

Indirect, but Not Direct, Down-Regulation of Visual Long-Term Memory Encoding Through Strategic Biasing of Attentional Allocation

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Visual long-term memory allows us to store a virtually infinite amount of visual information (Brady, Konkle, Alvarez, & Oliva, 2008; Standing, 1973). Despite its massive storage capacity, our ability to encode visual long-term memory fluctuates from moment-to-moment, and for that reason, not every piece of visual information that we wish to encode gets stored into our visual long-term memory. At the same time, we occasionally encounter visual information that we do not wish to remember. To what extent can we control our memory encoding ability at will? Here, we showed that although there are multiple mechanisms to directly up-regulate memory encoding, it is more difficult, if not impossible, to down-regulate memory encoding directly. However, we are capable of down-regulating memory encoding indirectly by biasing attentional allocation away from the encoding of an unwanted stimulus and toward the encoding of a simultaneously encoded item. However, this strategy is effective only if it is exerted prior to perceptual encoding of the unwanted stimulus. Thus, our findings not only support the existence of the biased competition mechanism of voluntary control of memory encoding but also reveals its critical period in indirectly down-regulating memory encoding of unwanted information.

Keywords: visual long-term memory encoding, attentional control, biased competition

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We are constantly bombarded with visual information that we need to remember in order to later retrieve it when needed (e.g., where we parked our car in a busy shopping mall parking lot). Fortunately, our visual long-term memory allows us to store a virtually infinite amount of information for an extended period of time (Brady et al., 2008; Standing, 1973). However, not all visual information that we wish to remember gets encoded into this massive storage due to moment-to-moment fluctuations in our ability to encode new visual long-term memories (e.g., Fukuda & Vogel, 2019; Fukuda & Woodman, 2015; Sundby, Woodman, & Fukuda, 2019). At the same time, we occasionally encounter visual information that we wish to not remember (e.g., a spoiler of a movie you are planning to watch this weekend). However, we do not always succeed in avoiding the encoding of unwanted information into our visual long-term memory, and in extreme cases, such failures can cause severe clinical symptoms such as those

experienced in posttraumatic stress disorder (American Psychiatric Association, 2013). These challenges make us question whether we are capable of regulating our memory encoding ability from moment to moment at will. Previous studies have demonstrated that we can voluntarily allocate attentional resources to prioritize the information processing of a target stimulus while actively suppressing the information processing of distracting information (Gaspelin, Leonard, & Luck, 2015, 2017; Hickey, Di Lollo, & McDonald, 2009; Noonan et al., 2016; Noonan, Crittenden, Jensen, & Stokes, 2018; Sawaki & Luck, 2011). Given a number of studies demonstrating the close link between the attentional control and memory encoding (e.g., Chun & Turk-Browne, 2007; deBettencourt, Norman, & Turk-Browne, 2018; Moray, 1959; Turk-Browne, Golomb, & Chun, 2013; Uncapher, Hutchinson, & Wagner, 2011), it is reasonable to hypothesize that we can enhance (or *up-regulate*) and degrade (or *down-regulate*) our ability to encode visual long-term memory through voluntary control of attention.

Previous studies have suggested that we might be capable of exerting voluntary control on visual long-term memory encoding. For example, recent studies have demonstrated that individuals are capable of up-regulating memory encoding on a moment-to-moment basis when successful encoding of certain items were incentivized by monetary reward (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Gruber & Otten, 2010; Gruber, Watrous, Ekstrom, Ranganath, & Otten, 2013). However, it is unclear from these studies whether external incentives are required for individuals to exert such control, thus questioning the intrinsic nature of such control. On the other hand, the directed forgetting

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literature argues that humans are capable of disrupting memory encoding at will when instructed to forget recently encoded stimuli (Anderson & Hanslmayr, 2014; Bjork, Bjork, & Anderson, 1998; Fawcett, Lawrence, & Taylor, 2016). However, the directed forgetting effect is typically demonstrated as impaired memory performance for cued-to-forget items when compared with that of cued-to-remember items. This contrast makes it difficult to determine if the observed difference in memory performance is the result of voluntary down-regulation of memory encoding for cued-to-forget items or the result of voluntary up-regulation of memory encoding for cued-to-remember items (see also Gao et al., 2016; Zwissler, Schindler, Fischer, Plewnia, & Kissler, 2015).

Our recent study (Sundby et al., 2019) examined these unresolved issues in the following manner. First, we presented a sequence of pictures of real objects for participants to remember. Importantly, each picture was preceded by four types of cues that instructed participants to voluntarily regulate memory encoding in the following ways. When the preceding cue was black, participants were asked to remember the following picture (i.e., baseline condition). When the cue was green, participants were asked to “try harder” to remember the following picture (up-regulation condition). Importantly however, no external incentive was promised for successful encoding of such items. When the cue was red, participants were asked to “try not” to remember the following picture (down-regulation condition). Lastly, when the cue was yellow (neutral condition), participants were asked to encode the following item in the same way as the baseline condition. This allowed us to control for a potential confound introduced by the physical distinctiveness of the colored cue used in up- and down-regulation condition. The results showed that our voluntary control of memory encoding is asymmetrical in nature. More precisely, while we found behavioral and electrophysiological evidence that we are capable of voluntarily up-regulating memory encoding in absence of external incentives, we failed to observe any evidence for voluntary down-regulation of memory encoding. That is, although we did see a difference in memory performance between the up-regulation condition and down-regulation condition, memory performance for the down-regulation condition was statistically equivalent to that for neutral and baseline conditions. Thus, our results suggested that the typical directed forgetting effect might be the result of voluntary up-regulation of memory encoding for cued-to-remember items but not of voluntary down-regulation of memory encoding for cued-to-forget items.

This might seem puzzling considering previous demonstrations of voluntary down-regulation (i.e., suppression) of attentional allocation (Gaspelin et al., 2015; Gaspelin & Luck, 2018) and the integral role of attentional control in regulating memory encoding (e.g., Chun & Turk-Browne, 2007; deBettencourt et al., 2018; Moray, 1959; Turk-Browne et al., 2013; Uncapher et al., 2011). If we are capable of voluntarily suppressing attentional allocation to a given stimulus, why doesn't it lead to down-regulation of memory encoding for such stimulus?

One potential explanation for this conundrum can be linked to a critical difference between our memory control and attentional control paradigms. In the attentional control paradigms, the to-be-down-regulated stimulus is always presented with other items that participants could choose to allocate their attention toward instead of the cued-to-down-regulate stimulus. In other words, the voluntary down-regulation of attentional allocation has always been

demonstrated in a situation in which multiple stimuli are competing for capacity-limited cognitive resources such as attention (e.g., Gaspelin et al., 2015, 2017; Hickey et al., 2009; Noonan et al., 2016, 2018; Sawaki & Luck, 2011) and working memory (e.g., Feldmann-Wüstefeld & Vogel, 2019; Johnson & Johnson, 2009; Shapiro & Miller, 2011; Vogel, McCollough, & Machizawa, 2005; Williams & Woodman, 2012). Consequently, the attentional down-regulation of the cued item could have been indirectly achieved by biased attentional allocation toward other competing stimuli. This biased competition account inspired by the seminal work of Desimone and Duncan (1995) (see also Hutchinson, Pak, & Turk-Browne, 2016; Mather & Sutherland, 2011; Shapiro & Miller, 2011 for theoretical extensions) led us to hypothesize that successful down-regulation of memory encoding requires simultaneous up-regulation of memory encoding of other items that are competing for capacity-limited encoding resources. In other words, voluntary down-regulation of memory encoding can be indirectly achieved by the biased attentional allocation toward the to-be-up-regulated stimulus. If this hypothesis is correct, we should observe reliable down-regulation of memory encoding only when there is biased competition for attentional allocation away from the to-be-down-regulated stimulus and toward the other items.

Experiment 1

In Experiment 1, we tested if down-regulation of memory encoding can be induced indirectly when there is a biased competition for attentional allocation away from the cued-to-down-regulate stimulus and toward the other stimuli. More specifically, we presented either one or two items at a time and instructed participants to remember them. In some of the trials, a precue preceded the stimuli to instruct participants to either up- or down-regulate memory encoding of one of the stimuli. If down-regulation of memory encoding can be exerted as a result of the biased competition of attentional allocation away from the cued-to-down-regulate items and toward the other items, we should observe reliable memory down-regulation only when the cued-to-down-regulate item accompanied a stimulus whose memory encoding is up-regulated.

Method

Power calculation. In Experiment 1, we conducted a series of planned *t* tests to compare the recognition performance for items encoded in different encoding conditions (i.e., up-regulation and down-regulation) against the recognition performance for baseline items. Anticipating that we will obtain a large effect size of Cohen's $d = 0.8$ (Cohen, 1988) based on our previous study (Sundby et al., 2019), the a priori-power calculation with an alpha level of 0.05 and statistical power of 0.8 indicated that we would need 15 subjects (Faul, Erdfelder, Lang, & Buchner, 2007). This assures that our sample size was sufficient to detect a large effect size with 0.8 statistical power.

Bayes factor estimation. In addition, to appreciate the statistical significance and nonsignificance of our results, we used JASP software (JASP Team, 2018) and calculated Bayes factor using a default parameter setting (Cauchy prior centered on 0 with a scale = 0.707). BF_{10} denotes the odds ratio favoring the

alternative hypothesis over the null hypothesis, and BF_{01} denotes the odds ratio favoring the null hypothesis over the alternative hypothesis.

Intrapair analysis for biased competition for memory encoding. To examine whether individuals strategically biased attentional allocation to indirectly down-regulate memory encoding of cued-to-down-regulate items, we examined the correlation of the recognition performance for two simultaneously presented stimuli (Set Size 2 conditions) for each individual. The recognition performance for each item was scored as 1 = old with 100% confidence, 2 = old with 80% confidence, 3 = old with 60% confidence, 4 = new with 60% confidence, 5 = new with 80% confidence, and 6 = new with 100% confidence. If individuals indirectly down-regulated memory encoding of a cued-to-down-regulate item by up-regulating memory encoding of the accompanying uncued item, the intrapair correlation between cued-to-down-regulate items and the accompanying uncued items should be more negative than that for the stimulus pairs presented in the baseline condition. To statistically examine this prediction, individuals' correlation coefficients for up- and down-regulation conditions were compared against those for the baseline condition.

Participants. Thirty participants gave written informed consent according to procedures approved by the Research Ethics Board at the University of Toronto. All volunteers self-reported that they were neurologically normal, had normal or corrected-to-normal visual acuity, and were not color blind.

Stimuli. The stimuli were adapted from a published set of photographs (Brady et al., 2008) and presented in MATLAB using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997). Participants were seated approximately 60 cm from the LCD monitor. Cues were presented in the center of the screen and were one of two colors depending on the task and condition (red, $x = .634$ $y = .36$, 14.5 cd/m^2 ; green, $x = .286$ $y = .603$; black = 0.06 cd/m^2). Stimuli subtending 11.5×11.5 degrees in visual angle were presented on a gray background (54.3 cd/m^2).

Tasks.

Encoding task. Participants performed six blocks of the encoding task. In each block, participants were sequentially presented with 144 pictures of real-world objects (see Figure 1) in 96 encoding trials. Each trial started with the presentation of a fixation dot at the center of the screen, and participants were instructed to keep their gaze fixated at the central fixation throughout the encoding task. After 300 ms, two dots flanking the central fixation dot were presented as placeholders for following pictures for 750 ms. Then, in one half of the trials, one picture was presented at one of the placeholder locations (Set Size 1 conditions). Alternatively, pictures were presented at both placeholder locations (Set Size 2 conditions). All set size condition trials were randomized. After 500 ms of picture presentation, the pictures were removed for 500 ms until the next trial started.

