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Sustained Attentional State Is a Floodlight Not a Spotlight

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Maintaining attention to a task is essential for accomplishing it. However, attentional state fluctuates from moment to moment, and task-irrelevant information may compete for processing. What are the consequences of attentional fluctuations for what we remember? Do fluctuations in sustained attention vary the spotlight of selective attention, prioritizing task-relevant at the expense of task-irrelevant information? Or, are increases in a sustained attentional state akin to a floodlight, enhancing processing of all information, regardless of task relevance? In an online sample of 215 adults, participants were presented simultaneous streams of images and sounds and instructed to make responses based on only one modality. Afterward, recognition memory for both images and sounds was tested. Across individuals, we found no evidence of a trade-off between memory for task-relevant and task-irrelevant items. Within individuals, successful memory for a task-relevant item predicted successful memory for its task-irrelevant pair. Thus, the spotlight metaphor of attention does not extend to the dynamics of sustained attention. Rather, fluctuations in attention are more akin to a floodlight, affecting the processing of all task information, regardless of relevance.

Public Significance Statement

Selective attention is controversially characterized as a metaphorical "spotlight," enhancing information at the focus of attention and filtering irrelevant information. However, it is not clear how the scope of selective attention is affected by sustained attentional state, which fluctuates over time. We examine behavioral signatures of sustained attention and their consequences for memory and find no evidence of a trade-off, such that task-relevant items are not remembered at the expense of task-irrelevant items. Instead, we found that better memory for a task-relevant item predicts better memory for its task-irrelevant pair. These results call into question the generalizability of a spotlight metaphor of attention. Instead, they suggest that sustained attention can act as a flickering floodlight, enhancing memory for information encountered in engaged attentional states—whether or not it is relevant to a task at hand.

Keywords: sustained attention, attentional state, recognition memory, visual attention, auditory attention

Supplemental materials: https://doi.org/10.1037/xge0001769.supp

While daily tasks like commuting to work require selectively attending goal-relevant information from multiple perceptual modalities, our ability to do so fluctuates over time (Esterman et al., 2013). Previous work using visual stimuli demonstrates that the attentional state in which task-relevant information is encountered affects how it is processed and whether it is later remembered (deBettencourt et al., 2018; Decker et al., 2022; Wakeland-Hart et al., 2022). When accomplishing tasks, however, relevant information is often accompanied by information irrelevant to the task at hand. What is the fate of task-irrelevant information that is presented during

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The final data and code are publicly available on the Open Science Framework at https://osf.io/mjy7a/. This study was not preregistered. Results in this article were shared in a poster and a talk presented at the annual meeting of the Vision Sciences Society in 2023 and 2024, respectively. A preprint of this article is publicly available on the Open Science Framework at https://osf.io/preprints/psyarxiv/k9cnm_v1. Megan T. deBettencourt is an employee of and has equity in Ruby Neurotech.

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Anna Corriveau played a lead role in formal analysis and writing–original draft and an equal role in conceptualization, investigation, and methodology. Anthony R. James Jr., played an equal role in conceptualization, formal analysis, investigation, methodology, and writing–review and editing. Megan T. deBettencourt played an equal role in methodology and writing–review and editing. Monica D. Rosenberg played a lead role in funding acquisition, resources, and supervision and an equal role in conceptualization, methodology, and writing–review and editing.

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moments of engaged sustained attention? To test this, we use a novel audio–visual continuous performance task (avCPT) in which participants are presented simultaneous task-relevant and task-irrelevant information in separate auditory and visual perceptual modalities. We first validate the avCPT by testing whether sustained attention to auditory and visual information is related within individuals and can be indexed by behavioral signatures. Next, we investigate how sustained attentional state during encoding affects memory for task-relevant and task-irrelevant images and sounds. Do moments of high sustained attention sharpen selective attention's spotlight, prioritizing task-relevant information at the expense of task-irrelevant information? Or do high sustained attentional states broaden processing like a floodlight, increasing the processing of all information regardless of task relevance? The present study aims to characterize sustained attentional state and its influence on subsequent memory judgments as a function of perceptual modality and task relevance.

