Category-based and location-based volitional covert attention affect memory at different timescales

Kirsten Ziman[1,2], Madeline R. Lee[1], Alejandro R. Martinez[1], Ethan D. Adner[1], and Jeremy R. Manning[1,*]

[1]Dartmouth College

[2]Princeton University

[*]Address correspondence to jeremy.r.manning@dartmouth.edu

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Abstract

Our ongoing subjective experiences, and our memories of those experiences, are shaped by our prior experiences, goals, and situational understanding. These factors influence how we allocate our attentional resources over different aspects of our ongoing experiences. These attentional shifts may happen overtly (e.g., when we change where we are looking) or covertly (e.g., without any external physical manifestation). Additionally, we may attend to what is happening at a specific spatial location (e.g., because we think something important is happening there) or we may attend to particular features irrespective of their locations (e.g., when we search for a friend's face in a crowd versus a desired item in a grocery store). We ran a covert attention experiment with two conditions that differed in how long they asked participants to maintain the focus of the categories and locations they were attending. Later, the participants performed a recognition memory task for attended, unattended, and novel stimuli. Participants were able to shift the location of their covert attentional focus more rapidly than they were able to shift their focus of covert attention to stimulus categories, and the effects of location-based attention on memory were longer-lasting than the effects of category-based attention.

Keywords: covert attention, volitional attention, location-based attention, category-based attention, recognition memory

Introduction

Our brains' cognitive systems detect and exploit patterns in our prior and ongoing experiences, enabling us to function and adapt in an ever-changing world. However we do not attend to or treat all types of remembered or incoming information equally, and our ability to flexibly adapt our thinking and behaviors can vary markedly with the specific set of concepts or tasks relevant to a given setting or situation (Adam & deBettencourt, 2019; Aly & Turk-Browne, 2017; Chun & Turk-Browne, 2007; deBettencourt et al., 2021; Hakim et al., 2020; Hardt & Nadel, 2009; Hirschstein & Aly, 2022; Jayakumar et al., 2023; Keene et al., 2022; Ranganath & Ritchey, 2012). There is also substantial variability across people with respect to which aspects of experience (sensory, social, emotional, etc.) are noticed, discriminated between, and acted upon (E. Hunt et al., 1989). This implies that the same physical (objective) experience may give rise to very different perceived (subjective) experiences across people (Chang et al., 2021; Freeman & Simoncelli, 2011).

The aspects of our experience we attend may be under our volitional control or may be unconscious or automatic (Jacoby et al., 1992). Both volitional and unconscious attention may be expressed overtly, for example through intentional eye movements (Hoffman & Subramaniam, 1995) or covertly, without any volitional physical change (Engbert & Kliegl, 2003). Prior work has explored the similarities and differences in the neural basis of overt versus covert attention (A. R. Hunt & Kingstone, 2003; Posner et al., 1987) as well as the behavioral and neural underpinnings of volitional versus unconscious attention (Dijksterhuis & Aarts, 2010) and their differential effects on memory. There is a general consensus that sustained volitional attention enhances memory relative to unconscious attentional processes (Turk-Browne et al., 2013; Uncapher et al., 2011). However, volitional attention takes many forms, such as attention to particular spatial locations or attention to particular visual features or other stimulus properties. How different *types* of volitional attention combine (or compete) to enhance memory remains an open question. Volitional covert attention is of particular interest in that it allows us to dynamically and intentionally manipulate our experience, even when our sensory input remains largely static (i.e., constant physical stimulus, retinal image, etc.; O'Craven et al., 1999; Yi et al., 2006).

Here we examine the ways two different types of volitional covert attention interact to affect memory. We designed an experimental paradigm (following Posner, 1980) that asked participants to attend to a series of presented composite image pairs while keeping their gaze fixed on a central point. The image pairs comprised a left and right image, each constructed by blending an image of a face and place (indoor or outdoor scene). The stimuli and presentation durations were held constant across the two experimental conditions, but the conditions differed in how often we asked participants to change the focus of their attention with respect to image category (face versus place) and image location (left versus right). After the participants attended to a series of images, we used a recognition memory test to assess which aspects of the presented images had been encoded into memory. In both conditions we found that the images participants covertly attended to were better recognized than other images, supporting the notion that attention enhances memory encoding (i.e., they rated attended images as more familiar than unattended images; Yonelinas, 2002). To a lesser extent, participants in both conditions also recognized partially attended images (e.g., images from the attended category but unattended location, or images at the attended location but from the unattended category). However, the ways the category-based and location-based attention affected participants' memories for these partially attended stimuli differed across the two experimental conditions. These partial attention differences suggest that different forms of attention affect memory encoding on different timescales.

Materials and methods

We ran a total of 53 participants across two experimental conditions (Fig. 1). The two conditions differed in how often we cued participants to change the focus of their attention. All code and documentation pertaining to our experiment and analyses, along with the experimental stimuli and data, may be downloaded from `http://www.github.com/ContextLab/attention-memory-task`.

Participants

A total of 53 Dartmouth College undergraduate students enrolled in our study (30 in the sustained attention condition and 23 in the variable attention condition). Following a pilot study using a similar experimental design, we had aimed to enroll 30 participants in each condition. However, we fell short of our enrollment target in the variable attention condition when in-person testing was discontinued at our institution due to the COVID-19 pandemic. We nonetheless chose to analyze and report on our findings from this smaller-than-anticipated cohort of participants using all of the viable data we were able to collect. All participants in our study had self-reported normal or corrected-to-normal vision, memory, and attention. Participants gave written consent to enroll in the study under a protocol approved by the Committee for the Protection of Human Subjects at Dartmouth College.