Importantly, the placeholder dots could take one of three colors (black, red, and green), and each color served as a cue to prompt the exertion of differential voluntary control for memory encoding on the upcoming picture. When the two placeholders were black, participants were instructed to remember the upcoming pictures (baseline condition). This baseline condition consisted of two thirds of the trials (64 trials). In one sixth of the trials (16 trials), one of the placeholders was green and the other one was black (up-regulation condition). In this condition, participants were in-

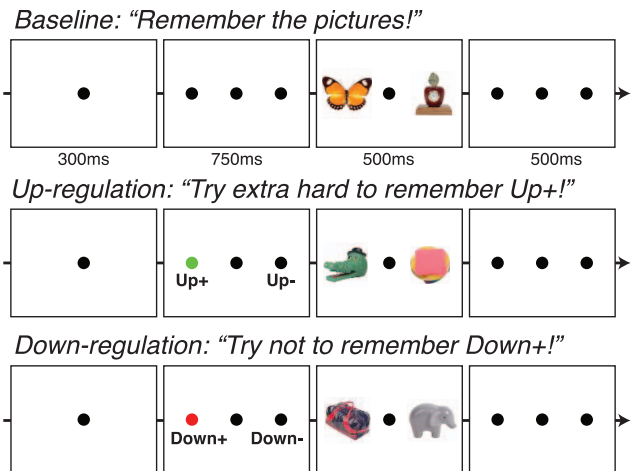


Figure 1. The schematic of the encoding task in Experiment 1. The figure above shows three Set Size 2 conditions in the encoding task. See the online article for the color version of this figure.

structed to “try extra hard” to remember the upcoming picture at the green placeholder location. The picture presented at the green dot location was referred to as an up + picture. In Set Size 2 conditions, another picture was presented at the black dot location accompanying the up + picture. This picture was referred to as an up – picture. In the remaining one sixth of the trials (16 trials), one of the placeholders was red and the other one was black (down-regulation condition). In this condition, participants were instructed to “try not” to remember the upcoming picture at the red placeholder location. The picture presented at the red dot location was referred to as a down + picture. In Set Size 2 conditions, another picture was presented at the black dot location accompanying the down + picture and was referred to as a down – picture. For both up- and down-regulation conditions, participants were encouraged to use any strategy that they saw effective. The only constraint was that they kept their eyes open and fixated at the center of the screen. The location of color-based cueing was 100% valid such that there was always a picture presented at the green and red placeholder locations irrespective of set sizes. To control for a potential confound of cue colors, the assignment of cue colors for up- and down-regulation conditions were counterbalanced across participants.

Recognition task. Following each encoding block, a recognition memory test was administered. The recognition memory test started with the onset of a central fixation dot. After 300 ms, a picture of a real-world object was presented at the center of the screen, and participants were instructed to indicate whether they remembered seeing this picture anytime during the experiment irrespective of encoding condition. They also provided a simultaneous confidence rating by pressing one of six buttons on the keyboard. This ensured that participants had to make recognition judgments based on one criterion across all the items presented, irrespective of encoding condition (i.e., “Did I see this item during the encoding task or not?”), and therefore justified the construction of the encoding-condition-specific receiver operating characteristics (ROC) curves using a common false alarm rate for the new pictures (e.g., Fukuda & Woodman, 2015; Yonelinas, Dobbins, Szymanski, Dhaliwal, & King, 1996). Three

buttons on the right side of the keyboard (i.e., 8, 9, and 0 keys on the top of the keyboard) were used to indicate that they did not remember the item and the three buttons on the left side of the keyboard (i.e., 1, 2, and 3 on the top of the keyboard) were used to indicate that they did remember the item. Of the three buttons on each side, the outermost indicated 100% confidence (i.e., definitely) in their judgment, the middle button indicated 80% confidence (i.e., probably), and the innermost button indicated 60% confidence (i.e., maybe). After the response, the picture was removed from the computer screen and the next trial started. Participants were tested on 144 encoded pictures (32 pictures for Set Size 1 baseline condition, eight pictures each for Set Size 1 up-regulation and down-regulation conditions, and $32 \times 2 = 64$ pictures for Set Size 2 baseline condition, $8 \times 2 = 16$ pictures each for Set Size 2 up-regulation and down-regulation conditions) and 72 new pictures after each encoding block. Of note, there were more old pictures presented than new pictures during the recognition test. This likely induced response bias favoring “remember” responses across the board. However, any response bias should affect all encoding conditions equally, and therefore does not cause problems for interpreting differences observed among different encoding conditions.

Results

Asymmetry in direct control of visual memory encoding.

To quantify memory encoding success for each encoding condition, we calculated the area under the ROC curve (AUC) for each encoding condition. To statistically evaluate the differences in the AUCs, we performed a series of planned *t* tests comparing the AUCs for the conditions of interest (e.g., Set Size 1 upregulation condition) against that for the corresponding baseline condition (e.g., Set Size 1 baseline condition). This was done because our experimental design was not fully factorial (e.g., there were no uncued items in Set Size 1 cueing conditions but there were in the Set Size 2 conditions) and therefore did not allow a straightforward application of repeated-measures ANOVAs.

First, we examined whether participants were able to exert voluntary control to up- and down-regulate memory encoding when the stimulus was presented in isolation (i.e., Set Size 1 conditions), thus in absence of encoding competition. As Figure 2 shows, we found that the AUC for the up-regulation condition was significantly higher than that for the baseline condition, $t(29) = 4.32, p < .001$, Cohen's $d = 0.79$, 95% CI [0.37, 1.20], $BF_{10} = 164.43$. This shows that voluntary upregulation of memory encoding can be exerted in absence of encoding competition. On the other hand, the AUC for the down-regulation condition was not different than that for the baseline condition, $t(29) = 1.03, p = .31$, Cohen's $d = 0.19$, 95% CI [-0.18, 0.55], $BF_{01} = 3.17$. The Bayes factor indicated that it is 3.17 times more likely that there is no difference between the AUCs for down-regulation and baseline conditions than there is a difference. Even if there was a difference, the sample size estimation procedure revealed that it would require a sample size of 224 for it to achieve statistical significance with a power of 0.8. This replicated our previous demonstration of the asymmetric nature of voluntary regulation of memory encoding (Sundby et al., 2019).

Next, we examined whether participants were able to exert voluntary control to up- and down-regulate memory encoding when two stimuli were simultaneously presented (i.e., Set Size 2 conditions), thus inducing competition for attentional allocation. First, to confirm that simultaneous encoding of two stimuli result

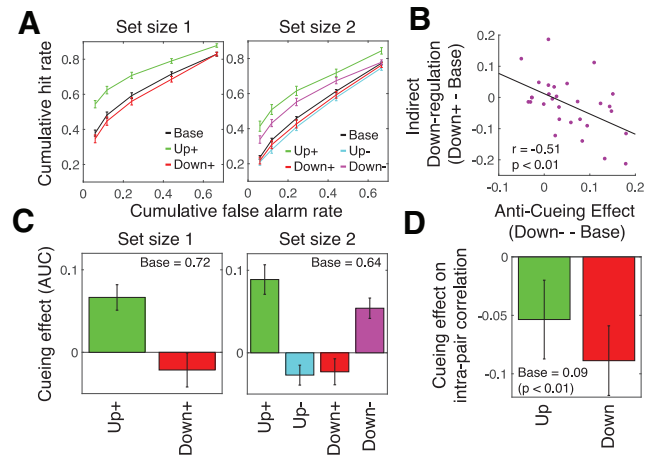


Figure 2. Results of Experiment 1. Panel A shows the ROC curves for Set Size 1 conditions (left) and Set Size 2 conditions (right). Panel B shows the cueing effects (i.e., the AUC for the cueing condition – the AUC for the baseline condition) for Set Size 1 conditions (left) and Set Size 2 conditions (right). Panel C shows the interindividual correlation between indirect down-regulation effect and anticueing effect. Panel D shows the cueing effects on intrapair correlation for up- and down-regulation conditions. The error bars represent within-subject standard errors of the mean. See the online article for the color version of this figure.

in encoding competition, we compared the AUCs for Set Size 1 and Set Size 2 baseline conditions. The result showed that the AUC for the Set Size 2 baseline condition was significantly lower than that for the Set Size 1 baseline condition, $t(29) = 10.47, p < .001$, Cohen's $d = 1.91$, 95% CI [1.30, 2.51], $BF_{10} = 4.02 \times 10^8$, thus confirming the existence of encoding competition. Next, we found that the AUC for the Set Size 2 cued-to-up-regulate items (i.e., up +) was significantly higher than that for the Set Size 2 baseline items, $t(29) = 4.96, p < .001$, Cohen's $d = 0.91$, 95% CI [0.48, 1.33], $BF_{10} = 846.82$. Interestingly, we also observed that the AUC for the uncued item presented in the up-regulation condition (i.e., Up-) was statistically lower than that for the baseline items, $t(29) = 2.24, p = .03$, Cohen's $d = 0.42$, 95% CI [0.03, 0.78], $BF_{10} = 1.67$. These results suggest that memory encoding for the cued items can be selectively up-regulated and that it can impair memory encoding of accompanying uncued items. Thus, these results support our hypothesis that there exists a competitive mechanism for the voluntary up-regulation of memory encoding.

Next, we examined if our participants strategically induced this biased competition to indirectly down-regulate memory encoding for the Set Size 2 cued-to-down-regulate items (i.e., down +). If so, we should observe that the AUC for the uncued items (i.e., down – item) that accompanied down + items should be higher than that for the baseline items. This was indeed the case, $t(29) = 4.38, p < .001$, Cohen's $d = 0.80$, 95% CI [0.38, 1.21], $BF_{10} = 191.48$. Consequently, the AUC for down + items was numerically lower than that for baseline items, but it did not reach statistical significance, $t(29) = 1.45, p = .16$, Cohen's $d = 0.27$, 95% CI [-0.10, 0.63], $BF_{10} = 2.00$.

Between-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation. The results so far only demonstrate partial support for our account

that memory encoding can be indirectly down-regulated by biasing the attentional allocation away from cued-to-down-regulate stimuli and toward the accompanying uncued stimuli. One possibility for this limited support could be that not all participants took advantage of the biased attentional allocation, and as a result, Down + items were not indirectly down-regulated consistently across individuals. To test this, we examined the correlation between the degree of up-regulation of down – items (i.e., the difference in AUCs between down – items and baseline items) and the degree of down-regulation of down + items (i.e., the difference in AUCs between down + items and baseline items). This exploratory analysis found a significant negative correlation ($r = -0.51, p < .001$, Figure 2C), and thus suggests that those who up-regulated the down – items more also down-regulated the down + items more.

Within-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation.

Although the result of our exploratory correlational analysis was in line with our interpretation, it is problematic to rely solely on this result because correlation coefficients derived from a small sample size (e.g., $n \leq 30$) are known to be highly variable and thus prone to false positive and negative results (Schönbrodt & Perugini, 2013).¹ Therefore, to gain converging evidence in line with our exploratory between-subjects correlational analysis, we sought to directly characterize the interstimulus competition for attentional allocation between simultaneously encoded items in a within-subject manner. More precisely, we examined the correlation of recognition performance between simultaneously encoded items in each Set Size 2 condition (i.e., intrapair correlation of recognition performance). If individuals took advantage of biased attentional allocation to facilitate voluntary control of memory encoding, then the intrapair correlation will be more negative when such control is exerted than when it is not (i.e., baseline condition).

First to establish the baseline, we examined the intrapair correlation in absence of voluntary control (i.e., Set Size 2 baseline condition). Here, we found that the intrapair correlation was small but consistently above 0 across individuals ($mean r = .09, t(29) = 3.76, p < .001$, Cohen's $d = 0.69$, 95% CI [0.28, 1.08], $BF_{10} = 42.4$). This suggests that although the recognition performance for each item was largely determined by the intrinsic memorability of each stimulus (Bainbridge, Dilks, & Oliva, 2017), it was also influenced by the moment-to-moment fluctuation of endogenous factors that influence memory encoding for simultaneously encoded items (e.g., sustained attention, deBettencourt et al., 2018).

If some individuals strategically biased attentional allocation toward down – items and away from down + items to induce indirect memory down-regulation, then the intrapair correlation for recognition performance between down + and down – items should be less positive than that for Set Size 2 baseline items. Consistent with this prediction, the intrapair correlation between down + and down – items ($mean r = .001$) was reliably less positive than that for baseline items, $t(29) = 2.98, p = .01$, Cohen's $d = 0.54$, 95% CI [0.16, 0.92], $BF_{10} = 7.16$ (see Figure 2D).

If voluntary up-regulation of memory encoding always requires biased attentional allocation between simultaneously encoded items, then one would expect that the intrapair correlation of recognition performance between up + and up – items to be also less positive than that for the baseline condition. We hypothesized that this was unlikely because there also exists a distinct up-

regulation mechanism that does not necessitate biased competition for attentional allocation (see Set Size 1 result). Consequently, participants likely utilized a mixture of the two mechanisms, thus leading to a less clear manifestation of biased competition for attentional allocation. This was precisely what we observed; the intrapair correlation between up + and up – items was numerically less positive ($mean r = .04$) than that for baseline items, but the difference did not reach statistical significance, $t(29) = 1.59, p = .12$, Cohen's $d = 0.29$, 95% CI [-0.08, 0.65], $BF_{01} = 1.68$ (see Figure 2D). These results, although exploratory, support our hypothesis that a group of participants up-regulated the down – items to take advantage of the biased competition of attentional allocation to indirectly down-regulate memory encoding of down + items.

