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Errors of attention adaptively warp spatial cognition

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James A. Brissenden[1], **Yitong Yin**[1], **Michael Vesia**[2] & **Taraz G. Lee**[1]

Adaptation is the process by which we adjust internal models of the body, world and mind in response to sensory feedback. Although adaptation is studied extensively in the context of motor control, there is limited evidence that cognitive functions such as working memory are subject to the same error-driven adaptive control mechanism. To examine the possibility that internal spatial representations undergo adaptation, we had participants perform a task that interleaved a perceptual discrimination task and a spatial working memory task. Perceptual discrimination trials (85% of trials) presented an initial peripheral cue to exogenously capture attention, immediately followed by a displaced target stimulus. This sequence of events served to repeatedly induce a covert attentional allocation error. Interleaved spatial working memory trials (15% of trials) presented a stimulus at a pseudorandom peripheral location followed by a delay interval. On half of the working memory trials, the stimulus was surreptitiously presented at the same location as the initial attentional cue. We found that as attentional errors accumulated over the course of the experiment, participants' spatial recall shifted to counteract the attentional error. The magnitude of this shift was proportional to the number of induced errors. Recall performance recovered rapidly following the offset of error trials. Multiple control experiments ruled out alternative explanations for these results, such as oculomotor confounds and attentional biases unrelated to error. These findings indicate that the computational mechanisms governing the adaptation of motor commands appear to similarly serve to adjust and calibrate spatial cognition.

Effectively interacting with the world around us requires continuous adjustment of behaviour. Consider the act of driving a different car from the one you are used to driving. You might find that the sensitivity of the brake pedal is different, the acceleration response is quicker or slower, or the steering feels lighter or heavier. Initially, you will make numerous errors, such as braking harder than necessary. After driving the new car for some time, you adapt to these differences and your control of the vehicle becomes smooth and accurate. Adaptation is the process by which we fine-tune behaviour in response to internal disturbances such as fatigue, injury and disease, and external perturbations such as the weight of an object we lift or the terrain over which we are moving[1]. The adaptation of motor actions such as saccades has been studied extensively in both humans and non-human primates[2–7] and has been shown to be distinct from other types of learning (for example, reinforcement learning or explicit strategy-based learning)[8–12]. Typical saccade adaptation tasks involve displacing a peripheral target mid-saccade to induce a mismatch between where the eye lands and the position of the target[2]. This mismatch represents an error between the predicted outcome of the action command and the actual outcome. Over repeated trials (and repeated error signals), eye movement

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[1]Department of Psychology, University of Michigan, Ann Arbor, MI, USA. [2]School of Kinesiology, University of Michigan, Ann Arbor, MI, USA.
e-mail: brissend@umich.edu; tarazlee@umich.edu

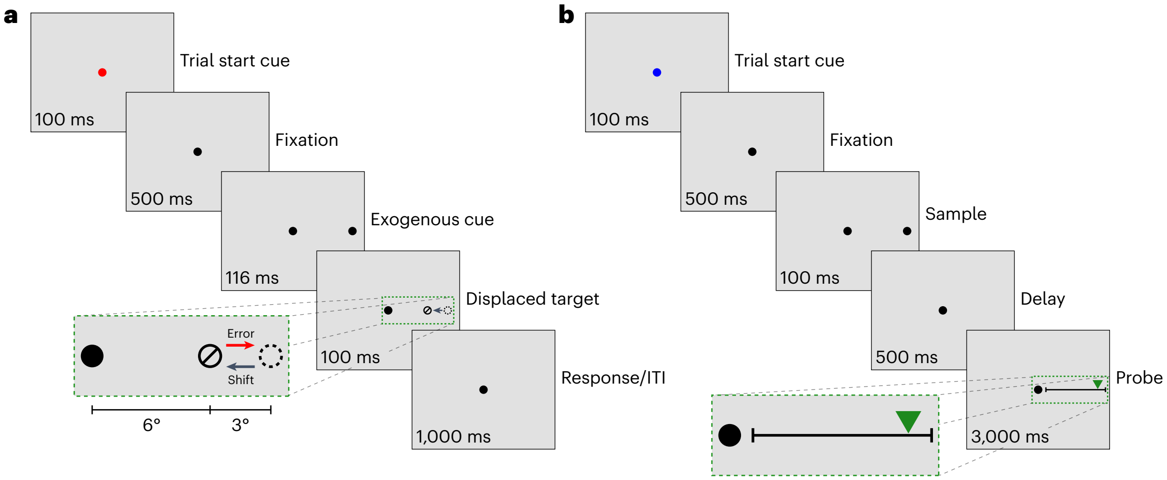

Fig. 1 | Exogenous attention error and spatial working memory experimental paradigm. a, Example trial sequence for the perceptual discrimination task that induces attentional errors (Att-error trials; ~85% of trials). At the start of each trial, the central fixation dot briefly turns red to indicate the start of the trial and to reorient participants to the centre of the display. Following a blank fixation interval, a small disc stimulus is presented in the periphery to capture attention. Immediately following the offset of this initial attentional cue, a small circular stimulus containing an oriented line is presented at a displaced location from the initial cue. Participants are instructed to indicate with a key-press whether the line was oriented at 45° or 135°. Inset shows an enlarged view of the presented stimuli during the target presentation period. The dashed circle represents the location of the previously presented cue stimulus and the black and red arrows represent the shift and error directions, respectively. The dashed circle and arrows were not visible to participants. Below the inset, stimulus eccentricity is shown in degrees of visual angle for in-person experiments (Experiments 4 and 5) in which spatial coordinates could be explicitly defined and held constant across individuals. **b**, Spatial working memory trial sequence (~15% of trials). A fixation dot turns blue to indicate the start of a working memory trial. A disc stimulus is then presented along the horizontal meridian in one hemifield. Fifty per cent of trials present the stimulus at a random location (WM-random trials), whereas the other 50% of trials present the stimulus at the same location as the initial attention cue (WM-fixed trials). Following a delay period, participants are asked to recall the location of the sample stimulus. Inset shows an enlarged view of the probe display. Participants adjust a slider stimulus (green triangle) to match the location of the remembered item. ITI, inter-trial interval.

commands are adapted such that saccades land closer to the shifted target location.

Although adaptation is typically studied in the context of motor control, there is reason to suspect that higher-level cognitive functions such as attention and working memory may obey similar adaptive control mechanisms. For example, when driving an unfamiliar car, you may also find that critical visual inputs that must be attended or remembered, such as the speedometer or rearview mirror, are in a different location from expected. Effective performance would necessitate a change in how cognitive resources are allocated in this new environment. However, there is scant experimental evidence that visual cognitive functions are subject to the same mechanisms of adaptation as (eye) movements.

Here, we aimed to investigate whether spatial cognition as measured by a visual working memory task is subject to error-based adaptation. A challenge in studying the role of adaptation in visuospatial cognition is in determining how to elicit a prediction error without eliciting a concurrent motor error. Attention has been characterized as a gatekeeper that serves to determine which visual inputs are given priority for subsequent spatial cognition processes such as storage in working memory[13–19]. This relationship raises the possibility that the misallocation of attention could serve as an error signal for the adaptation of spatial cognition more generally. We created a paradigm that interleaves an independent visual working memory task among trials that induce errors in the covert allocation of spatial attention. We aimed to determine whether internal spatial representations are adaptively warped in response to spatial errors. If so, we should observe a change in the working memory representation of the specific location associated with spatial attention allocation errors. Such a result would indicate that the phenomenon of adaptation is a domain-general learning process and would have far-ranging implications for our understanding of learning mechanisms underlying both motor and cognitive control.