We used a voluntary pre-experimental survey to collect self-reported demographic information about each partipant. All 53 participants elected to fill out the survey. Participants ranged in age from 18–21 years old (mean: 18.7 years; standard deviation: 0.8 years). Participants reported their genders as female (34 participants), male (18 participants), and gender non-binary (1 participant). Participants reported their

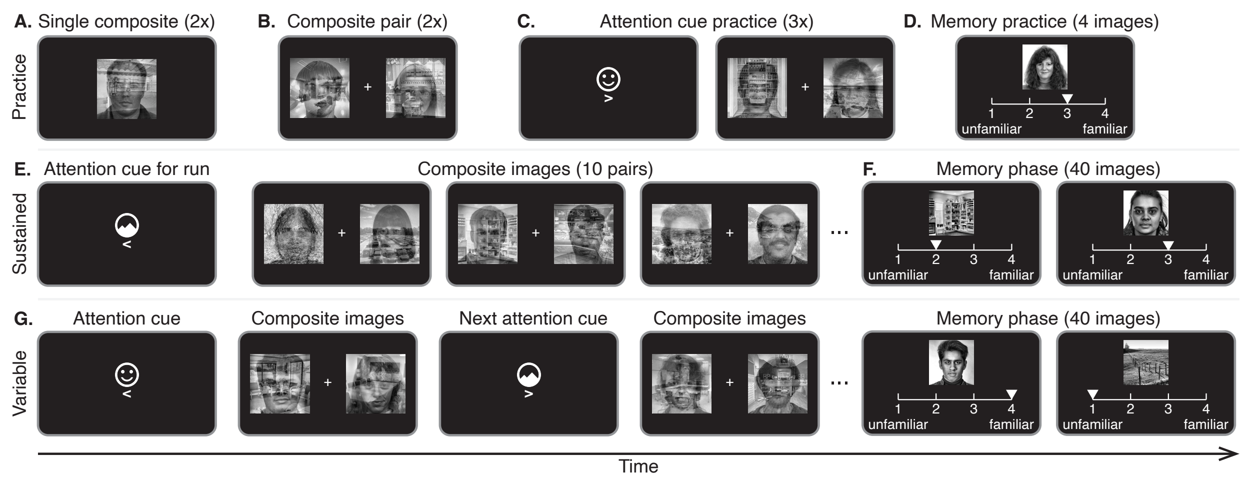

Figure 1. **Experimental paradigm. A.–D. Practice phase. A.** Composite face/place image. **B.** A single pair of composite images and a central fixation cross. **C.** One attention cue practice trial. **D.** Familiarity judgement practice trial. **E. Sustained attention condition.** Participants receive an attention cue, followed by a sequence of 10 composite image pairs (Panel E), and then they make of familiarity judgements on each of 40 face and place images, presented in sequence (Panel F). **G. Variable attention condition.** Participants study a succession of 10 composite image pairs, each preceded by an attention cue. After studying the images, they make a series of 40 familiarity judgements about face and place images, as in the sustained attention condition (Panel F). Note: illustrations are not drawn to scale; see the main text for sizing information.

ethnicities as Not Hispanic or Latino (44 participants), Hispanic or Latino (7 participants), or declined to respond (2 participants). Participants reported their race as White (37 participants), Asian (13 participants), American Indian or Alaska Native (4 participants), Black or African American (2 participants), and Other (1 participant). Note that each participant could report one or more racial categories, as they deemed appropriate.

Forty-nine participants reported having no reading impairments, and 4 participants reported having reading impairments such as mild dyslexia. Fifty participants reported having normal color vision and 3 reported having abnormal color vision such as colorblindness. Fifty participants reported taking no medications and having no recent injuries. One participant reported that they had recently "hit [their] head very hard." Another reported having taken concerta (methylphenidate) in the past, but mentioned they had not taken it recently. One participant reported using amphetamines regularly, but also clarified that they had not used amphetamines on their testing day.

We also asked participants to self-report on their sleep, alertness, and coffee consumption. Participants reported having gotten between 4 and 9 hours of sleep on the night prior to testing (mean: 6.9 hours; standard deviation: 1.3 hours). Participants reported their alertness at the time of testing, and we converted their responses to point values as follows: "Very alert" (5 points), "A little alert" (4 points), "Neutral" (3 points), "A little sluggish" (2 points), and "Very sluggish" (1 point). Across all participants, the full range of alertness values were used (maximum: 5 points; minimum: 1 point; mean: 3.4 points; standard deviation: 1.0 point). Participants reported having consumed between 0 and 2 cups of coffee so far on their testing day (mean: 0.3 cups; standard deviation: 0.5 cups).

Stimulus selection and presentation

Participants viewed photographs of faces, places, and composite images each comprising an equal blend of one face image and one place image. The pool of 360 face images included photographs of adult human male and female faces selected from the FERET database (Phillips et al., 1998). The pool of 360 place images included photographs of indoor and outdoor scenes selected from the SUN database (Xiao et al., 2010). The images we used from both databases came from a stimulus subset that was manually curated by Megan deBettencourt (personal communication). All images were resized to 256×256 pixels, converted to greyscale, and processed so that every image was matched for mean contrast and intensity. We selected 20 face images and 20 place images from the stimulus pool to use in the instructional and practice phases of the experiment (Fig. 1A–D).

In addition to the face and place images, we presented (in white) attention cues to direct the participant's focus of attention. The attention cues comprised a stylized icon of a face or mountain peaks, directing attention to the face or place component of the images, respectively; and a left- or right-facing angled bracket, directing attention to the left or right image, respectively (e.g., Figs. 1C, E, and G).