Discussion

In Experiment 1, we first replicated our previous findings that voluntary control of memory encoding is up-regulatory in nature. That is, even though we are capable of voluntarily up-regulating memory encoding, it is more difficult, if not impossible, to voluntarily down-regulate memory encoding when the stimulus is presented in isolation (i.e., Set Size 1 conditions). Importantly, this finding also demonstrates that voluntary up-regulation does not always necessitate biased competition for attentional allocation among simultaneously encoded stimuli. Next, we examined Set Size 2 conditions to demonstrate a distinct up-regulation mechanism based on the biased competition for attentional allocation among simultaneously encoded stimuli and its utility in indirect down-regulation of memory encoding. First, our results demonstrated that we can voluntarily up-regulate memory encoding of cued-to-up-regulate items in the presence of encoding competition with uncued items, and this can lead to indirect impairment of memory encoding for the accompanying uncued items. Next, we examined whether individuals took advantage of this indirect down-regulation of memory encoding by up-regulating memory encoding of uncued items that accompanied cued-to-down-regulate items. Here, we found that a subset of participants did so and successfully down-regulated memory encoding of cued-to-down-regulate items. This is in line with the previous demonstrations that individuals are capable of allocating attentional resources away from a distractor item when it is presented with other items (e.g., Fukuda & Vogel, 2009, 2011; Gaspelin et al., 2015, 2017; Hickey et al., 2009; Noonan et al., 2016, 2018; Sawaki & Luck, 2011). An alternative hypothesis for explaining this memory down-regulation effect however, is that memory down-regulation is so resource-demanding (Cheng, Liu, Lee, Hung, & Tzeng, 2012; Fawcett & Taylor, 2008) that only a subset of participants with superior cognitive abilities such as fluid intelligence (Salthouse, Siedlecki, & Krueger, 2006) and/or working memory (Delaney & Sahakyan, 2007; Salthouse et al., 2006) were capable of doing so. Thus, as a result of their superior memory control, they were also able to up-regulate memory encoding of the accompanying uncued items. To tease these hypotheses apart in Experiment 2, we included a condition in which we explicitly instructed participants to

¹ Although not theoretically motivated, the correlation coefficients for other cueing effects are reported in the [online supplemental materials](#) for completeness.

up-regulate memory encoding of one item while down-regulating memory encoding of the accompanying item.

Experiment 2

In Experiment 2, we examined if the observed down-regulation of memory encoding in a subset of participants was the result of a strategy used to bias their attentional allocation away from the cued-to-down-regulate items, or the result of superior cognitive abilities used to induce effortful memory down-regulation. To do so, we included a double cue condition in which both up- and down-regulation cues were presented simultaneously. If the observed memory down-regulation was the result of indirect memory down-regulation due to the biased attentional allocation away from the cued-to-down-regulate items, the explicit instruction to up-regulate memory encoding of the accompanying item should also result in a reliable down-regulation of memory encoding of cued-to-down-regulate items. On the other hand, if the observed down-regulation was the result of superior cognitive abilities (e.g., fluid intelligence, working memory) some participants possessed, adding an extra task on top of already effortful memory down-regulation should be more taxing for participants. Therefore, we should observe attenuated up- and down-regulation of memory encoding in the double cue condition when compared with the conditions in which each type of cue was presented in isolation.

Method

Power calculation. In Experiment 2, we conducted a series of planned *t* tests to compare the recognition performance for items encoded in different encoding conditions (i.e., up-regulation and down-regulation) against the recognition performance for the baseline items. Anticipating that we would obtain a large effect size of Cohen's $d = 0.8$ (Cohen, 1988) based on our previous study (Sundby et al., 2019) as well as the results of Experiment 1, the a priori-power calculation with an alpha level of 0.05 and statistical power of 0.8, indicated that we would need 15 subjects (Faul et al., 2007). This assures that our sample size was sufficient to detect a large effect size with 0.8 statistical power.

Participants. Thirty participants gave written informed consent according to procedures approved by the Research Ethics Board at the University of Toronto. All volunteers self-reported that they were neurologically normal, had normal or corrected-to-normal visual acuity, and were not color blind.

Stimuli. The same set of stimuli were used as in Experiment 1.

Tasks.

Encoding task. The encoding task was identical to that in Experiment 1 except the following (see Figure 3). First, we removed the Set Size 1 condition and instead, participants encoded two pictures of real objects on every trial. Second, in addition to baseline, up-regulation and down-regulation conditions, we also included the double cue condition in which one placeholder dot was red and the other was green. In this condition, participants were instructed to up-regulate memory encoding of the picture presented at the up-regulation placeholder location (denoted as "double-up") while down-regulating memory encoding of the picture presented at the down-regulation location (denoted as "double-down"). Each cueing condition (i.e., up-regulation, down-regulation, and double cue condition) consisted of one sixth of the

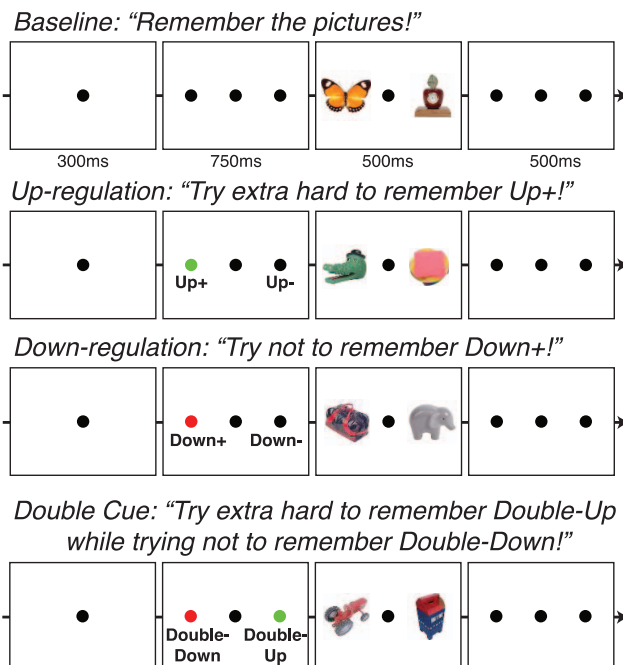


Figure 3. The schematic of the encoding task in Experiment 2. The figure above shows four conditions in the encoding task. See the online article for the color version of this figure.

trials and was presented randomly together with the baseline condition. As a result, each block presented 144 pictures to encode in 72 trials (96 pictures in 48 baseline trials, 16 pictures each in eight up-regulation, eight down-regulation, and eight double cue trials), and participants completed 6 blocks of the encoding task in total.

Recognition task. The recognition task was identical to that in Experiment 1 except that we removed Set Size 1 conditions and added the double cue condition instead. As a result, each recognition block presented 144 old items (96 baseline pictures, 16 pictures each for up-regulation, down-regulation, and double cue condition) and 72 new items.

Results

Asymmetry in direct control of visual memory encoding. Similarly to Experiment 1, we conducted a series of planned *t* tests comparing the AUCs for the items of interest (e.g., Set Size 2 up + items) against that for the corresponding baseline items (e.g., Set Size 2 baseline items). This was done because our experimental design was not fully factorial (e.g., there were no uncued items in double-cue conditions but there were in up- and down-regulation condition) and therefore did not allow a straightforward application of repeated-measures ANOVAs.

First, we examined the AUC for the up-regulation condition (Figure 4A and B). Here we found that the AUC for the cued-to-up-regulate items (i.e., up +) was significantly higher than that for the baseline items, $t(29) = 6.02$, $p < .001$, Cohen's $d = 1.10$, 95% CI [0.64, 1.55], $BF_{10} = 1.20 \times 10^4$. The AUC for the accompanying uncued items (i.e., up -) was numerically smaller than that for the baseline items, but it did not reach statistical significance,

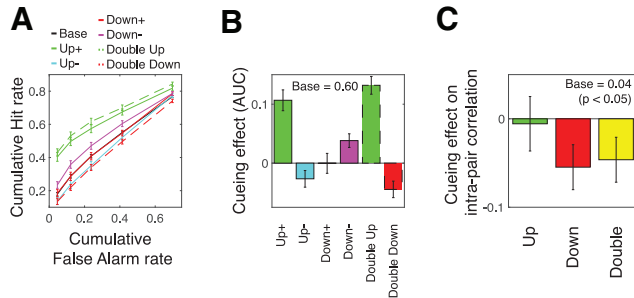


Figure 4. Results of Experiment 2. Panel A shows the ROC curves. Panel B shows the cueing effects (i.e., the AUC for the cueing condition – the AUC for the baseline condition). Panel C shows the cueing effects on intrapair correlation. The error bars represent within-subject standard errors of the mean. See the online article for the color version of this figure.

$t(29) = 1.88, p = .07$, Cohen's $d = 0.34$, 95% CI $[-0.03, 0.71]$, $BF_{10} = 1.09$. This is consistent with our hypothesis that there exists competitive (i.e., biased attentional allocation) and noncompetitive mechanisms for voluntary up-regulation of memory encoding and that not every individual took advantage of the competitive mechanism to up-regulate memory encoding of cued-to-up-regulate items.

Next, we examined the AUC for the down-regulation condition. The AUC for the uncued items that accompanied the cued-to-down-regulate items (i.e., down –) was statistically higher than that for the baseline items, $t(29) = 3.32, p < .01$, Cohen's $d = 0.61$, 95% CI $[0.21, 0.99]$, $BF_{10} = 15.1$. The AUC for the items presented at the down-regulation location (i.e., down +) was numerically lower than that for baseline items, but it did not reach statistical significance, $t(29) = 0.01, p = .99$, Cohen's $d = 0.00$, 95% CI $[-0.35, 0.35]$, $BF_{01} = 5.14$. This is consistent with the results of Experiment 1 that not all of the participants utilized the indirect memory-down regulation strategy of inducing biased competition of attentional allocation away from the cued-to-down-regulate stimulus (i.e., down +) and toward the uncued stimulus (i.e., down –).

Lastly, we examined the AUCs for the double cue condition. The AUC for the cued-to-up-regulate items in the double cue condition (i.e., double-up) was significantly higher than that for the baseline items, $t(29) = 8.78, p < .001$, Cohen's $d = 1.60$, 95% CI $[1.05, 2.14]$, $BF_{10} = 1.02 \times 10^7$. It was also statistically higher than the AUC for the cued-to-up-regulate items that did not accompany the to-be-down-regulated item (i.e., up +), $t(29) = 3.14, p < .01$, Cohen's $d = 0.57$, 95% CI $[0.18, 0.96]$, $BF_{10} = 10.2$. This suggests that concurrent up- and down-regulation of memory encoding did not tax our ability to up-regulate memory encoding of the to-be-up-regulated item. If anything, the simultaneous down-regulation enhanced the efficacy of voluntary up-regulation of memory encoding. What this suggests instead, is that in the double cue condition, individuals consistently utilized the competitive mechanism in addition to the noncompetitive mechanism to up-regulate memory encoding of the cued-to-up-regulate items.

If this was the case, then we should observe reliable down-regulation of memory encoding for cued-to-down-regulate items presented in the double cue condition. When we examined the AUC for cued-to-down-regulate items in the double cue condition

(i.e., double-down), it was significantly lower than that for the baseline items, $t(29) = 3.19, p < .01$, Cohen's $d = 0.58$, 95% CI $[0.19, 0.97]$, $BF_{10} = 11.37$. It was also statistically lower than the AUC for the cued-to-down-regulate items that did not accompany the cued-to-up-regulate items (i.e., down +), $t(29) = 3.92, p < .001$, Cohen's $d = 0.72$, 95% CI $[0.31, 1.11]$, $BF_{10} = 61.0$. This indicates that the concurrent up-regulation of memory encoding of an accompanying item (i.e., double-up) led to more successful down-regulation of memory encoding of the cued-to-down-regulate item than when the cued-to-down-regulate item was presented alone (i.e., down +). These results effectively negate the alternative hypothesis that the failure to observe voluntary down-regulation in the down-regulation condition (i.e., down +) was due to the insufficient cognitive resources (e.g., fluid intelligence, working memory capacity) in some individuals. Instead, our results demonstrate that it was due to the inconsistent use of indirect down-regulation via biased competition for attentional allocation.

Between-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation.