Results

Across five independent experiments, we had participants perform a task that interleaved a perceptual discrimination task with irrelevant spatial cues to exogenously capture attention (Fig. 1a) with a spatial working memory task (Fig. 1b). The perceptual discrimination task reflexively drew attention to a peripheral location before presenting a target to be discriminated at a location shifted relative to the initial attentional cue location. The position of the initial attention-capturing cue stimulus and subsequent target stimulus were constant throughout the experiment. As a result, a consistent covert attentional allocation error was induced on each trial (Att-error trials; ~85% of trials). This task can be likened to a covert attentional version of the intrasaccadic target jump or double-step paradigm[2,5,20] used to elicit adaptation of saccadic eye movements. An independent working memory task was interleaved among these Att-error trials (~15% of trials). Fifty per cent of working memory trials presented the to-be-remembered stimulus at a random location along the horizontal meridian in one hemifield (WM-random trials) and the other half of trials presented the stimulus at the same location as the initial attention cue (the location associated with the induced attentional error) (WM-fixed trials). We aimed to determine whether spatial cognition exhibits signatures of adaptation that would be evidenced by a shift in spatial recall that counteracts the induced error.

Covert attentional errors induce shift in spatial recall

Our first experiment consisted of five blocks of trials each comprising a mix of covert attentional error trials (220 Att-error trials) and working memory trials (20 WM-random trials and 20 WM-fixed). We observed overwhelming evidence for a shift in spatial recall across WM-fixed trials (mean difference between block 1 and block 5: −15.81 ± 3.41% of backstep error; Bayes factor (BF) = 2.42×10^{24}) (Fig. 2a). 72.22% of participants (26 of 36) exhibited some degree of adaptation (>5% shift counteracting the covert attentional error). To characterize the time

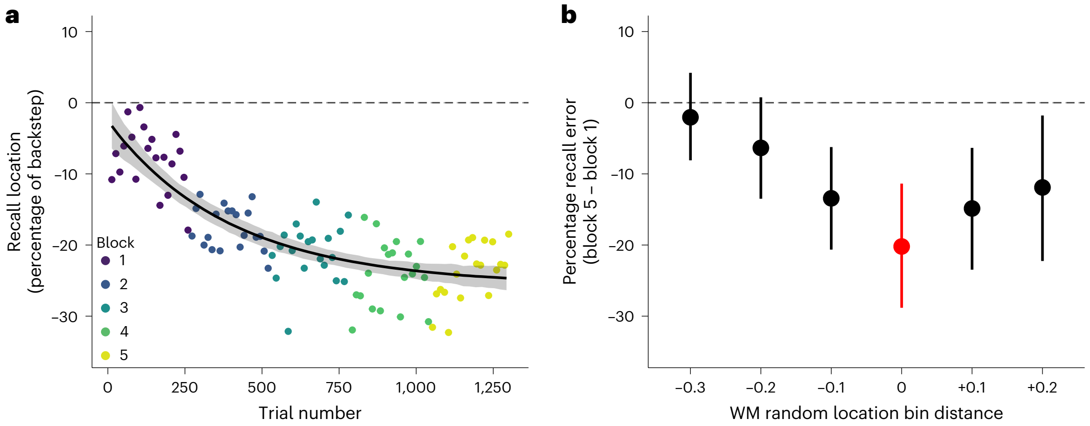

Fig. 2 | Time course and spatial specificity of spatial recall adaptation in response to spatial attention errors. a, Experiment 1 time course of spatial recall. Individual data points represent mean recall location ($n = 36$) as a percentage of the backstep size on Att-error trials across subjects for each WM-fixed trial. The target stimulus appeared at the same location in all depicted data points (0%). The x axis represents the absolute trial number across all trial types (Att-error, WM-random and WM-fixed). Each WM-fixed trial was preceded by 11 Att-error trials (and 1 WM-random trial). Colour denotes the block number. The time course of spatial recall adaptation follows an exponential decay function. The black line represents the mean of the model posterior predictive distribution as a function of trial number and the shaded area denotes the 95% CI of the expected values. The dashed line at 0% represents the location of the to-be-remembered stimulus on WM-fixed trials. **b**, Transfer of working memory adaptation across space. The y axis shows per cent change in spatial recall from the first to the last block as a function of distance from the location associated with the covert attentional error. WM-random trials were binned according to distance from the adapted location. Red denotes the bin containing the adapted location. The x axis represents the centre-to-centre distance between bins in normalized 'height' units, which scale stimuli relative to the height of each participant's screen (Methods). Data points represent mean per cent change in spatial recall across participants. Error bars represent bootstrap standard error (1,000 bootstrap samples). The dashed line at 0% represents no change in spatial recall error between block 1 and block 5.

course of learning, we averaged spatial recall across participants for each WM-fixed trial and then fit three models (linear, single exponential and double exponential) and performed model comparison. The time course was best fit by an exponential decay model consistent with previous motor adaptation studies, whereby accumulating attentional errors lead to a gradual shift in internal spatial representations in the direction of the induced error (linear expected pointwise log predictive density (ELPD) = 335.1; single exponential ELPD = 349.7; double exponential ELPD = 349.2). There was a negligible difference in fit between the two exponential decay models. Exponential decay was apparent in individual subjects (Supplementary Fig. 1).

How spatially specific is this adaptation? Previous saccade adaptation studies have demonstrated limited transfer of gain adaptation to locations nearby in space, which indicates the existence of a so-called 'adaptation field'[4,5,21]. We grouped WM-random trials based on distance from the adapted location and found that adaptation was maximal at the adapted location. Adaptation magnitude decreased with increasing distance from the spatial location associated with the covert attentional error (BF = 30.46; linear slope = 5.38% per bin, 95% credible interval (CI) [2.08%, 8.57%]) (Fig. 2b).

Spatial recall shift cannot be explained by foveal bias

Although Experiment 1 established a gradual shift in internal spatial representations that increased in magnitude along with the accumulation of induced attentional errors, it is possible that this finding could be due to factors aside from adaptation. The previous experiment could not rule out the possibility that participants are simply biased to report the remembered stimulus closer to the central portion of the visual field with repeated working memory trials. Experiment 1 also could not determine whether the observed adaptive shift in spatial recall is followed by rapid de-adaptation, a hallmark feature of motor adaptation in which full or partial unlearning of an adaptation is faster than the initial learning[22]. In Experiment 2, the first and the last block consisted entirely of working memory trials (75 WM-random trials and 25 WM-fixed trials). This enabled us to determine whether there were any sequential biases in spatial recall, as well as establish an estimate of a pre-adaptation baseline. There was limited evidence for a change in spatial recall across trials during the first pre-adaptation block (BF = 0.18; linear slope = −0.04% of backstep per trial, 95% CI [−0.09%, 0.02%]), indicating that performing repeated working memory trials (in the absence of induced covert attentional error) does not induce a foveal bias in internal spatial representations. We again found robust evidence for the adaptation of spatial recall between the pre-adaptation block and the final adaptation block (−20.28 ± 3.50%; BF = 1.71×10^{47}) (Supplementary Fig. 3a). Some 77.5% of participants (31 of 40) exhibited some degree of adaptation (>5% shift counteracting the covert attentional error). We additionally found strong evidence for de-adaptation between the last adaptation block and the post-adaptation block (10.86 ± 1.84%; BF = 1.89×10^{18}), indicating that spatial recall rapidly de-adapts following the offset of attentional errors. De-adaptation magnitude was strongly correlated with the magnitude of adaptation across subjects (Pearson's $r(38) = -0.64$, BF = 1,975.41). Model comparison indicated that an exponential decay model best fit the time course of adaptation across adaptation blocks (linear ELPD = 260; single exponential ELPD = 289.3; double exponential ELPD = 291.5) (Fig. 3a; also see Supplementary Fig. 2 for individual subject data and fits), with negligible difference between the two exponential decay models. We replicated the finding from Experiment 1 that adaptation was maximal on WM-random trials at the adapted location and adaptation transfer decreased with distance (BF = 95,583; linear slope = 6.61% per bin, 95% CI [4.30%, 9.18%]) (Fig. 3b).