Our experiment was conducted in a sound- and light-attenuated testing room containing a chair, desk, and 27-inch iMac desktop computer (display resolution: 2048×1152). The participant sat in the chair and rested their chin on a chin rest located 60 cm from the display. The active portion of the display screen occupied 52.96° (width) and 31.28° (height) of the participant's field of view from the chin rest. Stimuli were sized to occupy 6.7° (width and height) of the participant's field of view from the chin rest. We maintained a black background (with any text or cues displayed in white) throughout the experiment.

Eye-tracking

We recorded participants' eye gaze positions using a desk-mounted video-based eye tracker with a spatial resolution of 0.1° visual angle root mean squared error and a sampling rate of 30 Hz (Eye Tribe, The Eye Tribe, Copenhagen, Denmark). We calibrated the eye tracker using a 9-point gaze pattern. As described below, we re-calibrated the eye tracker at regular intervals throughout the experiment to protect against camera drift.

We used the eye-tracking data to home in on behavioral effects related to *covert* attention, as opposed to overt looking effects. Specifically, we excluded from further analysis any images from trials where participants shifted their gaze (for any non-zero amount of time) to any part of the attended composite image during a presentation trial (see Figs. S1, and S2).

Experimental paradigm

Our experiment comprised two testing conditions: a *sustained* attention condition and a *variable* attention condition. Both experimental conditions comprised a practice phase followed by a series of eight task blocks. Each task block was in turn comprised of a presentation phase and a memory phase. The practice and presentation phases differed across the two conditions, and the memory phases were identical across the two conditions. We implemented (coded) the experiment using PsychoPy (Peirce et al., 2019).

Practice phase

Several participants in pilot versions of our experiment reported that they found it difficult to modulate the focus of their attention quickly on command without moving their eyes. We therefore designed a practice sequence to orient the participant to the process of quickly modulating their focus of covert attention. The experimenter remained in the testing room throughout the practice phase and answered any questions about the experiment. The practice sequence builds up incrementally to provide a gradual on-ramping for the participant prior to beginning the main experimental tasks that we focused on in our analyses.

Practice shifting the focus of category-based attention to elements of a single composite image. At the start of the practice phase, we instructed the participant to look at a single composite (face-place blend) image at the center of the screen, and to try to bring the face component of the image into greater focus by attending to it (Fig. 1A). After pressing a button on the keyboard to indicate that they had done so, we displayed a second composite image and instructed the participant to bring the place component of the new composite image into focus. Again, they pressed a button to indicate that they had done so.

Practice shifting the focus of category-based and location-based attention while viewing two composite images. Next, we asked the participant to stare at a fixation cross presented in the center of the screen while two composite images were displayed on the left and right side of the screen, respectively (Fig. 1B). We first instructed the participant to attend to the place component of the left image without moving their eyes. Participants practiced shifting their attention, and they pressed a button on the keyboard to indicate that they had done so. We then displayed a second pair of composite images and instructed the participant to attend to the face component of the right image. Again, the participant shifted their attention in a self-paced manner, and pressed a button to indicate when they had successfully done so.

Practice *sustaining* category-based and location-based attention over a series of composite image pairs. We asked participants in the sustained attention condition to practice holding their focus of category-based and location-based attention constant (to the face component of the right image) while viewing a series of three composite image pairs presented in succession (Fig. 1C).

Practice *varying* category-based and location-based attention over a series of composite image pairs. We asked participants in the variable attention condition to practice varying their focus of category-based and location-based attention while viewing a series of three composite image pairs, each presented after a different attention cue (Fig. 1C).

Practice reaction time probe. After practicing modulating their focus of attention to a series of composite image pairs, we introduced a reaction time probe after each image presentation, whereby we presented either an $\times$ or $\circ$ on either the left or the right of the screen (not shown). We asked the participant to press the 1 key as quickly as possible when they saw an $\times$, or the 3 key as quickly as possible when they saw an $\circ$. We did not impose a time limit on their responses, other than asking participants to respond as quickly as they were able. Participants practiced three trials of modulating their focus of attention to a pair of composite images (3 s), and reacting as quickly as possible to the $\times$ or $\circ$ symbol presented after each composite image pair. The reaction time probe was intended to keep participants continually engaged in modulating the focus of their attention.

Practice recognition memory task. Finally, we asked the participant to practice reporting familiarity on a recognition memory task (Fig. 1D). We presented a single face or place image at the center of the screen, and asked them to press a button to indicate how "familiar" the image seemed: 1 (very confident they had not seen the image), 2 (somewhat confident they had not seen the image), 3 (somewhat confident they had seen the image), or 4 (very confident that they had seen the image). We instructed the participant to go with their "gut reaction" in the event that they were unsure of how to respond. We allowed the participant up to 2 s to provide their response. We gave participants a total of four practice images to rate.

After completing the practice phase of the experiment, the participant read the instructions for the task blocks (described next). The experimenter gave participants a chance to ask any remaining questions about the experiment. After answering the participant's questions, the experimenter calibrated the eye tracker and exited the testing room.

Task blocks

During each task block we asked the participant to modulate their attention while viewing a series of 10 composite image pairs (each followed by a reaction time probe), and then we tested the participant's memory using 40 familiarity judgements. Each participant completed a total of eight task blocks.

Sustained attention condition: presentation phase (Fig. 1E). Participants viewed an attention cue (1.5 s) instructing them to attend to either the face or place component of either the left or right images in each to-be-viewed composite pair. Next we displayed 10 composite images in succession (each preceded by a fixation cross and proceeded by a reaction time probe). All possible attention cue pairs appeared exactly twice across the eight task blocks.