First, to replicate and extend our between-subjects correlational analyses, we examined the relationship between the degree of up-regulation of down – items (i.e., the difference in AUCs between down – items and baseline items) and the degree of down-regulation of down + items (i.e., the difference in AUCs between down + items and baseline items). Here, we replicated the significant negative correlation shown in Experiment 1, $r = -0.45, p < .001$. This demonstrates that those who more strongly upregulated memory encoding of down – items subsequently down-regulated memory encoding of down + items more. This suggests that in the down-regulation condition, some individuals strategically induced biased competition for attentional allocation to indirectly down-regulate memory encoding of cued-to-down-regulate items. Next, we examined whether all individuals were capable of taking advantage of this strategy when they were explicitly told to up-regulate memory encoding of an accompanying item (i.e., double cue condition). If so, then we would expect the negative correlation to weaken due to consistent use of the strategy. When individuals were explicitly told to up-regulate memory encoding of accompanying items, the magnitude of the cued up-regulation effect did not predict the magnitude of the cued down-regulation effect, $r = -0.08, p = .67$. However, our data provided partial support for our hypothesis because the difference in the correlation coefficient between the down-regulation condition and double cue condition did not reach statistical significance (Fisher's $z = 1.49, p = .14$).

Within-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation.

Because correlation coefficients based on small sample sizes (e.g., $n \leq 30$) are highly variable (Schönbrodt & Perugini, 2013), we thought to obtain converging evidence by examining intrapair correlations for attentional allocation between simultaneously encoded items. First to establish the baseline, we examined the intrapair correlation in absence of voluntary control (i.e., baseline condition). Here, we replicated that the intrapair correlation was small but consistently above 0 across individuals ($mean r = .04, t(29) = 2.45, p = .02$, Cohen's $d = 0.45$, 95% CI $[0.07, 0.82]$, $BF_{10} = 2.46$). This replication suggests that again, although the recognition performance for each item was largely determined by the intrinsic memorability of each stimulus (Bainbridge et al.,

2017), it was also influenced by the moment-to-moment fluctuation of endogenous factors that influence memory encoding for simultaneously encoded items (e.g., sustained attention, deBetten-court et al., 2018).

Next, we examined the intrapair correlation for attentional allocation in the down-regulation condition. If some individuals strategically biased attentional allocation toward down – items and away from down + items to induce indirect memory down-regulation, then the intrapair correlation for recognition performance between down + and down – items should be more negative than that for baseline items. Consistent with this prediction, the interitem correlation between down + and down – items ($mean\ r = -0.02$) was reliably more negative than that for baseline items, $t(29) = 2.16, p = .04$, Cohen's $d = 0.39$, 95% CI [0.02, 0.76], $BF_{10} = 1.44$.

Lastly, we examined the intrapair correlation in the up-regulation condition. Here, we hypothesized that the correlation should be between that of baseline and down-regulation conditions due to the mixed use of competition-based and noncompetition-based strategies for memory up-regulation. Consistent with our prediction, we demonstrated that the intrapair correlation between up + and up – items ($mean\ r = .03$) was between that for baseline and down-regulation conditions, and it was not statistically different from either of them, $t(29) = 0.18, p = .86$, Cohen's $d = 0.03$, 95% CI [-0.33, 0.39], $BF_{01} = 5.07$ against baseline; $t(29) = 1.37, p = .18$, Cohen's $d = 0.25$, 95% CI [-0.12, 0.61], $BF_{01} = 2.22$ against down-regulation). Similarly, we predicted that the intrapair correlation in the double cue condition would be between that of the baseline and down-regulation conditions because of the availability of the two memory up-regulation strategies. Consistent with our prediction, the intrapair correlation between double-up and double-down items was numerically more negative ($mean\ r = -0.01$) than that for baseline items and it was not statistically different from either of them, $t(29) = 1.41, p = .17$, Cohen's $d = 0.26$, 95% CI [-0.11, 0.62], $BF_{01} = 2.12$ against baseline; $t(29) = 0.23, p = .82$, Cohen's $d = 0.04$, 95% CI [-0.32, 0.40], $BF_{01} = 5.03$ against down-regulation).

Discussion

The results of Experiment 2 confirmed that memory down-regulation observed in Experiment 1 was the result of memory up-regulation of an accompanying item. More precisely, we observed a reliable memory down-regulation effect when cued-to-down-regulate items were accompanied by cued-to-up-regulate items. Moreover, the fact that the magnitudes of the memory control effects were statistically larger in the double cue condition than in the corresponding single cue conditions (i.e., up-regulation and down-regulation conditions) negated the alternative hypothesis that memory down-regulation is so resource-intensive that only a subset of individuals with superior cognitive resources were able to achieve this successfully. Furthermore, our analyses of intrapair correlations for memory encoding replicated the existence of both competitive and non-competitive mechanisms for the voluntary up-regulation of memory encoding. Taken together, our results demonstrate that one can indirectly down-regulate memory encoding of an unwanted stimulus by biasing their attentional allocation toward simultaneously encoded stimuli.

Experiment 3

So far, we have demonstrated that voluntary control of memory encoding is up-regulatory in nature, and one can also indirectly down-regulate memory encoding by biasing attentional allocation away from unwanted information and instead toward accompanying information. This was the case when participants were provided with a precue that indicated the direction of the bias. However, in reality we are not always provided with such a preceding warning indicating that we are about to encounter information that we wish to remember or that we do not wish to remember. Therefore, it is important to examine if we are capable of voluntarily up- and down-regulating memory encoding *after* the information is already perceived and encoded into working memory.

To test this, we modified our paradigm used in Experiments 1 and 2 into a canonical item-method directed forgetting task (Anderson & Hanslmayr, 2014; Bjork et al., 1998; Fawcett et al., 2016) by swapping the temporal order of the cues and the stimuli of Experiment 1. Typical findings in this classic paradigm show that the memory performance for cued-to-down-regulate (i.e., to-be-forgotten) items is worse than that for cued-to-up-regulate (i.e., to-be-remembered) items. Although these findings are traditionally interpreted as the demonstration of intentional forgetting, this comparison makes it impossible to tease apart the effect of voluntary up-regulation of memory encoding for cued-to-up-regulate items and voluntary down-regulation for cued-to-down-regulate items. Our paradigm on the other hand, would allow us to separate the effect of voluntary up- and down-regulation of memory encoding by comparing the memory performance against the baseline condition. If the canonical directed forgetting effect is driven by voluntary down-regulation of memory encoding for cued-to-remember items, then the memory performance for cued-to-down-regulate items should be lower than that for baseline items. Alternatively, if it is the result of voluntary up-regulation of memory encoding for cued-to-remember items, then the memory performance for cued-to-down-regulate items should also be indistinguishable from that for baseline items.

In addition, we aimed to specify the locus at which biased attentional allocation enabled the indirect down-regulation of memory encoding. In the two previous experiments, the voluntary control of memory encoding was prompted prior to stimulus onset. Thus, it is unclear at what stage the biased attentional allocation contributed to indirect down-regulation of memory encoding. One possibility is that biased attentional allocation affected the perceptual encoding of the stimuli into visual working memory. Indeed, studies have demonstrated that individuals, some more so than others, are capable of selectively encoding a subset of visual objects into visual working memory (e.g., Fukuda & Vogel, 2009; Liesefeld, Liesefeld, & Zimmer, 2014; McNab & Klingberg, 2008; Vogel et al., 2005). Alternatively, the bias could have been implemented after stimuli were encoded into working memory but during their active maintenance. This postencoding voluntary control has also been demonstrated across multiple experimental paradigms (e.g., Ester, Nouri, & Rodriguez, 2018; Kuo, Stokes, & Nobre, 2012; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012; Williams & Woodman, 2012). More specifically, studies have demonstrated that individuals are capable of manipulating the attentional allocation among multiple working memory representations to prioritize the maintenance of a subset of them. If the

locus of biased competition was at working memory encoding, then prompting voluntary control after working memory encoding would be too late to induce indirect down-regulation of memory encoding. On the other hand, if the locus is at working memory maintenance, postencoding cues should be just as effective at inducing indirect down-regulation of memory encoding.

Method

Power calculation. In Experiment 3, we again conducted a series of planned t tests to compare the recognition performance for items encoded in different encoding conditions (i.e., up-regulation and down-regulation) against the recognition performance for baseline items. Anticipating that we would obtain a large effect size of Cohen's $d = 0.8$ (Cohen, 1988) based on our previous study (Sundby et al., 2019), the a priori-power calculation with alpha level of 0.05 and statistical power of 0.8 indicated that we would need 15 subjects (Faul et al., 2007). This assures that our sample size is sufficient to detect a large effect size with 0.8 statistical power.

Participants. Thirty participants gave written informed consent according to procedures approved by the Research Ethics Board at the University of Toronto. All volunteers self-reported that they were neurologically normal, had normal or corrected-to-normal visual acuity, and were not color blind.

Stimuli. The same set of stimuli were used as in Experiment 1.

Tasks.

Encoding task. The encoding task was identical to that in Experiment 1 except that the placeholders changed their colors after the stimuli were presented instead of before (see Figure 5). Each trial started with the presentation of a fixation dot at the center of the screen. After 300 ms, one picture was presented either to the left or to the right of the fixation dot (Set Size 1 conditions) in one half of the trials, and two pictures were presented at both lateral locations of the fixation dot (Set Size 2 conditions) on the other half of the trials. Participants were instructed to encode all the pictures presented. After 500 ms of picture presentation, the pictures were removed for 500 ms, after which two black placeholder

dots were presented for 750 ms. Critically, in one sixth of the trials, one of the placeholders was green, and this informed a random half of the participants to up-regulate memory encoding of the following stimulus presented at this location. In another one sixth of the trials, one of the placeholders was red, and this informed the same half of the participants to down-regulate memory encoding of the following stimulus presented at this location. For the other half of the participants, the instructions for the colors were swapped. Following the placeholder presentations, the next trial began.

Recognition task. The recognition task was identical to that in Experiment 1.

Results

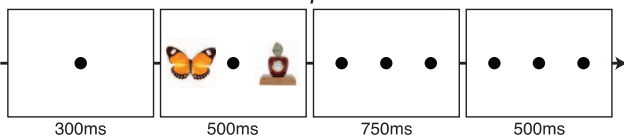
Asymmetry in direct control of visual memory encoding.

First, we examined whether participants were able to exert voluntary control postperceptually to up- and down-regulate memory encoding when the stimulus was presented in isolation. To do so, we compared the area under the ROC curve (AUC) for the Set Size 1 baseline condition with those for Set Size 1 up- and down-regulation conditions. As Figure 6 shows, we found that the AUC for the up-regulation condition was significantly higher than that for the baseline condition, $t(29) = 3.47, p < .01$, Cohen's $d = 0.63$, 95% CI [0.24, 1.02], $BF_{10} = 21.1$. On the other hand, the AUC for the down-regulation condition was not different from that for the baseline condition, $t(29) = 1.53, p = .14$, Cohen's $d = 0.28$, 95% CI [-0.09, 0.64], $BF_{01} = 1.82$. The Bayes factor indicated that it is 1.82 times more likely that there is no difference between the AUCs for down-regulation and baseline conditions than there is a difference. Even if there was a difference, the sample size estimation procedure revealed that it would require a sample size of 104 for it to achieve statistical significance with a power of 0.8.

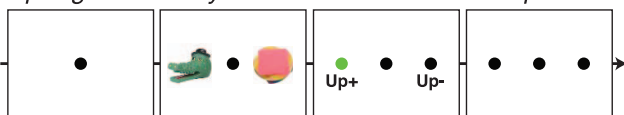
These results demonstrate that we are capable of regulating post-encoding processes (i.e., working memory maintenance) to directly up-regulate memory encoding without necessitating biased competition. However, such control is not as efficient at directly down-regulating memory encoding. This is consistent with our previous finding that voluntary control for memory encoding is up-regulatory in nature, and thus demonstrates that the typically observed item-based directed forgetting effect is better characterized as voluntary up-regulation of memory encoding for cued-to-remember items rather than voluntary down-regulation of cued-to-forget items.

Next, we examined Set Size 2 conditions to see if the competitive mechanism can also be recruited during postencoding processes (i.e., working memory maintenance) to influence visual long-term memory encoding. First, to confirm that simultaneous encoding of two stimuli result in encoding competition, we compared the AUCs for Set Size 1 and Set Size 2 baseline conditions. The result showed that the AUC for Set Size 2 baseline was significantly lower than that for Set Size 1 baseline condition, $t(29) = 9.54, p < .001$, Cohen's $d = 1.74$, 95% CI [1.16, 2.31], $BF_{10} = 4.02 \times 10^8$, thus confirming the existence of encoding competition. Next, we found that the AUC for the cued-to-up-regulate items (i.e., up +) was significantly higher than that for Set Size 2 baseline items, $t(29) = 4.08, p < .001$, Cohen's $d = 0.74$, 95% CI [0.33, 1.15], $BF_{10} = 90.2$. Contrary to what we found in Experiment 1, we found that the AUC for the uncued items that accompanied cued-to-up-regulate items (i.e., up -) was no different from that for the baseline items, $t(29) = 0.51, p = .57$, Cohen's $d = 0.10$, 95%

Baseline: "Remember the pictures!"