Visual and Auditory Attention Share Common Mechanisms

We use the avCPT to investigate the consequences of attentional fluctuations for recognition memory. Previous studies of auditory and visual sustained attention found that sustained attention ability, measured using continuous performance tasks (CPTs), is positively related within individuals across visual and auditory perceptual modalities (Seli et al., 2012; Terashima et al., 2021). Thus, the ability to maintain attention to stimuli from separate modalities seems to rely, at least partially, on some shared mechanism or process. Further, interference from auditory processing during a visual task suggests that attending auditory and visual stimuli relies on a common mechanism (Parmentier et al., 2008; although see Mandal et al., 2022). Neuroimaging studies also point to shared, modality-general neural mechanisms of sustained attention. Studies using electroencephalography demonstrate that an event-related potential component—the P300 or P3—is responsive to the detection of infrequent targets during auditory and visual oddball tasks (Katayama & Polich, 1999; Linden et al., 1999). The P300 response reflects a positive increase in activity over parietal areas, and its presence in both auditory and visual oddballs suggests that target detection in these modalities may involve a shared neural response. Functional MRI studies find further evidence that activity in the parietal lobe, particularly in the supramarginal gyrus and inferior parietal lobule as well as in areas of the frontal lobe, increases in response to visual and auditory infrequent targets (Stevens et al., 2000). Common neural mechanisms subserving vigilant attention make it possible to test the effects of sustained attention state when information is presented across perceptual modalities.

Reaction Time Measures Continuously Track Visual Sustained Attention

Classically, sustained attention was measured using vigilance tasks such as the Mackworth clock task (Mackworth, 1948), which asked participants to report rare, unusually large movements of clock hands occurring irregularly over long periods (0.5–2 hr). More recent CPTs require participants to attend to repetitive information and report deviations with the press of a button (X-CPTs, where "X" refers to the rare target requiring a response). CPTs are often designed such that the task of discriminating whether a stimulus reflects a deviation from the frequent category is not a perceptually demanding one. Rather, failure to detect a deviation can be attributed to lapses in sustained attention. However, these tasks provide a limited sampling of attentional state by requiring responses to rare targets only. This paradigm has been inverted to require responses to frequent stimuli and response inhibitions to rare targets (not-X-CPTs; Robertson et al., 1997; Rosenberg et al., 2013). The frequent-response paradigm provides nearly continuous behavioral insights into attentional state. Work measuring sustained attention to images has found that attention lapses are preceded by moments of faster and more variable reaction times (RTs; deBettencourt et al., 2018; Decker et al., 2022; Esterman et al., 2013; Rosenberg et al., 2013; Wakeland-Hart et al., 2022; Yamashita et al., 2021). Here, we test whether RT measures predict trial-to-trial sustained attention performance to both images and sounds.

Better Memory for Images Encountered in High Attentional State

How does sustained attentional state at encoding affect later memory? Previous work found that images encountered in moments of high sustained attention (indexed by slower or less-variable RTs) are better recognized (deBettencourt et al., 2018; Decker et al., 2022; Wakeland-Hart et al., 2022). Does sustained attentional state similarly affect memory for sounds? Further, if images and sounds are presented simultaneously, does an engaged attentional state enhance the spotlight nature of selective attention, processing the task-relevant stimulus while filtering the task-irrelevant one? Or, are moments of high sustained attention more analogous to a floodlight, increasing processing for all information, including information outside of selective attention's spotlight? Selective attention is indeed well-characterized by a spotlight analogy, such that stimuli in the focus of attention are processed and prioritized over stimuli outside the spotlight or irrelevant stimuli (Norman, 1968; Posner, 1980). However, it is less clear how fluctuations in sustained attentional state affect selection in a task wherein task-irrelevant stimuli are presented in a separate perceptual modality. Do increases in sustained attentional state enhance filtering, resulting in lower memory for irrelevant stimuli? Alternatively, increased attentional capacity afforded by increases in sustained attentional state may lead to enhanced processing and memory of irrelevant stimuli. Evidence for this alternative comes from work by Esterman et al. (2014), which showed increased processing of irrelevant distractor images during successful "in-the-zone" relative to unsuccessful "out-of-the zone" sustained attentional states.