Variable attention condition: presentation phase (Fig. 1G). Participants viewed a succession of 10 attention cues (1.5 s), each followed by a fixation cross (1 s), composite image (3 s), and a reaction time probe. The attention cues were selected randomly across trials within each block.

Memory phase (Fig. 1F). After the presentation phase of each task block, we asked the participant to rate the familiarity (on a 1–4 scale, as during the practice phase) of a succession of face and place images. Each image was preceded by a 1 s fixation cross, and participants had up to 2 s to input their rating of each image. Participants made a total of 40 familiarity judgements, about 20 face images and 20 place images. Of these, 20 of the images (10 faces and 10 places) were drawn randomly from the (attended and unattended) composite images that the participant had viewed during the presentation phase. The remaining 20 images (10 faces and 10 places) were novel images that the participant had not encountered during any part of the experiment. At the end of each memory phase, the participant was given the opportunity to take a short break. When they were ready to continue with the next task block, they indicated their readiness to the experimenter. The experimenter then entered the testing room, re-ran the eye tracker calibration sequence, and exited the testing room prior to the next task block.

Results

We ran a volitional covert attention experiment with two conditions; in the sustained attention condition we asked participants to *sustain* the focus of their attention over a succession of 10 stimulus presentations per block whereas in the variable attention condition we asked participants to *vary* their focus of attention with each new stimulus (also for a total of 10 stimulus presentations per block). Each stimulus comprised a pair of composite images (one on the left and one on the right side of the display), where each composite comprised an equal blend of a unique face and a unique place image. We followed the presentation phases of each experimental block with a memory phase, where participants performed a recognition memory task by rating the familiarity of previously experienced and novel face and place images (see *Experimental paradigm*, Fig. 1).

We first wondered whether (and how) shifts in covert attention might affect participants' ratings during the recognition memory task (Fig. 2). To ensure that our findings were not conflated with where people were physically looking, we excluded from further analysis any images presented during trials where the participant's gaze touched on any part of the attended composite image (see *Eye-tracking*, Figs. S1 and S2). For the remaining trials, the participants kept their gaze focused on a fixation cross at the center of the screen while *covertly* shifting the focus of their attention to the cued category component of the composite image at the cued location. In other words, during these remaining trials, participants' physical (external) experiences of the face and place components of every presented composite image remained relatively constant across trials (up to our ability to accurately measure where participants were looking using the eye tracker).

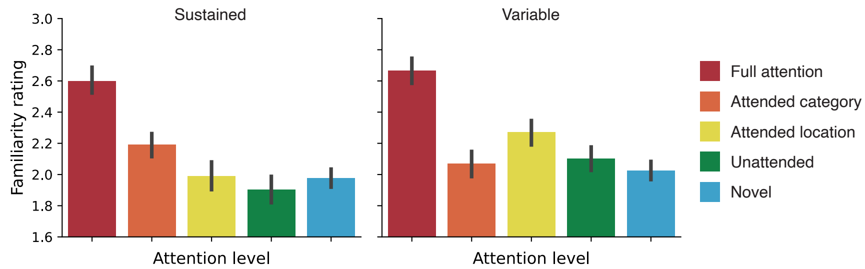

Figure 2. **Familiarity by attention level.** The bars display the average familiarity ratings participants gave to images from the same category and location as the attention cue (fully attended), the same category (but opposite location) as the attention cue (attended category), the same location (but opposite category) as the attention cue (attended location), the opposite category and location as the attention cue (unattended), or novel images. The left panel displays familiarity ratings from the sustained attention condition and the right panel displays familiarity ratings from the variable attention condition. All error bars denote across-participant bootstrap-estimated 95% confidence intervals. For results sub-divided by stimulus category, see Figure S3.

Simply by encoding their prior experiences into memory, we reasoned that participants should rate *any* presented images as more familiar than novel images, regardless of whether they were following the attention cues. We confirmed that this prediction held in both the sustained ($t(29) = 8.856, p < 0.001$) and variable ($t(22) = 5.144, p < 0.001$) conditions. In addition, to the extent that participants were following the attention cues, their *internal* experiences of each image should depend on their internal focus of attention during each image presentation. For example, we expected that the attended-category component of the composite image at the attended location might be better recognized than the other composite image components. Indeed, participants in both experimental conditions rated these "fully attended" images as more familiar than category-matched image components from unattended locations (sustained: $t(29) = 6.893, p < 0.001$; variable: $t(22) = 6.938, p < 0.001$), location-matched images from the unattended category (sustained: $t(29) = 6.710, p < 0.001$; variable: $t(22) = 7.633, p < 0.001$), unattended images that were neither from the attended category nor the attended location (sustained: $t(29) = 8.470, p < 0.001$; variable: $t(22) = 7.256, p < 0.001$), or novel images they had never seen before (sustained: $t(29) = 10.259, p < 0.001$; variable: $t(22) = 7.874, p < 0.001$).

We also wondered whether the ways participants attended to or remembered the images might depend on image-specific properties like the images' categories. We repeated the analysis displayed in Figure 2 separately for face and place images (Fig. S3). The same general patterns reported above also held for each stimulus category individually. For example, fully attended face and place images were both rated as more familiar than the category-matched images from the unattended location (sustained: ts$(29) \geq 3.366$, ps ≤ 0.002; variable: ts$(22) \geq 4.773$, ps ≤ 0.001), attended-location images from the unattended category (sustained: ts$(29) \geq 5.886$, ps ≤ 0.001; variable: ts$(29) \geq 4.277$, ps ≤ 0.001), images from the unattended category and location (sustained: ts$(29) \geq 6.628$, ps ≤ 0.001; variable: ts$(29) \geq 5.624$, ps ≤ 0.001), and novel images (sustained: ts$(29) \geq 5.987$, ps ≤ 0.001; variable: ts$(29) \geq 5.132$, ps ≤ 0.001). Taken together, the above results suggest that what we remember is guided in part by what we attended to, even after accounting for where we look or what specifically we are looking at.