Up-regulation: "Try extra hard to remember Up+!"



Down-regulation: "Try not to remember Down+!"

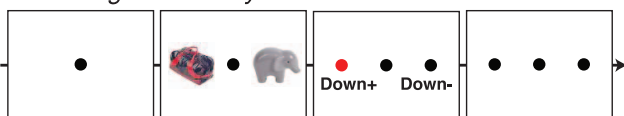


Figure 5. The schematic of the encoding task in Experiment 3. The figure above shows three Set Size 2 conditions in the encoding task. See the online article for the color version of this figure.

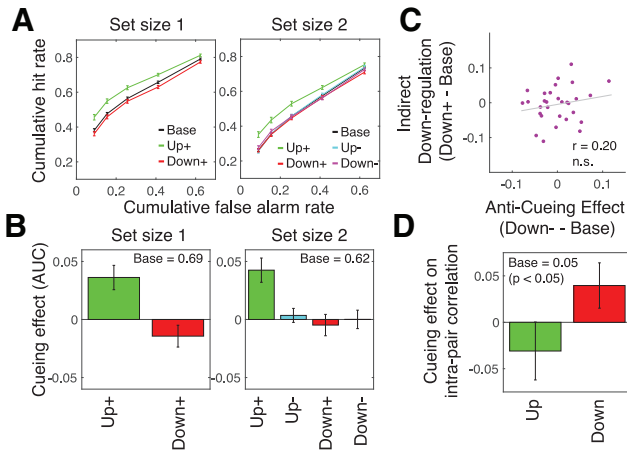


Figure 6. Results of Experiment 3. Panel A shows the ROC curves for Set Size 1 conditions (left) and Set Size 2 conditions (right). Panel B shows the cueing effects (i.e., the AUC for the cueing condition – the AUC for the baseline condition) for Set Size 1 conditions (left) and Set Size 2 conditions (right). Panel C shows the interindividual correlation between indirect down-regulation effect and anticueing effect. Panel D shows the cueing effects on intrapair correlations for up- and down-regulation conditions. The error bars represent within-subject standard errors of the mean. See the online article for the color version of this figure.

CI $[-0.27, 0.45]$, $BF_{01} = 4.43$. These results suggest that voluntary memory up-regulation of memory encoding did not impair memory encoding of the accompanying uncued item when exerted after working memory encoding. This result is thus inconsistent with the postencoding recruitment of a biased competition strategy to influence visual long-term memory encoding.

Next, we examined if an attempt to down-regulate memory encoding caused the biased attentional allocation away from cued-to-down-regulate items (i.e., down + items) but toward accompanying uncued items (i.e., down – items). If so, we should observe that the AUC for the down – items should be higher than that for the baseline items. However, contrary to the results of Experiment 1, the AUC for down – items was no different from that for the baseline items, $t(29) = 0.02$, $p = .98$, Cohen's $d = 0.001$, 95% CI $[-0.36, 0.35]$, $BF_{01} = 5.14$. Consequently, the AUC for down + items were no different than that for baseline items, $t(29) = 0.51$, $p = .61$, Cohen's $d = 0.09$, 95% CI $[-0.27, 0.45]$, $BF_{01} = 4.56$.

These results suggest two possibilities. First, biased attentional allocation can influence visual long-term memory encoding only when it is prompted prior to visual working memory encoding as shown in Experiments 1 and 2. When it is prompted afterward, it is too late to influence visual long-term memory encoding. Alternatively, our participants, for some reason, did not utilize the strategy to bias their attentional allocation away from the cued-to-down-regulate item and toward the accompanying uncued item when prompted after visual working memory encoding.

Between-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation.

Despite our failure to observe indirect down-regulation across all participants, it is still possible that some individuals were successful at inducing the biased attentional allocation post-perceptually toward down – items, and therefore indirectly down-regulated

memory encoding of down + items. To examine this possibility, we examined the correlation between the degree of up-regulation of down – items (i.e., the difference in AUCs between down – items and baseline items) and the degree of down-regulation of down + items (i.e., the difference in AUCs between down + items and baseline items). If some individuals were indeed successful at indirect down-regulation of memory encoding via biased attentional allocation, we should expect the correlation to be negative. However, we failed to observe such relationship, $r = .20$, $p = .29$ (see Figure 6).

Within-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation.

To gain converging evidence, we then examined the intrapair competition between simultaneously encoded items in a within-subject manner. First to establish the baseline, we examined the intrapair correlation of recognition performance between simultaneously encoded items in absence of voluntary control (i.e., Set Size 2 baseline condition). As expected, we replicated that the intrapair correlation was small but consistently above 0 across individuals ($mean r = .05$, $t(29) = 2.69$, $p = .01$, Cohen's $d = 0.49$, 95% CI $[0.11, 0.87]$, $BF_{10} = 3.96$).

Next, we examined the interstimulus correlation for the down-regulation condition. If some individuals strategically biased attentional allocation toward down – items and away from down + items to induce indirect memory down-regulation, then the interstimulus correlation for recognition performance between down + and down – items should be more negative than that for Set Size 2 baseline items. Contrary to this prediction, we found that the intrapair correlation ($mean r = .09$) was as positive, if not more, as the baseline condition, $t(29) = 1.63$, $p = .12$, Cohen's $d = 0.30$, 95% CI $[-0.07, 0.66]$, $BF_{01} = 1.59$. This suggests that postencoding prompts of memory down-regulation did not result in indirect down-regulation of memory encoding.

Similarly in the up-regulation condition, intrapair correlations between up + and up – items ($mean r = .02$) was statistically equivalent to that for baseline items, $t(29) = 1.00$, $p = .33$, Cohen's $d = 0.18$, 95% CI $[-0.18, 0.54]$, $BF_{01} = 3.27$. This suggests that the observed voluntary up-regulation of memory encoding in this condition does not reflect biased attentional resource competition during visual long-term memory encoding. These results collectively demonstrate that when memory control was prompted after perceptual encoding, our participants failed to indirectly down-regulate visual long-term memory encoding.

Discussion

The results of Experiment 3 demonstrated that although we are capable of up-regulating memory encoding with a postcue, we cannot down-regulate memory encoding directly. Together with our previous findings (Sundby et al., 2019), it suggests that regardless of the timing at which voluntary control is exerted, memory encoding can be up-regulated but not down-regulated from moment to moment. These findings directly challenge the traditional interpretation of the directed forgetting effect which purports that individuals can voluntarily down-regulate memory encoding when prompted. What our results demonstrate instead is that the difference in memory performance between to-be-remembered items and to-be-forgotten items is driven by individuals' ability to voluntarily up-regulate memory encoding of to-be-

remembered items, but not by their ability to voluntarily down-regulate memory encoding of to-be-forgotten items.

Additionally, these results confirm that there exist competitive and noncompetitive up-regulation mechanisms for visual long-term memory encoding. The noncompetitive mechanism can be exerted either prior to or after the perceptual encoding of a stimulus into visual working memory. On the other hand, we did not find evidence for competitive up-regulation of memory encoding when voluntary control was prompted after the perceptual encoding of a stimulus into visual working memory. This result suggests that the locus at which biased attentional allocation enabled the indirect down-regulation of memory encoding was prior to perceptual encoding into visual working memory but not during visual working memory maintenance. One alternative hypothesis, however, is that our participants in Experiment 3 did not utilize the strategy to bias attentional allocation away from cued-to-down-regulate items and toward the accompanying uncued items. To test these hypotheses apart, we conducted Experiment 4.

Experiment 4

In Experiment 4, we examined if our failure to observe indirect memory down-regulation with postcues was due to its critical time window or due to our participant's failure to up-regulate memory encoding of the accompanying items. To do so, we included the double cue condition (similar to Experiment 2) in which both up- and down-regulation postcues were presented simultaneously. If our failure to observe indirect memory down-regulation in Experiment 3 was the result of its critical time window, we should not observe a reliable down-regulation of memory encoding of the cued-to-down-regulate items despite the reliable up-regulation of the accompanying cued-to-up-regulate items. On the other hand, if the lack of the indirect memory down-regulation in Experiment 3 was the result of our participant's failure to up-regulate memory encoding of the uncued items (i.e., down - items) accompanying cued-to-down-regulate items (i.e., down + items), we should observe a reliable indirect memory down-regulation of cued-to-down-regulate items (i.e., double-down items) that were accompanied by cued-to-up-regulate items (i.e., double-up items).

Method

Power calculation. In Experiment 4, we conducted a series of planned t tests to compare the recognition performance for items encoded in different encoding conditions (i.e., up-regulation and down-regulation) against the recognition performance for baseline items. Anticipating that we would obtain a large effect size of Cohen's $d = 0.8$ (Cohen, 1988) based on our previous study (Sundby et al., 2019), the a priori-power calculation with alpha level of 0.05, the statistical power of 0.8 indicated that we would need 15 subjects (Faul et al., 2007). This assures that our sample size is sufficient to detect a large size effect with 0.8 statistical power.

Participants. Thirty participants gave written informed consent according to procedures approved by the Research Ethics Board at the University of Toronto. All volunteers self-reported that they were neurologically normal, had normal or corrected-to-normal visual acuity, and were not color blind.

Stimuli. The same set of stimuli were used as in all three previous experiments.

Tasks.

Encoding task. The encoding task was identical to that in Experiment 3 except the following (see Figure 7). First, we removed the Set Size 1 condition. In other words, participants encoded two pictures of real objects on every trial. Second, in addition to baseline, up-regulation and down-regulation conditions, we also included the double cue condition in which one placeholder dot was red and the other was green. In this condition, participants were instructed to up-regulate memory encoding of a picture presented at the up-regulation location while down-regulating memory encoding of a picture presented at the down-regulation location. Each cueing condition (i.e., up-regulation, down-regulation, and double cue condition) consisted of one sixth of the trials and was presented randomly intermixed together with baseline condition. As a result, each block presented 144 pictures to encode (96 baseline pictures, 16 pictures each for up-regulation, down-regulation, and double cue condition), and participants completed six blocks of the encoding task in total.

Recognition task. The recognition task was identical to that in Experiment 3 except that we removed Set Size 1 conditions and added the double cue condition instead. As a result, each recognition block presented 144 old items (96 baseline pictures, 16 pictures each for up-regulation, down-regulation, and double cue condition) and 72 new items.

Results

Asymmetry in direct control of visual memory encoding.

First, we examined the AUC for the up-regulation condition (see Figure 8). Here we found that the AUC for the cued-to-up-regulate

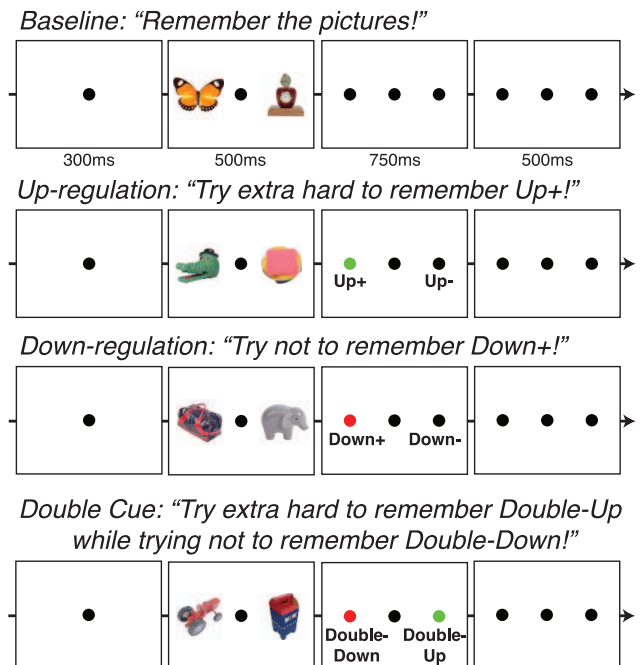


Figure 7. The schematic of the encoding task in Experiment 4. The figure above shows three Set Size 2 conditions in the encoding task. See the online article for the color version of this figure.