Spatial cognition adaptation is driven by error

Canonical examples of motor adaptation are associated with sensory prediction errors. If the observed shift in spatial recall can be explained by similar learning mechanisms to motor adaptation, then this shift should be associated with error. To determine whether the adaptive shift in spatial recall is error-driven, we eliminated the error from attention trials by presenting the initial attentional cue and target stimulus at the same location. This location was still shifted inward relative to the location of the mnemonic stimulus presented on WM-fixed trials. As a result, the behaviourally relevant location was displaced relative to the

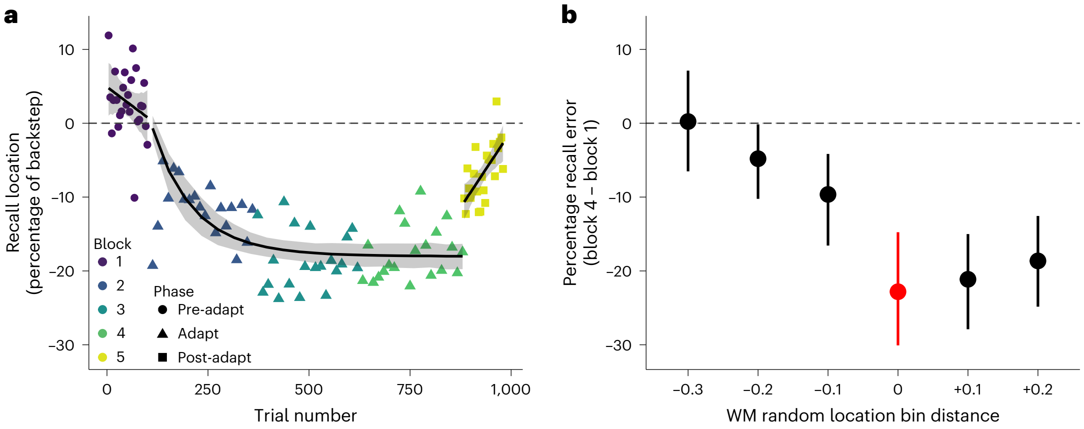

Fig. 3 | Spatial cognition adaptation displays hallmark features of visuomotor adaptation. a, Experiment 2 time course of spatial recall on WM-fixed trials. Individual data points represent mean recall location (*n* = 40) as a percentage of the backstep size on Att-error trials across subjects for each WM-fixed trial. Colour denotes block number (1–5) and shape represents the phase of the experiment (pre-adapt, adapt or post-adapt). The pre-adapt and post-adapt phases consisted solely of working memory trials (75 WM-random trials and 25 WM-fixed trials in each block) to assess baseline performance and rate of de-adaptation, respectively. The black lines spanning the pre- and post-adapt phases represent the mean of a linear model posterior predictive distribution, whereas the black line spanning the adapt phase is the mean of an exponential decay model posterior predictive distribution. The shaded area denotes the 95% CI of the expected value distribution for each model. The dashed line at 0% represents the location of the to-be-remembered stimulus on WM-fixed trials. **b**, Transfer of working memory adaptation across space. The *y* axis shows per cent change in spatial recall from the pre-adapt block to last block of the adaptation period as a function of distance from the location associated with the covert attentional error. WM-random trials were binned according to distance from the adapted location. Red denotes the bin containing the adapted location. The *x* axis represents centre-to-centre distance between bins in normalized 'height' units, which scale stimuli relative to the height of the participant's screen (Methods). Data points represent mean per cent change in spatial recall across participants. Error bars represent bootstrap standard error (1,000 bootstrap samples). The dashed line at 0% represents no change in spatial recall error between block 1 and block 4.

working memory stimulus, but no error was induced over the course of the experiment. If we observe the same shift in working memory representations it would suggest that the observed shift in spatial recall is not driven by covert attentional errors but is rather a bias towards a behaviourally relevant location (for example, position priming)[23]. All other aspects of the experiment other than the lack of error on attention trials were identical to Experiment 2. We found evidence in favour of no difference in WM-fixed recall between the first block consisting entirely of working memory trials and the last intermixed attention and working memory block (−2.04 ± 1.86%; BF = 0.42) (Fig. 4 and Supplementary Fig. 3b), indicating that repeatedly attending a nearby location does not bias spatial representations towards that location. Fitting linear and exponential models to the mean spatial recall time course resulted in slopes and amplitudes very close to zero (linear slope = −0.00004% per trial, 95% CI [−0.00006%, −0.00001%]). There was a negligible difference in model fit between all three models (linear ELPD = 322.4; single exponential ELPD = 322.5; double exponential ELPD = 322.0). In the WM-only block of trials at the end of the experiment, we find a small inward shift in WM-fixed recall in the opposite direction to Experiment 2 (−4.08% ± 1.96%; BF = 298.12), as well as a subtle positive linear effect across the block (BF = 11.77; linear slope = 0.07% per trial, 95% CI [0.03%, 0.11%]), although these effects seem to be driven by a handful of individuals (see Supplementary Fig. 4 for individual subject time courses). Because Att-error trials are no longer present, this shift cannot be attributed to a bias towards a behaviourally relevant location and cannot explain the direction of de-adaptation observed in Experiment 2.

Spatial cognition adaptation cannot be explained by saccades

Because Experiments 1–3 were conducted with online samples rather than in our laboratory, they could not conclusively rule out a motor explanation of the apparent adaptation of working memory representations. It is possible that participants were making saccadic eye movements to the presented stimuli despite our repeated instructions to maintain fixation. In this scenario, saccades would be adapted by the perceived mismatch between the saccade landing point and the presented grating stimulus. It is possible that on working memory trials participants made a saccade towards the to-be-remembered stimulus and were simply reporting the landing point of an adapted saccade independent of any mnemonic representation. To rule out this explanation, we ran two in-person studies with concurrent eye-tracking. These studies further enabled greater control of the experimental parameters (screen distance, stimulus size and so on) than in previous online experiments and so would be expected to yield less variability across individuals. Experiment 4 presented stimuli in the right hemifield (matching Experiment 2). Because Experiments 1–4 presented stimuli in the right hemifield, Experiment 5 presented stimuli in the left hemifield to ensure our results generalize to the entire visual field. Participants successfully maintained fixation for the period spanning the initial attentional cue, the grating stimulus and the 100 ms following the offset of the grating on the vast majority of trials (Experiment 4: 95.74 ± 1.25% of trials; Experiment 5: 94.87 ± 1.81% of trials) (see Supplementary Figs. 5a and 6a for the gaze density plots for each subject). This result indicates that the induced error on Att-error trials was indeed covert rather than overt and the shift in spatial recall cannot be attributed to eye movements to the attended hemifield on Att-error trials. Participants also maintained fixation during the period spanning presentation of the to-be-remembered stimulus and 100 ms following the offset of the memory stimulus during adaptation block WM-fixed trials (Experiment 4: all adaptation blocks = 91.06 ± 2.35% of trials, last adaptation block = 92.27 ± 2.48% of trials; Experiment 5: all adaptation blocks = 93.18 ± 2.90% of trials, last adaptation block = 93.64 ± 3.07%) (Supplementary Figs. 5b and 6b). Saccades following this interval would necessarily be memory-guided and cannot be attributed to visuomotor adaptation.