Splitting participants' responses to face versus place images also revealed that participants often rated attended (and partially attended) place images as more familiar than attention-matched face images (compare dark versus light bars in Fig. S3). We hypothesized that this might be explainable by some property of the relevant cognitive processes or by properties of the stimuli themselves. To help elucidate this distinction, we examined individual exemplars of the face and place images used in our paradigm (Fig. 3A). By design, the face images had consistent head sizes, viewing angles, expressions, and so on. In contrast, the place images varied more substantially across images. For example, some place images depicted human-made structures; others depicted natural scenes; some depicted indoor views; others depicted outdoor views; etc. This can also be seen by averaging the pixel intensity values across images, separately for the face and place stimuli (Fig. 3B). Whereas the average face image retains many of the landmarks characteristic of most faces (e.g., clearly defined hair, eyes, nose, mouth, head shape, etc.), the average place image does not show place-specific features as clearly, aside from a general tendency for the tops of place images to be lighter than the bottoms of place images. We also computed the pairwise similarities across images from each stimulus category (Fig. 3C) and found that face images tended to be much more similar to each other than place images (Fig. 3D; $t(115258) = 254.764, p < 0.001$). This analysis indicated to us that our experimental paradigm was not well-suited to identifying cognitively meaningful stimulus category differences, since participants' category-specific judgements may be confounded with within-category image similarity differences.

Next, we turned to identifying potential differences in participants' behaviors across the two experimental conditions. The main difference between the conditions' procedures was in how long participants were asked to maintain the same focus of category-based and location-based attention, across successive image presentations. Therefore, differences in participants' behaviors across the two conditions might reflect differences in the timescales of the relevant cognitive processes. We compared participants' familiarity ratings for images at each attention level across the two conditions. We saw no evidence that people rated fully attended images ($t(51) = -0.649, p = 0.519$), attended-category (but not location) images ($t(51) = 1.163, p = 0.250$), or novel images ($t(51) = -0.435, p = 0.665$) differently across the two conditions. However, participants in

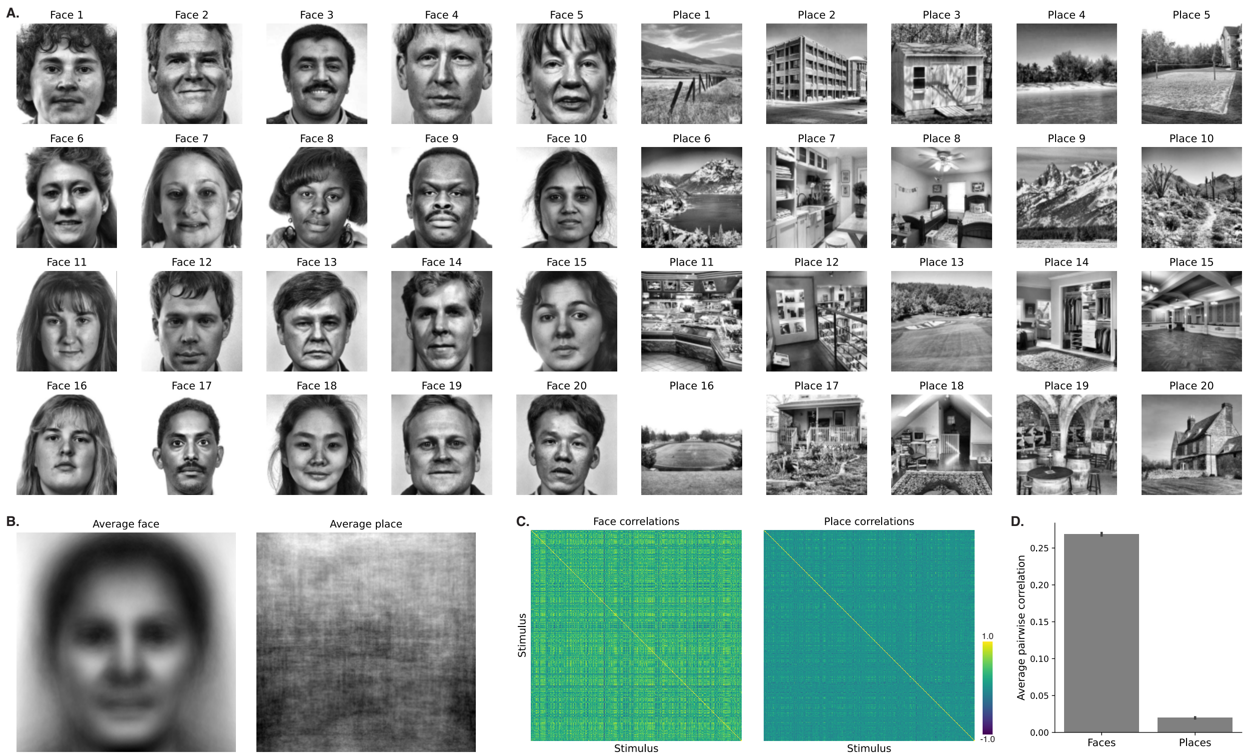

Figure 3. **Stimulus examples and properties. A. Example images from each stimulus category.** Randomly chosen subsets of 20 face images (left) and 20 place images (right) are displayed. **B. Across-image averages.** Each panel displays the average image, taken across all 360 face images (left) and 360 place images (right). **C. Pairwise correlations.** Each row and column of the matrices displays the correlation (across pixels) in intensity values for one pair of face images (left) or place images (right). **D. Average pairwise correlations.** The bar heights denote the average pairwise correlations between face and place images. Error bars denote across-pair bootstrap-estimated 95% confidence intervals.