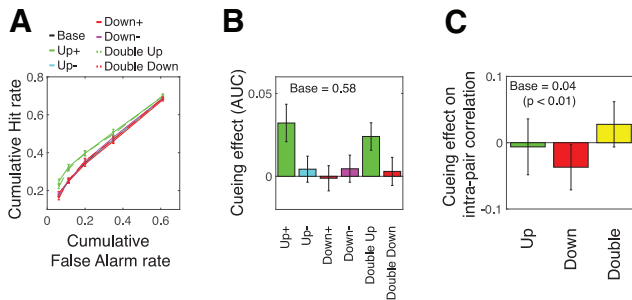


Figure 8. Results of Experiment 4. Panel A shows the ROC curves. Panel B shows the cueing effects (i.e., the AUC for the cueing condition – the AUC for the baseline condition). Panel C shows the cueing effects on intrapair correlations. The error bars represent within-subject standard errors of the mean. See the online article for the color version of this figure.

items (i.e., up +) was significantly higher than that for the baseline items, $t(29) = 2.87$, $p < .01$, Cohen's $d = 0.52$, 95% CI [0.14, 0.90], $BF_{10} = 5.64$. The AUC for the accompanying uncued items (i.e., up –) was not lower than that for the baseline items, $t(29) = 0.56$, $p = .58$, Cohen's $d = 0.10$, 95% CI [–0.26, 0.46], $BF_{01} = 4.45$. Next, we examined the AUC for the down-regulation condition. The AUC for the uncued items that accompanied cued-to-down-regulate items (i.e., down –) was not higher than that for the baseline items, $t(29) = 0.56$, $p = .58$, Cohen's $d = 0.10$, 95% CI [–0.26, 0.46], $BF_{01} = 4.45$. The AUC for the cued-to-down-regulate (i.e., down +) was not different from that for baseline items either, $t(29) = 0.14$, $p = .89$, Cohen's $d = 0.03$, 95% CI [–0.33, 0.38], $BF_{01} = 5.10$. Thus, we replicated the results from Experiment 3.

Next, we examined the AUCs for the double cue condition. The AUC for cued-to-up-regulate items in the double cue condition (i.e., double-up) was significantly higher than that for baseline items, $t(29) = 2.91$, $p < .01$, Cohen's $d = 0.53$, 95% CI [0.14, 0.91], $BF_{10} = 6.15$. It was not statistically different from the AUC for the cued-to-up-regulate items that did not accompany cued-to-down-regulate items (i.e., up +), $t(29) = 0.67$, $p = .51$, Cohen's $d = 0.12$, 95% CI [–0.24, 0.48], $BF_{01} = 4.19$. This suggests that concurrent attempts to down-regulate memory encoding of an accompanying item did not tax our ability to up-regulate memory encoding of the to-be-up-regulated item.

When we examined the AUC for cued-to-down-regulate items in the double cue condition (i.e., double-down), it was not different from that for the baseline items, $t(29) = 0.34$, $p = .74$, Cohen's $d = 0.06$, 95% CI [–0.30, 0.42], $BF_{01} = 4.87$. It was also not different from the AUC for the cued-to-down-regulate items that did not accompany the cued-to-up-regulate items (i.e., down +), $t(29) = 0.35$, $p = .73$, Cohen's $d = 0.06$, 95% CI [–0.30, 0.42], $BF_{01} = 4.87$. This suggests that concurrent up-regulation of memory encoding of an accompanying item did not lead to reliable memory down-regulation of unwanted items.

Between-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation.

To gain further evidence that participants failed to take advantage of biased competition to indirectly down-regulate memory encoding, we first examined the correlation between the degree of up-regulation of down – items (i.e., the difference in AUCs

between down – items and baseline items) and the degree of down-regulation of down + items (i.e., the difference in AUCs between down + items and baseline items). If some individuals were successful at indirect down-regulation of memory encoding via biased attentional allocation, we should expect the correlation to be negative. However, as we expected, there was no such relationship, $r = .01$, $p = .97$.

Within-subject analyses of indirect down-regulation of memory encoding through strategic attentional allocation. We also examined the intrapair competition between simultaneously encoded items in a within-subject manner (Figure 8C). First to establish the baseline, we examined the intrapair correlation of recognition performance between simultaneously encoded items in absence of voluntary control (i.e., baseline condition). Here again, we replicated that the intrapair correlation was small but consistently above 0 across individuals ($mean\ r = .04$, $t(29) = 2.83$, $p < .01$, Cohen's $d = 0.52$, 95% CI [0.13, 0.90], $BF_{10} = 5.25$).

Next, we examined the intrapair correlation in the three cueing conditions (i.e., up-regulation, down-regulation, and double cue conditions). If participants failed to induce biased attentional allocation, we should expect the intrapair correlations to be statistically equivalent to that of the baseline condition. That is precisely what we found; the intrapair correlation for the three cueing conditions were not different from the baseline conditions ($t(29) < 1.09$, $p > .29$, Cohen's $d < 0.20$, 95% CI [–0.49, 0.56], $BF_{01} > 3.0$). These results demonstrate that individuals failed to induce biased competition to indirectly down-regulate memory encoding of cued-to-down-regulate items even when they were explicitly told to up-regulate the accompanying items. Taken together, these results demonstrate that when memory control was prompted after perceptual encoding, our participants failed to indirectly down-regulate visual long-term memory encoding.

Discussion

The results of Experiment 4 confirmed that memory encoding can be up-regulated at will even with postcues. More importantly, despite the successful memory up-regulation of an accompanying item, we failed to observe a reliable memory down-regulation of cued-to-down-regulate items. These results confirm that there is a critical time window at which indirect memory down-regulation can be achieved via biased allocation of attentional resources. More precisely, this strategy is only successful when it is exerted prior to perceptual encoding of the cued-to-down-regulate stimulus into visual working memory. When it is prompted after the stimulus is represented in visual working memory, visual long-term memory encoding can no longer be down-regulated.

General Discussion

Flexible voluntary control over memory encoding enables an adaptive use of our visual long-term memory. However, previous studies have demonstrated limited flexibility in our voluntary control of memory encoding. More precisely, although we are capable of voluntarily up-regulating memory encoding, it is more difficult, if not impossible, to voluntarily down-regulate memory encoding when the stimulus is presented in isolation (Sundby et al., 2019). On the other hand, recent studies in attention literature have demonstrated that we are capable of allocating attentional

resources away from a task-irrelevant distractor item when it is presented with a task-relevant target item (Gaspelin et al., 2015, 2017; Hickey et al., 2009; Noonan et al., 2016, 2018; Sawaki & Luck, 2011). This led to our hypothesis that memory encoding can be indirectly down-regulated by biasing attentional allocation away from the unwanted item but toward the other items that accompany the unwanted item. The results of Experiment 1 confirmed this hypothesis. More precisely, although we replicated that participants failed to down-regulate memory encoding of to-be-down-regulated items when they were presented in isolation, they were instead able to successfully down-regulate encoding by up-regulating memory encoding of an accompanying item. In Experiment 2, we successfully induced reliable indirect memory down-regulation by explicitly instructing participants to up-regulate memory encoding of the accompanying item in our double cue condition.

In Experiments 3 and 4, we examined if indirect down-regulation of memory encoding can be achieved even when it is prompted after perceptual encoding of the stimulus into visual working memory. Here, we found that although participants were capable of up-regulating memory encoding post-perceptually, they failed to utilize it to indirectly down-regulate memory encoding of an accompanying cued-to-down-regulate item. These results demonstrated that there is a critical time period in which indirect memory down-regulation can be induced by biasing attentional allocation away from a cued-to-down-regulate item and toward the accompanying item. In other words, this strategy is effective only when it is exerted prior to perceptual encoding of cued-to-down-regulate items.

Dissociable Mechanisms for Voluntary Up-Regulation of Memory Encoding

In this study, we replicated that humans are capable of voluntarily up-regulating the encoding of visual long-term memory when prompted by external cues. Importantly, this up-regulation was observed in absence of external reward (e.g., money). This sets our findings apart from previous demonstrations of reward-driven up-regulation of memory encoding (Adcock et al., 2006; Gruber & Otten, 2010; Gruber et al., 2013) and thus help exemplify the voluntary nature of memory up-regulation. Interestingly, our results also demonstrated dissociable mechanisms for voluntary up-regulation of memory encoding. The first mechanism can be exerted without necessitating simultaneously encoded items to draw attentional allocation away. Thus, the exertion of this non-competitive mechanism does not lead to indirect down-regulation of memory encoding for simultaneously encoded stimuli. Additionally, our results demonstrated that this mechanism can be summoned before and after the perceptual encoding of the stimulus into visual working memory. This is consistent with up-regulation of sustained attention or vigilance that prevents attentional lapses (e.g., Adam, Mance, Fukuda, & Vogel, 2015; deBettencourt et al., 2018) and mind wondering (e.g., McVay & Kane, 2009; Unsworth, McMillan, Brewer, & Spillers, 2012; Xu, Friedman, & Metcalfe, 2018) as well as postperceptual processes that strengthen memory encoding. For example, one can strengthen memory encoding by subjecting the to-be-encoded information to deeper levels of processing (e.g., Challis, Velichkovsky, & Craik, 1996; Craik, 2002; Craik & Lockhart, 1972).

The second mechanism on the other hand, takes advantage of competition for attentional allocation. More precisely, when there are multiple stimuli competing for memory encoding, this mechanism biases the attentional allocation toward to-be-up-regulated items and away from to-be-down-regulated items. Thus, successful exertion of this mechanism will result in indirect down-regulation of memory encoding of to-be-down-regulated items. This mechanism, however, has to be summoned prior to perceptual encoding of to-be-down-regulated stimuli into visual working memory in order to take effect. In other words, once the unwanted information is perceptually encoded into visual working memory, this biased competition mechanism cannot down-regulate visual long-term memory encoding. One candidate mechanism to induce this biased competition is the top-down control of spatial attention. Spatial attention can be guided overtly as well as covertly to enhance perceptual processing of attended information, and as a consequence, perceptual processing of unattended information is compromised (e.g., Desimone & Duncan, 1995; Noudoost, Chang, Steinmetz, & Moore, 2010; Posner, 1980; Yantis, 2008).

One may wonder that participants simply looked away from cued-to-down-regulate location to down-regulate memory encoding of up-coming stimuli. Although we instructed participants to maintain central fixation throughout the experiments, it is still possible that participants failed to follow the instruction, as looking away is an effective way to covertly control spatial attention away from the cued-to-down-regulate items. However, we do not think that this oculomotor strategy was sufficient to cause down-regulation of memory encoding because not all down-regulation conditions exhibited reliable down-regulation of memory encoding. Had down-regulation of memory encoding been simply caused by participants' strategy to look away from the cued-to-down-regulate items, we should have observed reliable down-regulation of memory encoding across all conditions that presented the down-regulation cue. However, the fact that reliable down-regulation was only observed when memory encoding for the accompanying item was up-regulated (e.g., double cue condition) demonstrates the necessity of encoding competition.

Reinterpretation of Directed Forgetting Literature

Our findings may seem incompatible with a long line of research using directed-forgetting paradigms (Anderson & Hanslmayr, 2014; Bjork et al., 1998; Fawcett et al., 2016; Fawcett & Taylor, 2008). More precisely, in typical item-method directed forgetting paradigms, participants are presented with a cue to remember or forget the immediately preceding item, and such studies have consistently found that items that were followed by the "remember" cue are better remembered than items followed by "forget" cues (e.g., Anderson & Hanslmayr, 2014; Bjork et al., 1998; MacLeod, 1998, 1999). These findings have often been interpreted as evidence for individuals' ability to intentionally forget or down-regulate memory encoding of unwanted information. However, an alternative explanation that is compatible with our findings is that individuals are selectively up-regulating memory encoding of the cued-to-remember items compared with the cued-to-forget items. To tease these hypotheses apart, it is important to test the memory performance for cued-to-remember and cued-to-forget items against the "baseline" items that did not receive either of the cues while keeping other factors equal. How-

ever, the majority of directed forgetting studies, except for a few recent studies (Gao et al., 2016; Zwissler et al., 2015), have not performed this comparison due to the lack of a within-subject baseline condition. Interestingly, studies that included the within-subject baseline condition showed that memory performance for cued-to-forget items was no worse than that for baseline items.