All participants (100%) exhibited some degree of adaptation (>5%) from the baseline period to the last adaptation block in both experiments (Experiment 4: −49.90% ± 6.23%, BF = 2.68×10^{45}; Experiment 5: −33.11% ± 1.02%, BF = 5.77×10^{22}) (Fig. 5a,c; see Supplementary Figs. 8 and 9 for individual subject time courses). This shift in recall cannot be attributed to the small number of WM-fixed trials with an eye movement. Excluding trials in which a participant made a saccade during the period spanning presentation of the to-be-remembered stimulus and 100 ms following the offset of the memorandum still yielded robust evidence for adaptation (Experiment 4: −50.83 ± 5.86%, BF = 2.29×10^{45}; Experiment 5: −32.57 ± 10.0%, BF = 7.46×10^{20}) (Supplementary Fig. 7a,c). Expanding the exclusion period to span the stimulus presentation period and the entire delay period still produced strong evidence for adaptation (Experiment 4: −57.79 ± 8.98%, BF = 6.41×10^{21}; Experiment 5: 25.54 ± 12.02%, BF = 1.17×10^{13}) (Supplementary Fig. 7b,d). We found evidence in favour of no change in WM-fixed recall during the pre-adaptation block consisting entirely of working memory trials (Experiment 4: BF = 0.22; Experiment 5: BF = 0.13). We again observed strong evidence for de-adaptation following the offset of induced attentional errors (Experiment 4: 25.65 ± 7.64%, BF = 8,785,226,241; Experiment 5: 21.67 ± 8.27%, BF = 307,865,467). There was some evidence for a correlation in the magnitude of adaptation and de-adaptation across participants despite the small sample size (Experiment 4: $r(9) = -0.71$, BF = 4.37; Experiment 5: $r(9) = -0.85$, BF = 16.91). The double exponential decay model best fit the time course of adaptation in Experiment 4 (linear ELPD = −58.4; single exponential ELPD = −30.0; double exponential ELPD = −24.4) and was slightly preferred in Experiment 5 (linear ELPD = −42.7; single exponential ELPD = −29.3; double exponential ELPD = −26.0). We further found that adaptation was maximal on WM-random trials at the adapted location and adaptation transfer decreased with distance (Experiment 4: BF = 6.30; linear slope = 4.49% per degree of visual angle, 95% CI [1.06%, 7.88%]; Experiment 5: BF = 47.72, linear slope = 6.68% per degree of visual angle, 95% CI [2.82% 10.71%]) (Fig. 5b,d). There was robust evidence for an effect of hemifield on adaptation magnitude, with right hemifield attentional errors producing stronger adaptation than left hemifield attentional errors (block × hemifield: BF = 192.45; mean adaptation magnitude difference = 16.42%, 95% CI [8.20% 24.45%]).

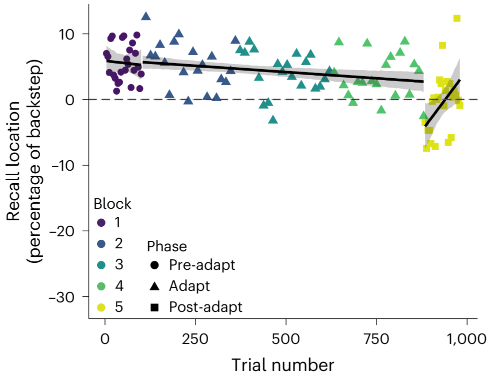

Fig. 4 | Attention without error cannot explain spatial cognition adaptation. Experiment 3 time course of spatial recall on WM-fixed trials. Experiment 3 eliminated the attentional error from perceptual discrimination trials by presenting the initial attention-capturing cue stimulus and the subsequent target stimulus at the same location. This location was still shifted inward relative to the location of the memory stimulus presented on WM-fixed trials. Individual data points represent mean recall location ($n = 40$) for each WM-fixed trial as a percentage of the distance between the location of the attentional cue stimulus and the location of the WM-fixed memory stimulus. The black lines spanning the pre-adapt, adapt and post-adapt phases represent the mean of a linear model posterior predictive distribution. The shaded area denotes the 95% CI of the expected value distribution for each model fit. Colour denotes block number (1–5) and shape represents the phase of the experiment (pre-adapt, adapt or post-adapt). The dashed line at 0% represents the location of the to-be-remembered stimulus on WM-fixed trials.

Discussion

The learning mechanisms underlying motor and cognitive control have traditionally been thought to be independent of one another. Across five experiments, we demonstrate that errors in the covert allocation of attention were associated with a dramatic shift in spatial working memory representations that counteracts the error. This adaptive shift could not be explained by attractive attentional biases or oculomotor processes. Rather, the effect was driven by covert spatial errors, paralleling the learning mechanisms shown to underlie motor adaptation. Every time attention was exogenously drawn to a peripheral location, an oriented target stimulus was presented at a location shifted relative to the initial attentionally cued location. As a result, a spatial attention allocation error was induced on every trial. We demonstrate that participants adaptively shift internal spatial representations to counteract these errors. In other words, when presented with an object at a location associated with an attentional allocation error, participants will recall that object as being located closer to where attention should have been allocated to best discriminate the target stimulus. These findings provide evidence that spatial cognition is subject to error-based adaptive mechanisms previously thought to be the sole domain of motor control.

Motor adaptation has been proposed to involve a mix of explicit and implicit mechanisms[8–10,12]. We find the scenario in which our effect is entirely explained by an explicit learning strategy to be unlikely for several reasons. The induced error on Att-error trials was irrelevant to task performance. Participants were instructed to report the orientation of the target stimulus and were simply told that a stimulus would appear at a peripheral location before the target appearing. The task instructions made no mention of the initial attentional cue and the target appearing at different locations. Moreover, the working memory task was entirely independent of the attention task and participants were not provided feedback on their working memory performance. An explicit explanation of our findings would not only require participants to formulate a strategy based on an aspect of the design that was unrelated to their performance on attention trials, but to apply that strategy to an independent task in which that strategy confers no performance benefit. Furthermore, if we assume that participants do transfer an explicit strategy between tasks, we would have expected to observe such a strategy in Experiment 3, in which the exogenous cue and target stimulus appeared at the same location. In this experiment, participants were presented with multiple cues (exogenous cue and target) highlighting the behavioural relevance of the displaced location (relative to the stimulus location presented on WM-fixed trials). If participants were to apply an explicit strategy based on the spatial location of stimuli in the attention task to the independent working memory task, evidence for such an explicit strategy should be most apparent in the experiment with consistent spatial cues. Yet, we observed no shift in spatial recall in this experiment. This finding indicates that any learning that occurred in the other experiments was driven by the induced spatial allocation error. Lastly, we would expect a purely explicit strategy to yield a step function in spatial recall across trials because of the sudden application of the strategy. Instead, we observe a gradual shift in recall over the adaptation phase of the experiment as attentional errors accumulate. This gradual shift was apparent in both the group average time course and in individual subjects (Supplementary Figs. 1, 2, 8 and 9).