the variable attention condition rated attended-location (but unattended category) images as more familiar than participants in the sustained attention condition ($t(51) = 2.174, p = 0.034$). We found a trending effect for unattended category and location images, whereby participants in the variable attention condition tended to rate these images as more familiar than participants in the sustained attention condition ($t(51) = 1.600, p = 0.116$). We also observed some within-condition differences in how participants rated partially attended versus novel images. In the sustained attention condition, participants rated attended-category images at the unattended location as more familiar than novel images ($t(29) = 6.205, p < 0.001$), but participants in the variable attention condition did not show this pattern ($t(22) = 1.042, p = 0.309$). On the other hand, whereas participants in the sustained attention condition showed no reliable differences in familiarity between attended-location images from the unattended category and novel images ($t(29) = 0.165, p = 0.870$), participants in the variable attention condition rated attended-location images as more familiar than novel images ($t(22) = 3.026, p = 0.006$). Taken together, our analyses highlight several familiarity differences in partially attended images from the attended category or at the attended location across the two experimental conditions. These differences suggest that the aspects of category-based versus location-based attention that affect how people remember what they attend operate over different timescales.

Given the above results suggesting potential differences in the timescales of category-based and location-based attention, we carried out two additional exploratory analyses aimed at identifying other timing effects. First, we wondered whether participants' familiarity ratings might show serial position effects analogous to those reported in classic recognition memory studies (e.g., McElree & Dosher, 1989; Neath, 1993; Wickelgren & Norman, 1966). For each participant, for each composite image pair (presented in each trial during the study phase of the experiment), we labeled each composite's face and place image component according to whether it matched the cued category and/or location. We discarded any face or place images that did not appear in the participants' memory phases. We tagged the remaining (probed) images with the familiarity ratings that participants would later give the images during the memory phase and plotted these ratings against the images' presentation positions (Figs. 4A and B). Across both experimental conditions and across all serial positions, we generally found that the average ordering of familiarity ratings by attention level (Fig. 2) were preserved. This suggests that the encoding-related affects of attention on subsequent recognition memory are relatively stable over time (e.g., we did not observe clear primacy or recency effects during the study phase of the experiment). Second, we carried out an analogous analysis to identify potential serial position effects of recall order. For each probed item a participant rated during the memory phase, we assigned the image a label according to whether the participant's attention cue (at the time the image was presented as part of its composite pair) matched the image's category and/or location, or

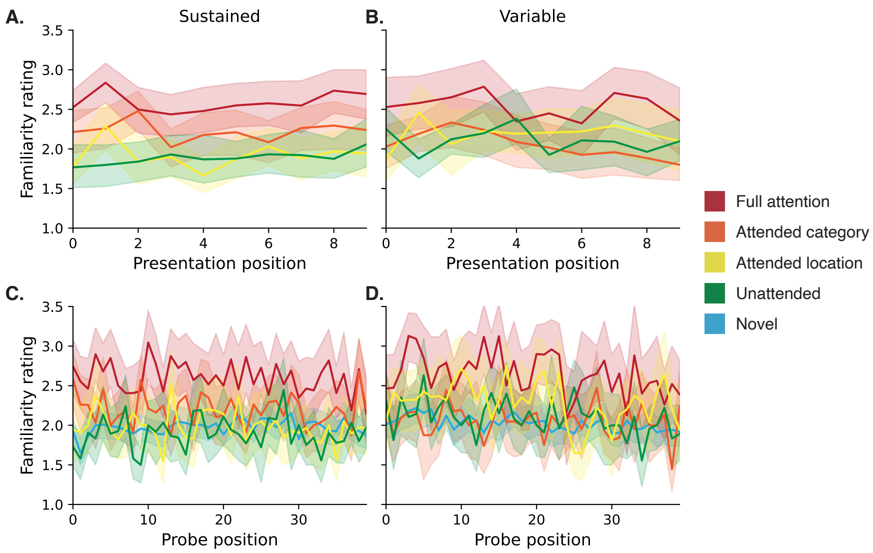

Figure 4. **Familiarity ratings by serial positions and attention level. A. Subsequent familiarity ratings by presentation position (sustained attention condition).** The curves' colors denote the attention levels of each presented image. The x-axis denotes the presentation positions of each image within the sequence of 10 composite image pairs during the run when it was presented. The y-axis denotes the average familiarity ratings later given to the corresponding items. **B. Subsequent familiarity ratings by presentation position (variable attention condition).** This panel is in the same format as Panel A, but displays ratings for the variable attention condition. **C. Familiarity ratings by memory probe position (sustained attention condition).** The curve's colors denote the attention levels (or novelty) of each probe image. The x-axis denotes the position of each probed image within the sequence of 40 images that participants judged during the memory phase of the experiment. The y-axis denotes the average familiarity ratings given to the corresponding probes. **D. Familiarity ratings by memory probe position (variable attention condition).** This panel is in the same format as Panel C, but displays ratings for the variable attention condition. All panels: error ribbons denote across-participant bootstrap-estimated 95% confidence intervals.

whether the image was novel (i.e., not presented during the study phase). Again, we found that (across both experimental conditions and all probe positions) in general the average ordering of familiarity ratings by attention level (Fig. 2) were preserved. This suggests that the retrieval-related affects of attention on subsequent recognition memory are relatively stable over time (e.g., we did not observe clear primacy or recency effects during the memory phase of the experiment).