Collectively, our findings indicate that voluntary down-regulation of memory encoding is at least much more difficult, if not impossible, than voluntary up-regulation of memory encoding when such cognitive control is required on a trial-by-trial basis. Additionally, this voluntary up-regulation of memory encoding for cued-to-remember items was sufficient to account for the difference in memory performance between cued-to-remember items and cued-to-forget items observed in the item-method directed forgetting studies. That being said, it is still possible that down-regulation of memory encoding is so effortful that it requires much more time than up-regulation (Cheng et al., 2012; Fawcett & Taylor, 2008). Indeed, typical item-method directed forgetting studies provide longer durations (up to several seconds) after the stimulus presentation for this cognitive process to be complete (Fawcett et al., 2016; Fawcett & Taylor, 2008). Future studies should examine if down-regulation of memory encoding is possible even when much more time is provided between the cue and the stimulus (but see also Bancroft, Hockley, & Farquhar, 2013). If individuals are capable of down-regulating memory encoding below baseline when provided with a much longer time, our current findings still demonstrate that voluntary down-regulation of memory encoding, unlike up-regulation, cannot be exerted promptly.

Furthermore, traditional item-method directed forgetting studies have used verbal stimuli instead of visual stimuli. This leaves a possibility that the asymmetric voluntary control of memory encoding only applies to visual memories. Therefore, future studies should examine whether the same asymmetric control is observed for memory encoding of verbal stimuli.

Indirect Down-Regulation of Memory Encoding Through Biased Attentional Allocation

One of the major motivations for our study stemmed from the importance of voluntary down-regulation of memory encoding. In everyday life, we sometimes encounter information that we do not wish to encode, and in extreme cases, failure in down-regulating memory encoding for such unwanted information can lead to severe clinical symptoms (e.g., posttraumatic stress disorder). Our results demonstrated that it is difficult to “not encode” such unwanted information even when we are told to do so before we encounter the information. However, if we are also told to “try extra hard” to encode other simultaneously presented information, we are capable of “not encoding” the unwanted information via biased competition for attentional allocation. Thus, our result offers an effective strategy to induce indirect down-regulation of memory encoding of unwanted information. It would be interesting to investigate whether the same strategy could be used to down-regulate memory encoding of unwanted information in clinical populations of interest.

Despite its promise, this indirect down-regulation strategy has its limitations. That is, this strategy is effective only if it is exerted prior to the perceptual encoding of the unwanted information into

visual working memory. In other words, if one wishes to “not remember” visual information that is already encoded into visual working memory, this strategy is not effective. In such cases, one should rely on other strategies to down-regulate the “retrieval” of unwanted memories instead.

Reinterpretation of Other Forgetting Paradigms

Previous studies demonstrated that one can render unwanted memories less accessible by repeatedly suppressing their “retrieval” (see Anderson & Green, 2001; Anderson & Levy, 2009 for a review). One interesting commonality between these demonstrations and our results is that successful memory down-regulation requires biasing of cognitive resources and processing away from the unwanted memory and toward the competing memory. To be more specific, in a standard retrieval suppression paradigm (i.e., think-no-think paradigm), there are two strategies that are known to lead to successful down-regulation of the retrieval of unwanted memories when faced with a retrieval cue (e.g., Benoit & Anderson, 2012). One approach is to not think about the associated unwanted memories by focusing one’s mind on the retrieval cue itself (i.e., thought suppression). Alternatively, one can suppress retrieval of the unwanted memories by focusing one’s mind on associating the presented cue to different memories (i.e., thought substitution). In both cases, the key to successful memory down-regulation is biasing cognitive resources and processing away from the unwanted memories and toward the alternative (i.e., the retrieval cue itself or alternative memories). This is in line with our finding that we are capable of indirectly down-regulating memory encoding by biasing attentional resources away from unwanted information and toward accompanying information.

Another line of work showed that we can down-regulate retrieval of unwanted memories by repeatedly practicing the retrieval of other “competing” memories (Anderson, Bjork, & Bjork, 1994; Maxcey & Woodman, 2014). Again, striking is the commonality in what leads to successful down-regulation of memory, namely the biased allocation of cognitive resources and processes away from what is to be forgotten. Taken together, although direct down-regulation of memory might be difficult, strategic biasing of cognitive resources away from unwanted information and toward alternative information seems to be an effective way to indirectly down-regulate memory across multiple stages of memory processes.

Limitations and Future Directions

Our results consistently showed that it is difficult, if not impossible, to directly down-regulate the encoding of visual long-term memory on a moment-to-moment basis. However, it is not clear whether this generalize to encoding of other long-term memories (e.g., verbal memories, semantic memories). Considering its theoretical importance, future studies should examine whether the same inability is observed in memory encoding of other types of stimuli.

Additionally, studies have demonstrated that recognition memory is contributed by dissociable types of episodic memories (e.g., Yonelinas, 2002; Yonelinas & Jacoby, 1994). Recollection-based memories are retrieved with high subjective confidence as well as a source memory about how the memory was encoded. On the

other hand, familiarity-based memories lack source memory and are retrieved with varying degrees of subjective confidence. Previous studies have demonstrated that manipulation of attentional allocation (e.g., divided attention) impacts recollection-based memory more severely than familiarity-based memory (e.g., Eichenbaum, Yonelinas, & Ranganath, 2007; Yonelinas, 2002). Although our current study was not designed to dissociate the effect of indirect memory down-regulation on recollection- and familiarity-based memory with sufficient statistical power, it would be interesting to do so in future studies.

Lastly, it is also interesting to examine the nature and the extent of voluntary control on attentional control in general. For example, recent studies have demonstrated that we are capable of attentionally suppressing task-irrelevant distractors to enhance target discrimination performance (Gaspelin et al., 2015; Gaspelin & Luck, 2018a, 2018b). However, such down-regulatory control has only been demonstrated in the face of other stimuli whose processing can be strategically up-regulated. This leaves the possibility that the previously demonstrated attentional suppression might have also been the result of a strategic up-regulation of accompanying stimuli. If so, one stimulating hypothesis is that our voluntary cognitive control is ubiquitously up-regulatory, and voluntary down-regulation can only be achieved indirectly by a strategic resource allocation toward other competing information. To our knowledge, this hypothesis has not been extensively examined because to-be-down-regulated information has always been presented with other information whose processing can be up-regulated.

An alternative hypothesis is that direct up- and down-regulatory control differs in the speed of execution. More precisely, in contrast to the quick exertion of up-regulatory control, down-regulatory control may be too slow to be exerted on a moment-to-moment basis. There is some supportive evidence for this alternative account. For example, Cunningham and Egeth (2016) demonstrated that explicit cueing of distractors can speed up a visual search of a target but only after an extensive practice period. Also, Noonan et al. (2016) demonstrated that knowing the location of to-be-ignored items (i.e., distractor) in advance helped target discrimination performance only when the distractor location remained the same throughout an experimental block. When the location of the distractor changed from trial to trial, the foreknowledge of the distractor location no longer facilitated the target discrimination performance. These demonstrations are certainly compatible with the alternative hypothesis that direct down-regulation is possible when provided with longer time (and practice) to execute it. However, these studies also presented the to-be-ignored item with other items, and this makes it unclear whether the demonstrated down-regulatory effect was the result of strategic up-regulation of other items. If so, these demonstrations of down-regulatory control are better characterized as indirect down-regulation of items via biased attentional allocation toward other items. Thus, it still remains to be seen whether it is possible at all to exert direct down-regulatory control on unwanted information processing. Given its theoretical impact, future studies should examine the efficacy of down-regulatory cognitive control with and without accompanying stimuli and cognitive processes that can be up-regulated simultaneously.

Context Paragraph

This study was motivated by the puzzling discrepancy between our previous finding (Sundby et al., 2019) and the directed forgetting literature. More precisely, although the directed forgetting literature suggests that humans are capable of forgetting information at will, our recent study failed to find an evidence for direct down-regulation of visual long-term memory encoding. Given the importance of not encoding unwanted information into long-term memory, we attempted to establish an indirect strategy to down-regulate memory encoding that was inspired by attentional control literature (e.g., Desimone & Duncan, 1995; Gaspelin et al., 2015). Our demonstration of indirect memory down-regulation via biased attentional allocation not only demonstrates the flexibility and the rigidity of our voluntary control of memory encoding but also suggests reinterpretations of various memory and attentional control phenomena (e.g., memory suppression, retrieval-induced forgetting, active attentional suppression).

References

- Adam, K. C., Mance, I., Fukuda, K., & Vogel, E. K. (2015). The contribution of attentional lapses to individual differences in visual working memory capacity. *Journal of Cognitive Neuroscience*, *27*, 1601–1616. http://dx.doi.org/10.1162/jocn_a_00811
- Adcock, R. A., Thangavel, A., Whitfield-Gabrieli, S., Knutson, B., & Gabrieli, J. D. (2006). Reward-motivated learning: Mesolimbic activation precedes memory formation. *Neuron*, *50*, 507–517. <http://dx.doi.org/10.1016/j.neuron.2006.03.036>
- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author. <http://dx.doi.org/10.1176/appi.books.9780890425596>
- Anderson, M. C., Bjork, R. A., & Bjork, E. L. (1994). Remembering can cause forgetting: Retrieval dynamics in long-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*, 1063–1087. <http://dx.doi.org/10.1037/0278-7393.20.5.1063>
- Anderson, M. C., & Green, C. (2001). Suppressing unwanted memories by executive control. *Nature*, *410*, 366–369. <http://dx.doi.org/10.1038/35066572>
- Anderson, M. C., & Hanslmayr, S. (2014). Neural mechanisms of motivated forgetting. *Trends in Cognitive Sciences*, *18*, 279–292. <http://dx.doi.org/10.1016/j.tics.2014.03.002>
- Anderson, M. C., & Levy, B. J. (2009). Suppressing unwanted memories. *Current Directions in Psychological Science*, *18*, 189–194. <http://dx.doi.org/10.1111/j.1467-8721.2009.01634.x>
- Bainbridge, W. A., Dilks, D. D., & Oliva, A. (2017). Memorability: A stimulus-driven perceptual neural signature distinctive from memory. *NeuroImage*, *149*, 141–152. <http://dx.doi.org/10.1016/j.neuroimage.2017.01.063>
- Bancroft, T. D., Hockley, W. E., & Farquhar, R. (2013). The longer we have to forget the more we remember: The ironic effect of postcue duration in item-based directed forgetting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 691–699. <http://dx.doi.org/10.1037/a0029523>
- Benoit, R. G., & Anderson, M. C. (2012). Opposing mechanisms support the voluntary forgetting of unwanted memories. *Neuron*, *76*, 450–460. <http://dx.doi.org/10.1016/j.neuron.2012.07.025>
- Bjork, E. L., Bjork, R. A., & Anderson, M. C. (1998). Varieties of goal directed forgetting. In J. M. Golding & C. M. MacLeod (Eds.), *Intentional forgetting: Interdisciplinary approaches* (pp. 103–137). Hillsdale, NJ: Erlbaum.
- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details.