Although there is a relatively substantial body of work showing that the contents of working memory can influence ongoing action and vice versa (see ref. 24 for review), these studies do not predict the results presented here: the error-based updating mechanism used to calibrate motor commands in a changing environment also operates on spatial cognition (for example, attention and working memory). A limited number of studies have examined the relationship between spatial working memory and visuomotor adaptation (see ref. 25 for review). This line of work finds that individual differences in spatial working memory capacity predict the rate of learning in sensorimotor adaptation tasks. However, this body of literature argues that working memory

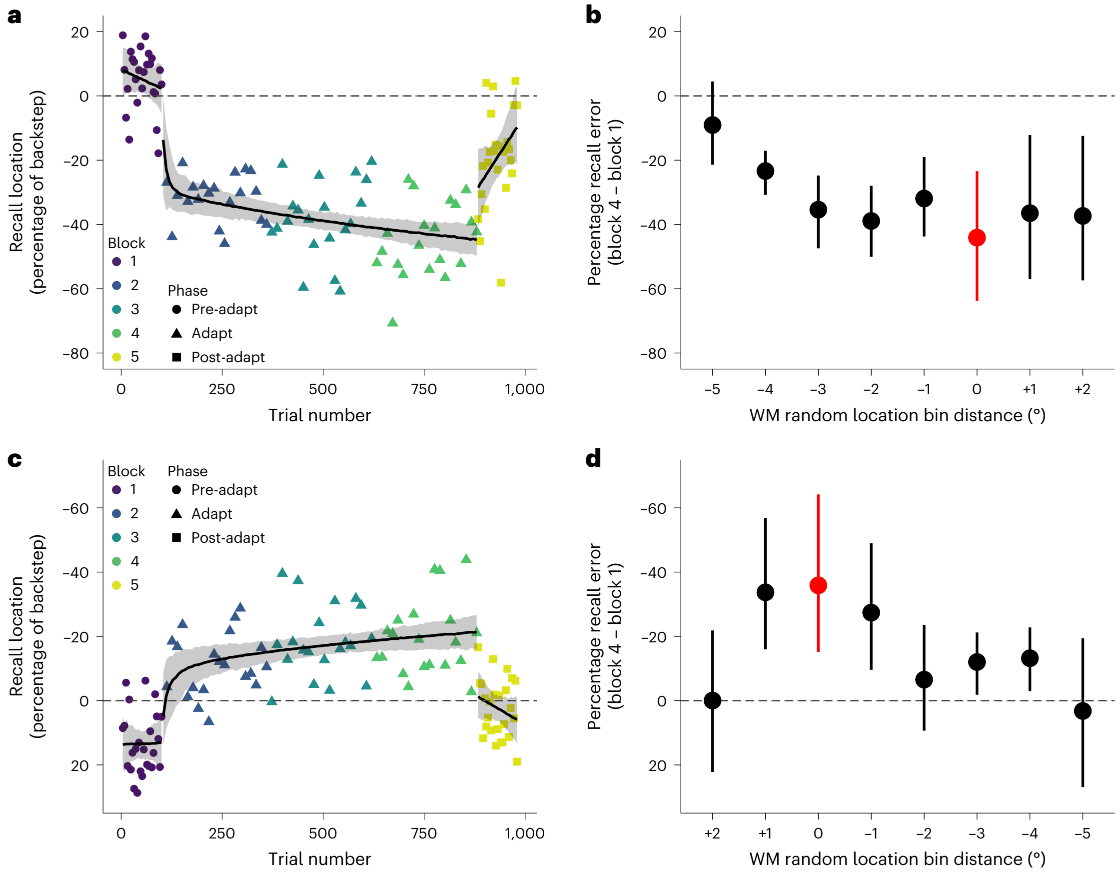

Fig. 5 | Replication of working memory adaptation across the visual field and controlling for potential oculomotor confounds. **a**,**c**, Time courses of spatial recall on WM-fixed trials for Experiments 4 (**a**) and 5 (**c**). Experiments 4 and 5 were conducted in-person with concurrent eye-tracking to control for potential oculomotor confounds. Experiment 4 presented stimuli in the right hemifield and Experiment 5 presented stimuli in the left hemifield. Individual data points represent mean recall location (Experiment 4: $n = 11$; Experiment 5: $n = 11$) as a percentage of the backstep size (3°) on Att-error trials across subjects for each WM-fixed trial. Colour denotes block number (1–5) and shape represents the phase of the experiment (pre-adapt, adapt or post-adapt). The black lines spanning the pre- and post-adapt phases represent the mean of a linear model posterior predictive distribution, whereas the black line spanning the adapt phase is the mean of an exponential decay model posterior predictive distribution. The shaded area denotes the 95% CI of the expected value distribution for each model. The dashed line at 0% represents the location of the to-be-remembered stimulus on WM-fixed trials. **b**,**d**, Transfer of working memory adaptation across space for Experiments 4 (**b**) and 5 (**d**). The *y* axis shows the per cent change in spatial recall from the pre-adapt block to the last block of the adaptation period as a function of distance from the location associated with the covert attentional error. WM-random trials were binned according to distance from the adapted location. Red denotes the bin containing the adapted location. The *x* axis represents the centre-to-centre distance between bins in degrees of visual angle. Data points represent mean per cent change in spatial recall across participants. Error bars represent bootstrap standard error (1,000 bootstrap samples). The dashed line at 0% represents no change in spatial recall error between block 1 and block 4.

only contributes during early learning and is involved in implementing goal-directed strategic adjustments (for example, aiming) that are distinct from and operate concurrently with more implicit error-based sensorimotor adaptation mechanisms[8–10,26–31]. By contrast, we find that the observed shift in recall seems to mirror the gradual implicit component identified in previous sensorimotor adaptation studies.

Previous saccade adaptation studies have found graded transfer of adaptation to nearby spatial locations[4,5,21]. We also found evidence of adaptation transfer that decreased with distance from the adapted location. However, we only examined transfer along a single dimension (horizontal) and fixed error direction (inward). Our experiments were also underpowered in terms of the number of trials needed to fully determine the spatial specificity of the adaptation field. Further work is needed to better characterize the selectivity of working memory adaptation across the visual field and assess the influence of eccentricity and error direction in greater detail.

The cerebellum has been extensively implicated in visuomotor adaptation[32–34]. Empirical studies and computational modelling of cerebellar function indicate that the cerebellum instantiates a forward model that predicts the sensory consequences of motor actions[32,33,35–41]. Recent evidence indicates that the cerebellum is also recruited by working memory and other cognitive paradigms[42–53]. Relative to the cerebral cortex, the cerebellum is cyto-architecturally homogenous[54,55]. This has led to proposals that there exists a universal cerebellar transform or computation that is applied to the diverse array of inputs the cerebellum receives[55–57]. A major challenge to testing this hypothesis empirically has been translating well-established theories of cerebellar contributions to motor control to the cognitive domain. This has been difficult to test because task demands of motor and cognitive paradigms are often quite disparate. Here, we show that adaptive learning mechanisms known to be supported by the cerebellum[41,58] also appear to play a role in spatial cognition. Our findings raise the possibility that the cerebellum may generally support error-related adaptive control for both motor and cognitive processes. Yet, further research is necessary to conclusively determine whether spatial cognition adaptation relies on cerebellar function and whether such a role differs from canonical visuospatial cognitive cortical regions such as the intraparietal sulcus or frontal eye fields.

Although our results show that recall of a location stored in spatial working memory shifts dramatically in response to repeated covert attentional errors, it is currently unclear what aspect of spatial cognition is specifically adapted by our paradigm. The spatial working memory task used here involves multiple processes: the initial attentional selection of display items, encoding and/or consolidation of those items and the maintenance or retention of information over the delay period[13,59–61]. Covert attention can be subdivided into two types: exogenous and endogenous attention. Exogenous attention is reflexive and stimulus-driven, whereas endogenous attention is voluntary and goal-driven[62]. One previous study provided some evidence that covert exogenous shifts of attention may undergo adaptive changes that look qualitatively similar to that seen in saccade adaptation[63]. However, the primary dependent measure indexing the locus of exogenous attention in this study was derived from self-report of an illusory line motion effect[64]. There is currently some debate as to whether this illusion reflects attention or a lower-level pre-attentive sensory process[65–69]. To our knowledge, no previous study has examined whether endogenous attention, working memory encoding or maintenance are subject to error-based adaptation. Our current results cannot isolate the adaptation effect to a particular phase (selection, encoding or maintenance) and further work is needed to determine which components of spatial cognition are specifically adapted. Regardless of the specific phase that is adapted, the net effect is the same: recall of a stimulus that is no longer perceptually available is robustly shifted in a direction that counteracts the induced error.