Our finding that location-attended items appear to receive a familiarity boost in the variable attention condition but not the sustained attention condition is consistent with two possible interpretations. One possibility is that focusing attention requires just a brief trigger (in this case, an attention cue), but different forms of attention (in this case, category-based attention versus location-based attention) require different amounts of time to "ramp up" to full efficacy such that they begin to affect memory encoding. For example, if category-based attention ramps up more slowly than location-based attention, this might explain why the relative ordering of category-matched versus location-matched unattended images changes between the sustained attention and variable attention conditions (orange and yellow bars in Fig. 2). A second possibility is that each attention cue provides a "boost" to memory encoding for the relevant aspects of one's experience (e.g., image categories, spatial locations), but the size of the boost varies across different forms of attention. If so, the *number* of successive attention cues one receives should predict how effectively the attended and partially attended images are encoded. We developed a sequence length analysis to distinguish between these possibilities. For each probed (target) image that had been presented as a composite image pair, we computed the number of matching attention cues the participant had received by the time the given images were presented (up to and including the image's composite pair). We computed these sequence lengths by defining "matching" cues in three ways: (a) a match means the cues are for the same category *and* location, (b) a match means that the cues are for the same category, and (c) a match means that the cues are for the same location. This yielded, for each target image, an associated count of how many successive matching attention cues the participant had received up to and including that image's presentation. As shown in Figure S4, we used linear regressions of familiarity ratings on sequence lengths to identify potential sequence length effects. For both experimental conditions, all attention levels, and for all three approaches to defining matching cue sequence lengths, we found virtually no reliable associations between cue sequence length and familiarity. This finding is most parsimonious with the first possibility mentioned above– i.e., that attention may be guided by a brief trigger, but that different forms of attention may take differently long to affect memory encoding.

Finally, we wondered whether participants' familiarity ratings might be influenced in part by response bias effects. For example, a participant who had recently received an "attend to face images" cue might rate even a novel face image as more "familiar" if they leveraged their memory of the attention cue (as opposed to solely relying on their memories of the composite images they studied) to help guide their familiarity ratings. Indeed, participants in the sustained attention condition do show some response biases. For example, participants tended to rate novel images as more familiar if they came from the just-cued category versus the unattended category (Fig. S5A; $t(29) = 4.371, p < 0.001$). Responses biases are more difficult to evaluate in the variable attention condition. For example, should cue recency be defined as the number studied composite image pairs that came between the image whose familiarity the participant is judging and the most recent same-category cue (i.e., temporal distance to the nearest same-category attention cue)? Or might response biases instead arise when a given category is cued more often near the end of the just-studied list? We assigned each probed image a label based on these two measures of category-matched cue recency. We then used linear regressions of familiarity ratings on these recency measures to identify potential response biases (Fig. S5B). Altogether we found no evidence that participants in the variable attention condition tended to rate images as more familiar solely due to how recently they had received a same-category attention cue.

Discussion

We ran a covert attention experiment with two conditions that asked participants to sustain or vary the focus of their covert attention, respectively. We then administered recognition memory tests that asked participants to rate the "familiarity" of attended, unattended, and novel images. In our analyses, we used eye-tracking data to focus in on trials where participants were specifically varying their focus of *covert* attention (i.e., with no change in where they were looking), as opposed to simply moving their eyes to look at the to-be-attended images. In both conditions, we found that participants recognized images from the attended category and location more readily than unattended or novel images. This effect was substantial and robust (in both conditions) and also held for individual image categories. Whereas prior work has focused primarily on *overt* changes in attention (e.g., changes in eye movements associated with attention cues), we show that what people *covertly* attend to also affects how they remember their ongoing experiences. Specifically, covert attention appears to boost memory encoding such that the focus of covert attention is recognized more readily later on.

We also found that partially attended images (e.g., from the attended category but unattended location, or at the attended location but unattended category) were rated as more familiar than novel images. However, these encoding benefits differed across the two experimental conditions. In the sustained attention condition, attended-category images from the unattended location were rated as more familiar than novel images, but attended-location images from the unattended category were not. Participants in the variable attention

