuring a consistent relative scaling while varying absolute magnitudes. Following successful completion of 5 familiarization trials, participants underwent a series of 122 experimental trials per participant. The majority (75%) of trials were critical adaptation trials in which participants were adapted to the extreme values of each set (smallest and largest numbers) randomly presented on the left and right discs, with subsequent testing at the intermediate value. The remaining 25% of trials were equally divided among three trial types - this was done to ensure honest responding and that subjects had some trials that were unambiguously more or less on the adapted discs. On one third of these trials, the larger numerical value from the adaptation phase was presented again on the same disc during the test phase, with the intermediate value on the opposite disc. On another third of these trials, the smaller numerical value from the adaptation phase was presented on the same disc at test, with the intermediate value presented on the opposite disc. The final third of trials involved adapting participants to the intermediate numerical value on both discs, followed by a test phase where the larger and smaller numbers were presented on the discs. Note that none of these trial types was designed to probe adaptation effects, but rather provide an estimate of accuracy under conditions in which the test stimuli veridically differed in dot count. As we report in the main text and below, accuracy was near-ceiling on these trials (all p's >.1).

Procedure

In Experiment 1, observers viewed two large red discs (RGB: (255, 0, 0), luminance: 9.741 cd/m^2, CIE Lxy: [9.741,0.6452,0.3333]) 250px in diameter that independently and randomly translated on either side (left or right) of a fixation cross centered on a 1920×1080px monitor at a speed of 2.5px/frame. The motion algorithm initialized each disc with a random travel direction (angle) uniformly between 0 and 2π radians, and on each frame the disc's center is updated by adding a fixed displacement ($\Delta x = 2.5 \cdot \cos\theta$, $\Delta y = 2.5 \cdot \sin\theta$) along this direction. The direction is largely maintained across frames (yielding linear movement at steady speed),

Current Biology
Report

CellPress

except for two cases in which the code alters the angle: (1) with a small probability (1% each frame) the direction is reset to a new random angle, introducing a random change of direction, and (2) if the disc is about to hit a boundary of its allowed region (either the vertical midline separating left/right hemifields or the display's top/bottom edges), the direction is adjusted to redirect the disc back within bounds. In this boundary-check logic, an impending collision on the left or right causes the angle to be randomized within the opposite 180° hemisphere (preventing the disc from going out of bounds).

In the adaptation phase, varying numbers of dots initially faded in over 500ms to reach full visibility. Once fully visible, the dots remained on each disc for 3000ms before beginning to fade out again. This cycle was repeated 3 times, each time with dots reappearing at new locations within the continuously-moving discs. After the 12 second adaptation phase, the dots disappeared and the discs continued moving for an additional 1000ms. Following this delay, a tone signaled the appearance of a new number of probe dots, appearing for 500ms in new locations within each disc; observers judged which disc contained more dots and recorded their responses (left vs. right) with a keypress. Observers were instructed to maintain fixation throughout the trial; reaction time was emphasized over accuracy. Experiment 2 was identical to Experiment 1, except the black dots moved about randomly within the discs as they faded in and out. Experiment 3 was identical to experiment 2, but the red discs were no longer present on screen: dots continued to move about randomly, and were still constrained by the (now invisible) disc boundary. Experiment 4 was identical to Experiment 1, except two discs were present in each hemifield. Within each hemifield, the two discs moved independently; there was no collision-avoidance or path-inhibition rule. On 50% of trials, test dots appeared on the same discs that were previously adapted (same-object condition), and on the remaining 50% of trials test dots appeared on the unadapted discs (different-object condition).

QUANTIFICATION AND STATISTICAL ANALYSIS

Data cleaning and analysis
All analyses were computed with R.[43] In all experiments, we excluded trials in which reaction time fell beyond 5 MAD of the median reaction time (≈5% of all trials.)

Proximity and overlap analyses
To assess whether spatial overlap between adaptor and test predicted the adaptation effect in Experiment 4, we computed a trial-level proximity metric for the entire set of critical trials. On each trial, we computed the adapted disc's entire swept area during the adaptation phase by taking the union of all logged disc centers and dilating each center by the disc radius. we calculated, for each trial, whether the location of the disc containing the test stimulus fell within this adapted region. We entered this overlap measure as a predictor in a mixed-effects logistic model predicting the adaptation effect (Adaptation effect ∼ Overlap * Object Condition + (1|subject)).

We also quantified spatial correspondence between adaptor and test continuously by computing, for each critical trial, the degree of overlap between the test disc and the adapted disc's swept path (0–100%). We used this continuous overlap measure in a mixed-effects logistic regression predicting the adaptation effect, with random intercepts for subject and fixed effects of overlap amount, object condition (same- vs different-object), and their interaction (Adaptation effect ∼ Overlap Amount * Object Condition + (1|subject)).

Comparing the magnitude of the adaptation effect for static and dynamic displays
To compare the magnitude of our number adaptation effects to effect sizes reported for canonical (static) cases of number adaptation, we also ran a methodologically-identical replication of Experiment 1, only changing the numbers of dots shown during adaptation and test phases. This allowed us to compare the PSE shift between adaptation and baseline conditions, a standard approach for quantifying perceptual aftereffects in numerosity adaptation paradigms (e.g., Burr and Ross,[6] Ross and Burr,[7] DeSimone et al.,[8] and Burr et al.[9]). Subjects (n = 30) were first simultaneously presented with a disc containing 48 dots (adaptor disc) and a disc containing 24 dots (reference disc). As in Experiment 1, the discs continued to translate for a 12-second period, with dots fading in and out at 3-second intervals. Following this adaptation phase and a 1-second delay, a tone signaled the onset of the test phase, and dots appeared in new locations on both the adapted (previously 48-dot disc) and neutral (previously 24-dot) discs. The number of dots presented on the adapted disc systematically varied across 9 test values (12, 14, 17, 20, 24, 29, 34, 40, or 48 dots), while the number of dots presented on the reference disc remained constant (24 dots). To measure the effect of adaptation on perceived numerosity, we measured subjects' probability of responding that the adapted disc contained more dots than the 24-dot reference disc as a function of test numerosity, and compared this adaptation condition to a baseline condition in which no adaptation occurred. Should adaptation occur, adaptation to 48 dots would result in a perceived reduction in the number of dots subsequently presented on the adapted disc at test.

We computed the proportion of trials in which each subject reported the test disc as containing more dots than the standard (24-dot) disc as a function of test numerosity for both baseline and adaptation conditions, and fit these data with cumulative gaussian functions. We then measured the point of subjective equality (PSE), given by the physical test numerosity at which subjects were equally likely to judge either test or reference disc as containing more dots.

Current Biology
Report

Controls and performance analyses

To ensure observers were not engaging in systematically biased response strategies, we analyzed performance on unambiguous trials where both adaptor discs contained an equal number of dots and only the number of dots appearing at test differed. We used mixed-effects logistic regression models to test whether the accuracy of participants was significantly above chance (0.5), including a random intercept for each subject to account for within-subject variability.

For experiments 1-3, we tested whether overall accuracy on non-critical trials differed across the three numerical scales used (e.g. [5, 10, 20], [7, 14, 28], or [10, 20, 40]), using mixed-effects logistic regression models accounting for within-subject variability. The dependent variable was accuracy, coded as 1 for correct responses and 0 for incorrect responses, analyzed as binomial data, and the model included the magnitude values used on that trial as a fixed effect and each subject as a random effect.