We cannot entirely rule out the possibility that an even earlier stage of processing, such as visual perception or iconic memory, is adapted and this adapted perceptual representation is then attentionally selected and encoded into a working memory store that is itself not adapted. However, it is more likely that the adaptation effect occurs at a later stage of processing for several reasons. A number of studies have previously examined whether saccade errors result in perceptual mislocalization[70–73]. Although there is some evidence that saccade adaptation produces some warping of perceptual representations, the effects reported in these studies are orders of magnitude weaker than those reported here. Furthermore, these small effects are abolished if participants are restricted from performing a saccade[20,72,74–76], suggesting that any ‘perceptual’ mislocalization can be accounted for by extraretinal factors (for example, changes in sensory–motor transform and extraretinal eye position signals) rather than a change in retinal (perceptual) signal. Note that, if anything, our adaptation effect is stronger when we restrict our analysis to trials with no eye movement. The delay period in our spatial working memory task was 500 ms in duration, which could be argued to be in the hypothetical duration of iconic memory (for example, ref. 77). However, more recent estimates suggest a much faster rate of decay[78–82]. Even if we assume that iconic memory for the sample stimulus extends beyond 500 ms, iconic memory is highly susceptible to backward masking[83–87]. Our probe stimulus was a slider bar along the horizontal meridian that completely spanned all possible sample stimulus locations. Because of this masking by the probe stimulus and the typical latency of the response (~1 s) we find it unlikely that our effect can be attributed to adaptation of iconic representations. It is more likely that what is adapted in our experiments are the processes associated with the error in the perceptual discrimination task: attentional selection and spatial encoding. Furthermore, we assume our effect is similar to motor adaptation and can be attributed to cerebellar mechanisms, but there is limited V1 input to the cerebellum[88,89]. As a result, early stages of perceptual processing would be less likely to be subject to cerebellar error-based computations than processes such as attention and working memory that have been shown to robustly recruit the cerebellum[47–49].

Our findings dovetail with recent work suggesting commonalities in the computational mechanisms that underlie both motor control and cognitive control[90–92]. Our work argues for further exploration of the extent to which learning mechanisms typically ascribed to motor control may contribute to cognitive function. These results suggest a more unified view of the brain’s capacity for adaptation, in which learning from errors acts as a central principle governing both motor and cognitive control, potentially mediated by common neural substrates such as the cerebellum. A greater appreciation for the role of error-based adaptive learning mechanisms in cognitive processes such as spatial cognition also has the potential to motivate the development of new rehabilitative strategies for psychiatric and neurological disorders associated with executive function deficits.

Methods

Participants

In total, 275 healthy adult volunteers participated in this study. Experiments 1 ($n = 94$), 2 ($n = 85$) and 3 ($n = 74$) were conducted online. For these experiments, participants were recruited using Prolific (www.prolific.co) and the experimental paradigm was hosted on Pavlovia (pavlovia.org). We defined strict criteria for inclusion in further analysis (detailed below) resulting in sample sizes of 36–40 participants for Experiments 1–3 (Experiment 1: 18 female and 18 male aged 22–35 years; Experiment 2: 17 female, 22 male and 1 not reported, aged 18–34 years; Experiment 3: 19 female, 20 male and 1 not reported, aged 18–35 years). Before running any experiments, we ran a power analysis for a partial eta-squared (η^2) of 0.2, a power of 0.8, and an alpha of 0.05, which resulted in a required sample size of 35. As a result, we aimed to recruit 40 participants for each experiment. Experiments 4 ($n = 11$, 8 female and 3 male, aged 19–32 years) and 5 ($n = 11$, 8 female and 3 male, aged 20–32 years) were conducted in-person on the University of Michigan campus. All research protocols were approved by the Health Sciences and Behavioral Sciences Institutional Review Board at the University of Michigan. All participants gave written informed consent. Online participants were paid US$10 per hour for their participation. In-person participants were paid US$15 per hour for their participation. In-person participants were recruited from University of Michigan and the surrounding community. All participants possessed normal or corrected-to-normal vision.

Stimuli and experimental paradigm

Stimuli were generated and presented using Python with the PsychoPy software package[93–95]. The task consisted of three trial types: exogenous attention backstep trials (Att-error), random working memory trials (WM-random) and fixed working memory trials (WM-fixed). Trials were separated into five blocks. In Experiment 1, all blocks were identical and consisted of 220 Att-error trials, 20 WM-random trials and 20 WM-fixed trials. During these blocks, participants were presented with five or six Att-error trials followed by either a WM-random or WM-fixed trial. Online experiments defined stimulus size and location using normalized ‘height’ units, which scale stimuli relative to the height of the participant’s screen (https://www.psychopy.org/general/units.html). For a standard widescreen (16:10 aspect ratio) the bottom left of the screen has the coordinates [−0.8, −0.5] and the top right of the screen has the coordinates [+0.8, +0.5]. Att-error trials presented an attention-capturing exogenous cue in the right hemifield (presented at [+0.5, 0]; diameter = 0.02 height units) along the horizontal meridian for 116.67 ms (seven frames at 60 Hz) (Fig. 1a). The presentation time was selected based on a previous study that estimated the mean shift time for exogenous attention to be 116 ms (ref. 63). Immediately following the offset of the exogenous attention cue, participants were presented with a line in a circle (diameter = 0.02 height units) that was randomly oriented at either 45° or 135° for 100 ms. The oriented line stimulus was displaced inwards relative to the initial attentional cue (presented at [+0.33, 0]). By surreptitiously shifting the to-be-attended location we induced an attentional allocation error on each trial. Participants were instructed to use the left and right arrow keys to indicate whether the line stimulus was oriented at 45° or 135° (right, 45°; left, 135°). WM-random and WM-fixed trials presented a circular stimulus (diameter = 0.02 height units) for 100 ms (Fig. 1b). On WM-random trials, the stimulus could appear anywhere along the horizontal meridian between [+0.22, 0] and [+0.7, 0]. On WM-fixed trials, the stimulus always appeared at the same location as the initial attentional cue on Att-error trials ([+0.5, 0]). Following a 500 ms delay interval, participants were presented with a slider stimulus and instructed to click the location on the line where the dot stimulus appeared. Once they clicked on the line a triangular marker appeared. Participants were able to drag this marker with their mouse to adjust their response. The slider spanned from [+0.17, 0] to [+0.75, 0] to avoid potential edge effects. Instructions emphasized the importance of fixating on the central dot stimulus and keeping head-to-screen relative position and distance constant.

Experiment 2 changed the trial sequence while keeping all other within-trial aspects of stimulus timing and appearance identical to Experiment 1. To account for potential sequential biases in spatial eccentricity recall with the performance of repeated working memory trials and to establish a pre-adaptation baseline, Experiment 2 included a block of trials consisting entirely of working memory trials (75 WM-random and 25 WM-fixed) before the adaptation blocks. To investigate the rate of de-adaptation, Experiment 2 also presented another working memory-only block at the end of the experiment following the adaptation period. To limit the total duration of the experiment we reduced the number of intervening adaptation blocks to three (660 Att-error trials, 60 WM-fixed trials, and 60 WM-random trials).