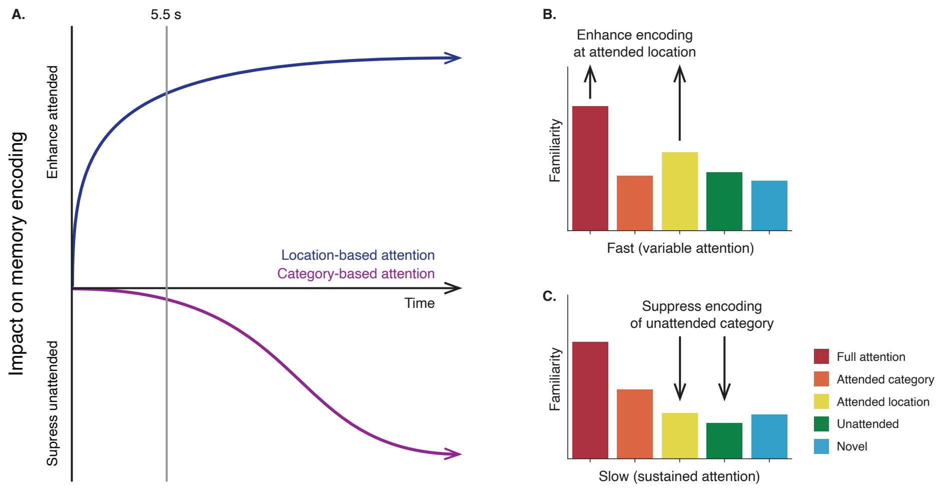

Figure 5. **How do covert location-based and category-based attention affect memory encoding? A. Hypothesized time courses of the impact of location-based and category-based attention on memory encoding.** Shifting the focus of location-based attention increases memory encoding at the attended locations (blue curve). This increase can be observed after 5.5 s (the duration of one presentation from the variable attention condition). Shifting the focus of category-based attention suppresses memory encoding for the unattended category. However, this suppression effect occurs relatively slowly (longer than the duration of a single image presentation in the experiment). **B. Location-based attention.** Focusing covert attention on one *location* enhances encoding of stimuli at the attended location (red and yellow bars), regardless of stimulus category. (This panel is based on the variable attention results presented in Fig. 2.) **C. Category-based attention.** Focusing covert attention on one *category* suppresses encoding of stimuli from the unattended category (yellow and green bars), regardless of spatial location. (This panel is based on the sustained attention results presented in Fig. 2.)

condition showed the opposite pattern. In particular, variable attention participants rated attended-*location* images from the unattended category as more familiar than novel images, but they rated attended-category images from the unattended location similarly to novel images. Because the primary difference between the sustained and variable attention conditions was the duration of participants' focus of attention, our analyses of partially attended images suggest that the effects of different aspects of attention on memory unfold over different timescales (Fig. 5). Specifically, location-based attention appears to affect memory encoding relatively quickly, which would explain why attended-location images from both the attended *and* unattended category receive a memory encoding benefit in the variable attention condition. In contrast, category-based attention appears to affect memory encoding more slowly, and it appears to operate in a "suppressive" manner (i.e., suppressing encoding of the unattended category, as opposed to enhancing encoding of the attended category). This would explain why unattended-category images at the attended location are rated as *less* familiar in the sustained attention condition.

The notion that location-based attention operates at a faster timescale than category-based attention is supported by prior work on the deployment of visual attention (Soto & Blanco, 2004; Stoppel et al., 2007). Our findings that location-based attention enhances the processing of attended stimuli whereas category-based attention suppresses the processing of unattended stimuli is also consistent with prior work on location-based attention (e.g., Itti & Koch, 2001) and category-based attention (e.g., Moher et al., 2014). Our finding that people better remember attended stimuli also follows prior work on interactions between attention and memory (Aly & Turk-Browne, 2016, 2017; Balestrieri et al., 2021; Chun & Turk-Browne, 2007; Morrison et al., 2014; Paller & Wagner, 2002; Wittig et al., 2018). Whereas much of this prior work focused on elucidating the neural basis of these interactions, our work extends these prior studies by elucidating the specific and separable behavioral impacts of location-based attention (enhancement with a fast onset) and category-based attention (suppression with a slow onset) and on subsequent recognition memory. Both of these effects persisted throughout the 2 min memory phases of both conditions. However, future work is needed to elucidate the longevity of these effects beyond 2 minutes.

Another important area for future study concerns how the flow of information between different brain structures is modulated according to the focus of volitional attention– particularly with respect to pathways from primary sensory regions (e.g., V1, A1) to regions implicated in encoding ongoing experiences into memory (e.g, medial temporal lobe structures such as the hippocampus and entorhinal cortex, prefrontal cortex, etc.). For example, several studies suggest that attention serves to modulate the *gain* of specific neural circuits (Chance et al., 2002; Eldar et al., 2013; Salinas & Thier, 2000; Treue & Trujillo, 1999), effectively facilitating or inhibiting the flow of specific neural representations (LaRocque et al., 2014; Vartanian et al., 2007). Prior work suggests that category-based attention may be supported by changes in connectivity with the thalamus (Schneider, 2011), whereas location-based attention may be supported by changes in connectivity with primary visual cortex (Noudoost et al., 2010). That category-based and location-based attention are mediated by different brain structures may explain why these different aspects of attention operate on different timescales and affect memory differently. A strong test of this hypothesis would entail directly measuring neural activity patterns as people modulate their focus of attention (e.g., using functional magnetic resonance imaging or electroencephalography), and then using neural decoding approaches (e.g., Haxby et al., 2001; Manning et al., 2018; Norman et al., 2006; Owen et al., 2021) to follow how neural representations of attended (or unattended) stimuli are transfered from primary sensory regions, to higher order sensory regions, to memory areas. If the effects of attention on memory are mediated by changes in network dynamics, the transmission rates of the representations of attended stimuli from primary sensory regions to memory areas should be facilitated relative to the transmission rates of unattended stimuli. Further, variability in these neural changes (e.g., as a participant focuses their attention with more or less success) should track with behavioral measures of memorability.

Which aspects of our ongoing experiences we choose to attend affects how we process and remember those experiences later. Different forms of attention—e.g., to specific stimulus categories or spatial locations—operate and affect memory at different timescales, and are likely mediated by different brain networks. Elucidating the behavioral and neural consequences of volitional changes in attention is central to discovering how our thoughts, feelings, goals, and situational understanding fluctuate from moment to moment.

Author Contributions

JRM and KZ developed the concept for this study. Experiment code was written by ARM and KZ, and testing and data collection were conducted by KZ and MRL. All authors contributed to analyzing the data. All authors contributed to writing and editing the manuscript. JRM supervised the project.

Data and code availability

All of the data analyzed in this manuscript, along with all of the code for running our experiment and carrying out the analyses may be found at `http://www.github.com/ContextLab/attention-memory-task`.

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