- Proceedings of the National Academy of Sciences of the United States of America*, 105, 14325–14329. <http://dx.doi.org/10.1073/pnas.0803390105>
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10, 433–436. <http://dx.doi.org/10.1163/156856897X00357>
- Challis, B. H., Velichkovsky, B. M., & Craik, F. I. M. (1996). Levels-of-processing effects on a variety of memory tasks: New findings and theoretical implications. *Consciousness and Cognition*, 5, 142–164. <http://dx.doi.org/10.1006/ccog.1996.0009>
- Cheng, S. K., Liu, I. C., Lee, J. R., Hung, D. L., & Tzeng, O. J. (2012). Intentional forgetting might be more effortful than remembering: An ERP study of item-method directed forgetting. *Biological Psychology*, 89, 283–292. <http://dx.doi.org/10.1016/j.biopsycho.2011.10.019>
- Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology*, 17, 177–184. <http://dx.doi.org/10.1016/j.conb.2007.03.005>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Mahwah, NJ: Erlbaum.
- Craik, F. I. M. (2002). Levels of processing: Past, present, and future? *Memory*, 10, 305–318. <http://dx.doi.org/10.1080/09658210244000135>
- Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11, 671–684. [http://dx.doi.org/10.1016/S0022-5371\(72\)80001-X](http://dx.doi.org/10.1016/S0022-5371(72)80001-X)
- Cunningham, C. A., & Egeth, H. E. (2016). Taming the white bear: Initial costs and eventual benefits of distractor inhibition. *Psychological Science*, 27, 476–485. <http://dx.doi.org/10.1177/0956797615626564>
- deBettencourt, M. T., Norman, K. A., & Turk-Browne, N. B. (2018). Forgetting from lapses of sustained attention. *Psychonomic Bulletin & Review*, 25, 605–611. <http://dx.doi.org/10.3758/s13423-017-1309-5>
- Delaney, P. F., & Sahakyan, L. (2007). Unexpected costs of high working memory capacity following directed forgetting and contextual change manipulations. *Memory & Cognition*, 35, 1074–1082. <http://dx.doi.org/10.3758/BF03193479>
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, 18, 193–222. <http://dx.doi.org/10.1146/annurev.ne.18.030195.001205>
- Eichenbaum, H., Yonelinas, A. P., & Ranganath, C. (2007). The medial temporal lobe and recognition memory. *Annual Review of Neuroscience*, 30, 123–152. <http://dx.doi.org/10.1146/annurev.neuro.30.051606.094328>
- Ester, E. F., Nouri, A., & Rodriguez, L. (2018). Retrospective cues mitigate information loss in human cortex during working memory storage. *The Journal of Neuroscience*, 38, 8538–8548. <http://dx.doi.org/10.1523/JNEUROSCI.1566-18.2018>
- Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39, 175–191. <http://dx.doi.org/10.3758/BF03193146>
- Fawcett, J. M., Lawrence, M. A., & Taylor, T. L. (2016). The representational consequences of intentional forgetting: Impairments to both the probability and fidelity of long-term memory. *Journal of Experimental Psychology: General*, 145, 56–81. <http://dx.doi.org/10.1037/xge0000128>
- Fawcett, J. M., & Taylor, T. L. (2008). Forgetting is effortful: Evidence from reaction time probes in an item-method directed forgetting task. *Memory & Cognition*, 36, 1168–1181. <http://dx.doi.org/10.3758/MC.36.6.1168>
- Feldmann-Wüstefeld, T., & Vogel, E. K. (2019). Neural evidence for the contribution of active suppression during working memory filtering. *Cerebral Cortex*, 29, 529–543. <http://dx.doi.org/10.1093/cercor/bhx336>
- Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *The Journal of Neuroscience*, 29, 8726–8733. <http://dx.doi.org/10.1523/JNEUROSCI.2145-09.2009>
- Fukuda, K., & Vogel, E. K. (2011). Individual differences in recovery time from attentional capture. *Psychological Science*, 22, 361–368. <http://dx.doi.org/10.1177/0956797611398493>
- Fukuda, K., & Vogel, E. K. (2019). Visual short-term memory capacity predicts the “bandwidth” of visual long-term memory encoding. *Memory & Cognition*. Advance online publication. <http://dx.doi.org/10.3758/s13421-019-00954-0>
- Fukuda, K., & Woodman, G. F. (2015). Predicting and improving recognition memory using multiple electrophysiological signals in real time. *Psychological Science*, 26, 1026–1037. <http://dx.doi.org/10.1177/0956797615578122>
- Gao, H., Cao, B., Zhang, Q., Qi, M., Li, F., & Li, H. (2016). Intending to forget is not easy: Behavioral and electrophysiological evidence. *International Journal of Psychophysiology*, 104, 1–9. <http://dx.doi.org/10.1016/j.ijpsycho.2016.03.007>
- Gaspelin, N., Leonard, C. J., & Luck, S. J. (2015). Direct evidence for active suppression of salient-but-irrelevant sensory inputs. *Psychological Science*, 26, 1740–1750. <http://dx.doi.org/10.1177/0956797615597913>
- Gaspelin, N., Leonard, C. J., & Luck, S. J. (2017). Suppression of overt attentional capture by salient-but-irrelevant color singletons. *Attention, Perception & Psychophysics*, 79, 45–62. <http://dx.doi.org/10.3758/s13414-016-1209-1>
- Gaspelin, N., & Luck, S. J. (2018). Distinguishing among potential mechanisms of singleton suppression. *Journal of Experimental Psychology: Human Perception and Performance*, 44, 626–644. <http://dx.doi.org/10.1037/xhp0000484>
- Gaspelin, N., & Luck, S. J. (2018a). Distinguishing among potential mechanisms of singleton suppression. *Journal of Experimental Psychology: Human Perception and Performance*, 44, 626–644. <http://dx.doi.org/10.1037/xhp0000484>
- Gaspelin, N., & Luck, S. J. (2018b). The role of inhibition in avoiding distraction by salient stimuli. *Trends in Cognitive Sciences*, 22, 79–92. <http://dx.doi.org/10.1016/j.tics.2017.11.001>
- Gruber, M. J., & Otten, L. J. (2010). Voluntary control over prestimulus activity related to encoding. *The Journal of Neuroscience*, 30, 9793–9800. <http://dx.doi.org/10.1523/JNEUROSCI.0915-10.2010>
- Gruber, M. J., Watrous, A. J., Ekstrom, A. D., Ranganath, C., & Otten, L. J. (2013). Expected reward modulates encoding-related theta activity before an event. *NeuroImage*, 64, 68–74. <http://dx.doi.org/10.1016/j.neuroimage.2012.07.064>
- Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience*, 21, 760–775. <http://dx.doi.org/10.1162/jocn.2009.21039>
- Hutchinson, J. B., Pak, S. S., & Turk-Browne, N. B. (2016). Biased competition during long-term memory formation. *Journal of Cognitive Neuroscience*, 28, 187–197. http://dx.doi.org/10.1162/jocn_a_00889
- JASP Team. (2018). JASP (Version 0.9) [Computer software]. Retrieved from <https://jasp-stats.org>
- Johnson, M. R., & Johnson, M. K. (2009). Top-down enhancement and suppression of activity in category-selective extrastriate cortex from an act of reflective attention. *Journal of Cognitive Neuroscience*, 21, 2320–2327. <http://dx.doi.org/10.1162/jocn.2008.21183>
- Kuo, B. C., Stokes, M. G., & Nobre, A. C. (2012). Attention modulates maintenance of representations in visual short-term memory. *Journal of Cognitive Neuroscience*, 24, 51–60. http://dx.doi.org/10.1162/jocn_a_00087
- Lewis-Peacock, J. A., Drysdale, A. T., Oberauer, K., & Postle, B. R. (2012). Neural evidence for a distinction between short-term memory and the focus of attention. *Journal of Cognitive Neuroscience*, 24, 61–79. http://dx.doi.org/10.1162/jocn_a_00140
- Liesefeld, A. M., Liesefeld, H. R., & Zimmer, H. D. (2014). Intercommunication between prefrontal and posterior brain regions for protecting

- visual working memory from distractor interference. *Psychological Science*, 25, 325–333. <http://dx.doi.org/10.1177/0956797613501170>
- MacLeod, C. M. (1998). Directed forgetting. In J. M. Golding & C. M. MacLeod (Eds.), *Intentional forgetting: Interdisciplinary approaches* (pp. 1–57). Mahwah, NJ: Erlbaum.
- MacLeod, C. M. (1999). The item and list methods of directed forgetting: Test differences and the role of demand characteristics. *Psychonomic Bulletin & Review*, 6, 123–129. <http://dx.doi.org/10.3758/BF03210819>
- Mather, M., & Sutherland, M. R. (2011). Arousal-Biased Competition in Perception and Memory. *Perspectives on Psychological Science*, 6, 114–133. <http://dx.doi.org/10.1177/1745691611400234>
- Maxcey, A. M., & Woodman, G. F. (2014). Forgetting induced by recognition of visual images. *Visual Cognition*, 22, 789–808. <http://dx.doi.org/10.1080/13506285.2014.917134>
- McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory. *Nature Neuroscience*, 11, 103–107. <http://dx.doi.org/10.1038/nn2024>
- McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35, 196–204. <http://dx.doi.org/10.1037/a0014104>
- Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *The Quarterly Journal of Experimental Psychology*, 11, 56–60. <http://dx.doi.org/10.1080/17470215908416289>
- Noonan, M. P., Adamian, N., Pike, A., Printzlau, F., Crittenden, B. M., & Stokes, M. G. (2016). Distinct mechanisms for distractor suppression and target facilitation. *The Journal of Neuroscience*, 36, 1797–1807. <http://dx.doi.org/10.1523/JNEUROSCI.2133-15.2016>
- Noonan, M. P., Crittenden, B. M., Jensen, O., & Stokes, M. G. (2018). Selective inhibition of distracting input. *Behavioural Brain Research*, 34, 36–47. <http://dx.doi.org/10.1016/j.bbr.2017.10.010>
- Noudoost, B., Chang, M. H., Steinmetz, N. A., & Moore, T. (2010). Top-down control of visual attention. *Current Opinion in Neurobiology*, 20, 183–190. <http://dx.doi.org/10.1016/j.conb.2010.02.003>
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10, 437–442. <http://dx.doi.org/10.1163/156856897X00366>
- Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, 32, 3–25. <http://dx.doi.org/10.1080/00335558008248231>
- Salthouse, T. A., Siedlecki, K. L., & Krueger, L. E. (2006). An individual differences analysis of memory control. *Journal of Memory and Language*, 55, 102–125. <http://dx.doi.org/10.1016/j.jml.2006.03.006>
- Sawaki, R., & Luck, S. J. (2011). Active suppression of distractors that match the contents of visual working memory. *Visual Cognition*, 19, 956–972. <http://dx.doi.org/10.1080/13506285.2011.603709>
- Schönbrodt, F. D., & Perugini, M. (2013). At what sample size do correlations stabilize? *Journal of Research in Personality*, 47, 609–612. <http://dx.doi.org/10.1016/j.jrp.2013.05.009>
- Shapiro, K. L., & Miller, C. E. (2011). The role of biased competition in visual short-term memory. *Neuropsychologia*, 49, 1506–1517. <http://dx.doi.org/10.1016/j.neuropsychologia.2011.02.017>
- Standing, L. (1973). Learning 10,000 pictures. *The Quarterly Journal of Experimental Psychology*, 25, 207–222. <http://dx.doi.org/10.1080/14640747308400340>
- Sundby, C. S., Woodman, G. F., & Fukuda, K. (2019). Electrophysiological and behavioral evidence for attentional up-regulation, but not down-regulation, when encoding pictures into long-term memory. *Memory & Cognition*, 47, 351–364. <http://dx.doi.org/10.3758/s13421-018-0871-z>
- Turk-Browne, N. B., Golomb, J. D., & Chun, M. M. (2013). Complementary attentional components of successful memory encoding. *NeuroImage*, 66, 553–562. <http://dx.doi.org/10.1016/j.neuroimage.2012.10.053>
- Uncapher, M. R., Hutchinson, J. B., & Wagner, A. D. (2011). Dissociable effects of top-down and bottom-up attention during episodic encoding. *The Journal of Neuroscience*, 31, 12613–12628. <http://dx.doi.org/10.1523/JNEUROSCI.0152-11.2011>
- Unsworth, N., McMillan, B. D., Brewer, G. A., & Spillers, G. J. (2012). Everyday attention failures: An individual differences investigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38, 1765–1772. <http://dx.doi.org/10.1037/a0028075>
- Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, 438, 500–503. <http://dx.doi.org/10.1038/nature04171>
- Williams, M., & Woodman, G. F. (2012). Directed forgetting and directed remembering in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38, 1206–1220. <http://dx.doi.org/10.1037/a0027389>
- Xu, J., Friedman, D., & Metcalfe, J. (2018). Attenuation of deep semantic processing during mind wandering: An event-related potential study. *Neuroreport*, 29, 380–384. <http://dx.doi.org/10.1097/WNR.0000000000000978>
- Yantis, S. (2008). The neural basis of selective attention: Cortical sources and targets of attentional modulation. *Current Directions in Psychological Science*, 17, 86–90. <http://dx.doi.org/10.1111/j.1467-8721.2008.00554.x>
- Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language*, 46, 441–517. <http://dx.doi.org/10.1006/jmla.2002.2864>
- Yonelinas, A. P., Dobbins, I., Szymanski, M. D., Dhaliwal, H. S., & King, L. (1996). Signal-detection, threshold, and dual-process models of recognition memory: ROCs and conscious recollection. *Consciousness and Cognition*, 5, 418–441. <http://dx.doi.org/10.1006/ccog.1996.0026>
- Yonelinas, A. P., & Jacoby, L. L. (1994). Dissociations of processes in recognition memory: Effects of interference and of response speed. *Canadian Journal of Experimental Psychology*, 48, 516–535. <http://dx.doi.org/10.1037/1196-1961.48.4.516>
- Zwissler, B., Schindler, S., Fischer, H., Plewnia, C., & Kissler, J. M. (2015). “Forget me (not)?” Remembering forget-items versus un-cued items in directed forgetting. *Frontiers in Psychology*, 6, 1741. <http://dx.doi.org/10.3389/fpsyg.2015.01741>

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