Experiment 3 investigated whether a shift in spatial recall can be attributed to mechanisms fundamentally different from the mechanisms governing motor adaptation. It is possible that repeatedly attending a particular location biases subsequent working memory towards that location. It has been previously shown that the deployment of attention is speeded by the repetition of a target position, an effect referred to as 'position priming'[23]. To examine whether an error signal is necessary to shift spatial recall, we presented the initial attentional cue at the same location as the subsequent oriented line stimulus ([+0.33, 0]). WM-fixed trials were identical to previous experiments with the stimulus appearing at [+0.5, 0]. If we observe the same shift in working memory representations it would suggest that attentional errors do not drive this change and that the observed shift is unlikely to reflect the same phenomenon observed in motor adaptation tasks. Rather, it would suggest that the observed shift reflects another form of bias such as attentional priming of a behaviourally relevant location. If we observe no shift in spatial recall, it would indicate that any learning observed in Experiments 1 and 2 is error-driven and can be likened to motor adaptation.

Experiments 4 and 5 were conducted in-person with concurrent eye-tracking (preprocessing and analysis of eye-tracking data detailed below). Gaze position was monocularly monitored and recorded from the right eye with a sampling rate of 1,000 Hz using a desktop-mounted EyeLink 1000 Plus eye-tracker (SR Research). To minimize head motion and control viewing distance, participants performed the experiment using a chin rest positioned 85 cm from the screen. A nine-point calibration procedure was performed before the beginning of the experiment as well as between each block. Stimulus size and location were defined in degrees of visual angle. Att-error trials either presented the attentional cue in the right hemifield (Experiment 4; [+9°, 0°]; diameter = 0.3°) or the left hemifield (Experiment 5; [−9°, 0°]; diameter = 0.3°) along the horizontal meridian. Immediately following the offset of the attention-capturing cue, participants were presented with a sine wave grating stimulus (diameter = 0.3°; spatial frequency = 10 cycles per degree; 100% contrast; raised cosine mask; 20% of stimulus diameter devoted to the raised cosine mask) at [6°, 0°] (Experiment 4) or [−6°, 0°] (Experiment 5) that was randomly oriented at either 45° or 135° for 100 ms. WM-random and WM-fixed trials presented a circular stimulus (diameter = 0.3°) for 100 ms followed by a 500 ms delay interval (Fig. 1b). On WM-random trials, the stimulus could appear anywhere along the horizontal meridian between [±4°, 0] and [±11°, 0]. On WM-fixed trials, the stimulus appeared at the same location as the initial attentional cue on Att-error trials ([±9°, 0]). The probe slider stimulus spanned from [±3°, 0] to [±12°, 0] to avoid potential edge effects.

Online exclusion criteria

We defined strict a priori exclusion criteria for online experiments. In Experiment 1, participants were excluded if their response rate was less than 66.67% of any trial type. For Experiments 2 and 3, we increased this criterion to a 75% response rate. In addition, any participants who performed with less than 66.67% accuracy on Att-error trials and/or possessed a mean absolute error greater than 0.15 normalized height units on WM-random trials were excluded from further analysis. The mean absolute error threshold of 0.15 normalized height units was determined by simulating responses drawn from a uniform distribution over the possible response interval and then computing mean absolute error relative to over these simulated slider responses. The average mean absolute error over repeated simulations was ~0.15 normalized height units. No participant was excluded because they exceeded this criterion. We included the following two self-report questions at the end of the experiment to determine whether participants potentially exhibited behaviour that would be expected to eliminate or reduce the hypothesized effect: 'How much did your head move relative to the screen over the course of the experiment'? (possible answers: None; Some (0–6 inches); Quite a bit (6–12 inches); An extreme amount (12+ inches)) and 'What percentage of the time were you able to keep your eyes focused on the centre of the display?' (possible answers: 0–100%). If participants responded 'Quite a bit' or 'An extreme amount' for the head movement question or <70% for the eye movement question they were excluded from further analysis. We further excluded participants if any one of the breaks between blocks was longer than 10 min. We realized during analysis that two participants were included in Experiment 1 analyses that had responded 'Quite a bit' for the head movement question while satisfying all other criteria, and another two participants did not respond to either the eye movement or head movement question. Conservatively, we removed these participants from all subsequent analyses, resulting in a slightly smaller sample size than planned ($n = 36$). Removing these participants does not change any of the inferences made with the full sample of 40. Note that all exclusion criteria are independent of performance on WM-fixed trials, which were used to compute our primary outcome (adaptation magnitude).

Statistical analysis

All analysis was performed with R (v.4.3.1). To assess the difference in spatial recall between the first block (Experiment 1: first adapt block; Experiments 2–5: pre-adapt block) and the last adaptation block (Experiment 1: fifth adaptation block; Experiments 2–5: third adaptation block) we used the BayesFactor package[96] to fit a hierarchical linear model and compute BF values. We compared a full model that included the effects of block and subject variability with an intercept-only model that accounted for random effects due to subject variability alone. The models were specified as follows:

$$M_{S+B} : \mathbf{y} = \mu 1 + \sigma(X_s \boldsymbol{\beta}_s + X_B \boldsymbol{\beta}_B) + \epsilon$$

$$M_S : \mathbf{y} = \mu 1 + \sigma X_s \boldsymbol{\beta}_s + \epsilon$$

where **y** is a vector of N observations, μ is a grand mean parameter, 1 is a column vector of length N consisting entirely of ones, X_s is a design matrix of size $N \times m$ subjects, X_B is a design matrix of size $N \times (n - 1)$ blocks, and $\boldsymbol{\beta}_s$ and $\boldsymbol{\beta}_B$ are vectors of standardized effects for subject and block. Effects were standardized relative to the standard deviation of the error (σ).

A Jeffreys prior[97] was placed on the grand mean μ and the variance σ^2, whereas independent scaled inverse-chi-square priors with one degree of freedom were set on the *g*-prior parameters characterizing the subject and block effects[98,99]. The scale parameter for the random subject effect was set to 1, which is appropriate for medium to large-sized effects that are not of primary interest[99]. The scale parameter for the fixed block effect was set to 0.5, which indicates that a priori we expect a medium effect size (BayesFactor package default). Critically, all reported effects were robust to this earlier definition.

BF values were computed by integrating the likelihood with respect to the priors. The full model BF (BF_{S+B}) was computed by specifying block and subject as predictors, with subject treated as a random effect. The intercept-only model Bayes factor (BF_S) included only the subject as a random effect. The ratio of BF_{S+B} to BF_S provides a measure of the evidence for the effect of block while accounting for subject variability.

To examine the difference in spatial recall following the cessation of covert attentional errors, we fit another hierarchical linear model to assess the degree of de-adaptation between the final adaptation block and the post-adaptation block for Experiments 2–5. We again assessed the evidence for a block effect by computing the ratio of BF_{S+B} to BF_S, which controls for variance associated with the grouping of trials under subject.

To test for any trends in spatial recall in the pre-adaptation period (Experiments 2–6) in the absence of covert attentional errors we additionally fit a linear model that included a fixed effect of trial and a random subject effect. We report the BF from this fit as well as the estimated slope.

To characterize the time course of adaptation, we further fit three continuous models: a linear model, a single exponential decay model and a double exponential decay model. Single and double exponential decay models have been used extensively to characterize the time course of visuomotor adaptation[22,100,101]. The single exponential was defined using the following formula:

$$y_{\text{recall}} = \alpha \times 2^{\frac{-t}{\tau}} + \beta$$

where y_{recall} represents the recalled location along the horizontal meridian for each trial, α represents the absolute change in recall, t represents the absolute trial number including all trial types (Att-error, WM-fixed and WM-random), τ represents the half-life (the number of trials it takes for the decay to reach $\alpha/2$) and β represents the asymptote.

It has been proposed that motor adaptation relies on two memory systems characterized by different rates of learning[22]. To account for multiple timescales of memory in adaptive control, we additionally fit a double exponential decay model. This model was defined using the following formula:

$$y_{\text{recall}} = \left(\alpha_1 \times 2^{\frac{-t}{\tau_1}}\right) + \left(\alpha_2 \times 2^{\frac{-t}{\tau_2}}\right) + \beta$$

where α_1 and α_2 represent the amplitudes for the fast and slow learning processes, and τ_1 and τ_2 represent the rates for the two learning processes.

For Experiments 2–6, which included a pre-adaptation baseline period, all pre-adapt trials were labelled as trial 0. A posterior distribution over possible parameter values for each model was sampled using Markov chain Monte Carlo sampling implemented in rstan[102] (v.2.21.8) via the brms package[103,104] (v.2.19.0). We then used the loo package[105,106] (v.2.6.0) to perform model comparison. The loo package computes an approximate leave-one-out cross-validation metric, the ELPD, using Pareto smoothed importance sampling[105]. We compared the ELPD between models. If the ELPD difference between two models was <4 the difference between models was considered negligible and we used the simpler model for plots and reporting (for example, single exponential decay model rather than the double exponential decay model)[107].

To examine the transfer of adaptation to nearby locations in space, we binned WM-random trials based on memory stimulus location. Experiments 1 and 2 used the following standardized screen unit bins: (−Inf, 0.15], (0.15, 0.25], (0.25, 0.35], (0.35, 0.45], (0.45, 0.55], (0.55, 0.65] and (0.65, Inf], whereas Experiments 4 and 5 used the following degrees of visual angle unit bins: (−Inf, 4.5°], (4.5°, 5.5°], (5.5°, 6.5°], (6.5°, 7.5°], (7.5°, 8.5°], (8.5°, 9.5°], (9.5°, 10.5°] and (10.5°, Inf]; Experiment 5 presented stimuli in the left hemifield so the sign of the bins was reversed (for example, (−9.5°, −8.5°]). Bin definitions were chosen to maximize the number of trials in each bin for each subject while maintaining location specificity. To examine the transfer of adaptation to nearby locations, we fit a Bayesian hierarchical linear regression model to examine the relationship between spatial recall and distance from the adapted location.

Eye-tracking analysis

Eye-tracking data were first converted from edf to asc format. Data were then parsed, preprocessed and analysed using a combination of functions from the GazeR R package[108] and custom R code. Eye blinks were detected and interpolated (±100 ms around detected blinks) using a linear interpolation procedure. We then performed offline drift correction by computing the median gaze position for the first 200 ms of each trial (100 ms trial start cue + 100 ms fixation) and then subtracting this value from the start and end points of all saccades for that trial. The onset and offset of saccades were detected using standard EyeLink parameters (velocity threshold of 30° per s, acceleration threshold 8,000° per s^2, 0.1° displacement threshold). For Att-error trials, we examined whether participants' gaze deviated from fixation more than 1° towards the stimulus (right hemifield for Experiment 4 and left hemifield for Experiment 5) during the epoch of presentation comprising the initial attentional cue, the shifted grating stimulus and 100 ms following the offset of the grating stimulus. For working memory trials, we examined whether participants broke fixation during the presentation of the to-be-remembered stimulus and the 100 ms following the offset of the memoranda.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data supporting the findings of this study are available at https://osf.io/egskw/.

Code availability

The analysis code supporting the findings of this study is available on GitHub at https://github.com/brissend/WM_adapt.

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Author contributions

J.A.B. and T.G.L. conceived the study. J.A.B. and Y.Y. collected the data. J.A.B. carried out data analysis and wrote the original draft of the paper. All authors reviewed the paper and provided critical revisions. T.G.L. and M.V. provided resources and supervision.

Competing interests

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to James A. Brissenden or Taraz G. Lee.

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Corresponding author(s): James Brissenden

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Reporting on race, ethnicity, or other socially relevant groupings	N/A – no such data were collected (besides age and sex) and they played no role in participant recruitment
Population characteristics	N/A
Recruitment	Participants were either recruited via Prolific (www.prolific.co) (Experiments 1-3) or were recruited from University of Michigan and the surrounding community (Experiments 4 and 5).
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Sample size	Prior to running any experiments, we ran a power analysis for a partial eta-squared of 0.2, a power of 0.8, and an alpha of 0.05, which resulted in a required sample size of 35. As a result, we aimed to recruit 40 participants for each experiment. These experiments yielded overwhelming evidence for an effect (Bayes Factor > 1 x 10^9). Experiments 4 and 5 aimed for a sample size of 10 as a convenience sample as a conventional power analysis would only require a handful of participants given the effect size yielded by Experiments 1 and 2.
Data exclusions	275 total healthy adult volunteers participated in this study. Experiments 1 (N = 94), 2 (N=85), and 3 (N=74) were conducted online. For these experiments, participants were recruited using Prolific (www.prolific.co) and the experimental paradigm was hosted on Pavlovia (pavlovia.org). We defined strict a priori criteria for inclusion in further analysis (detailed below) in online experiments (Experiments 1-3) resulting in sample sizes of 36-40 participants (Experiment 1: 18 female / 18 male; 22-35 years old; Experiment 2: 17 female / 22 male / 1 Not Reported; 18 – 34 years old; Experiment 3: 19 female / 20 male / 1 Not Reported; 18-35 years old).In Experiment 1, participants were excluded if they responded on less than 66.67% of any trial type. For Experiments 2 and 3, we increased this criterion to a 75% response rate. Additionally, any participants who performed with less than 66.67% accuracy on Att-error trials and/or possessed a mean absolute error greater than 0.15 normalized height units on WM-random trials were excluded from further analysis. The mean absolute error threshold of 0.15 normalized height units was determined by simulating responses drawn from a uniform distribution over the possible response interval and then computing mean absolute error relative to over these simulated slider responses. The average mean absolute error over repeated simulations was ~0.15 normalized height units. No participant was excluded due to exceeding this criterion. We included the following two self-report questions at the end of the experiment to determine if participants potentially exhibited behavior that would be expected to eliminate or reduce the hypothesized effect: "How much did your head move relative to the screen over the course of the experiment"? (Possible Answers: None; Some - 0-6 inches; Quite a bit - 6-12 inches; An extreme amount - 12+ inches) and "What percentage of the time were you able to keep your eyes focused on the center of the display?" (Possible Answers: 0%-100%). If participants responded "Quite a bit" or "An extreme amount" for the head movement question or <70% for the eye movement question they were excluded from further analysis. We further excluded participants if any one of the breaks between blocks was longer than 10 minutes. We realized during analysis that 2 participants were included in Experiment 1 analyses that had responded "Quite a bit" for the head movement question while satisfying all other criteria, and another 2 participants did not respond to either the eye movement or head movement question. Conservatively, we removed these participants from all subsequent analyses, resulting in a slightly smaller sample size than planned (N = 36). Removing these participants does not change any of the inferences made with the full sample of 40. Note that all exclusion criteria are independent of performance on WM-fixed trials, which were used to compute our primary outcome (adaptation magnitude).
Replication	Our main experimental finding, an adaptive shift in working memory recall in response to induced errors of spatial attention, was repeatedly replicated across 4 independent experiments (Experiments 1, 2, 4, and 5). Experiments 1 and 2 were conducted online and Experiments 4 and 5 were conducted in-person. Experiment 3 was a control experiment examining whether the observed effect could be explained by alternative biases unrelated to attentional error signals.

Randomization	Each experiment was a within-subject design without distinct experimental groups.
Blinding	N/A

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