Another related framework comes from perceptual load theory, which posits that task-irrelevant stimulus processing during selective attention tasks varies as a function of perceptual task load (Lavie, 1995). Under this theory, spare attentional capacity from conditions of low perceptual load may allow for greater processing of task-irrelevant information resulting in memory for irrelevant stimuli (Lavie et al., 2009). Conditions of high perceptual load, however, resulted in lower processing and poor explicit memory for irrelevant stimuli (Butler & Klein, 2009; Rees et al., 1999). Importantly, careful methodology demonstrates that irrelevant stimuli are indeed processed and remembered (Butler & Klein, 2009; Hutmacher & Kuhbandner, 2020; Kuhbandner et al., 2017; Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005). These results suggest that the mnemonic fate of irrelevant stimuli is related to the amount of processing during encoding. In the present study, task load—that is, selection demands—remains constant throughout a session. Instead, we ask how memory for irrelevant stimuli changes when processing varies not as a function of task load itself but instead as a function of fluctuating sustained attentional state throughout the task. The present study compares sustained attention and its consequences for recognition memory across auditory and visual perceptual modalities. We present results from a CPT during which participants are presented with sounds and images simultaneously but are instructed to make a response based on one modality, ignoring the other. To test consistency across modalities and participants, we utilized a within-subjects design in which participants performed the task over two sessions, one in which sounds were the relevant category and one in which images were the relevant category, counterbalanced across participants. Following the task, we tested memory for a randomly selected subset of the task-relevant and task-irrelevant images and sounds. Results demonstrate that sustained attention performance and rate of RT speeding are traitlike within individuals. Additionally, while both pretrial RT speed and variability predict upcoming lapses in sustained attention for both visual and auditory stimuli, RT variance predicts recognition memory for images only. Finally, we find support for a floodlight view of attentional state, such that stimulus pairs are remembered or forgotten together, regardless of task relevance.

Method

Data Collection and Exclusion Criteria

Data were collected following protocols approved by the University of Chicago's Institutional Review Board. Participants were recruited via the online platform Prolific (https://www.prolific.com/) to participate in a within-subject study that took place in two parts. Sessions were completed on separate days (mean time between sessions = 5.91 days, *SD* = 6.05 days), with each session lasting approximately 28.2 min (*SD* = 10.4 min). Participants who completed Session 1 were invited to return for a second session via Prolific messaging at least 24 hr after the initial session. Participants were compensated $9.75/hr for their time and received a $2 bonus for completing both study sessions. Experimental code was written using jsPsych (de Leeuw, 2015) and implemented via psiTurk (Version 3.2.1; Eargle et al., 2020; Gureckis et al., 2016).

Two hundred twenty-seven participants completed at least one online session during which they performed a task designed to test visual or auditory sustained attention (192 completed a visual session, 179 completed an auditory session). Exclusions were made to ensure that online participants were following task instructions and performed the task continuously without leaving their computer. All exclusions were conducted prior to confirmatory analyses. Participants who responded to fewer than half of all CPT trials (successful task performance requires key presses to 90% of trials) or who failed an attention check were not included in analyses (five participants were excluded in the visual session, three participants were excluded in the auditory session). Additional participants were excluded from analyses if performance on the avCPT (A') was more than 2.5 *SD* below the group mean task performance (six excluded in the visual condition, nine excluded in the auditory condition) or if participants were shown repeat stimuli due to experimenter error (four excluded in the visual condition, 24 excluded in the auditory condition). Participants were asked to report their biological sex at birth from a multiple-choice menu with the following options: male, female, intersex, none of these describe me, choose not to respond. They also provided their gender from the following options: man, woman, nonbinary, other, and choose not to respond. We report biological sex information here. The final sample included 215 participants (ages 18–35, 111 females, 103 males, one chose not to respond) in total: 177 participants in the visual condition, 143 participants in the auditory condition, and 105 participants who completed both sessions of the experiment. Of these 105 participants, 49 completed the auditory task, and 56 completed the visual task in Session 1.

Counterbalancing of stimulus presentation by task-relevant modality order and stimulus frequency resulted in eight possible conditions. We aimed for a sample of 104 participants (13 per condition) who completed both sessions. However, due to participant dropout between sessions, data collection continued until at least 13 participants completed each condition, resulting in some conditions containing more than 13 participants. A power analysis confirms that the final sample is greater than the minimal sample size required to achieve sufficient power ($1 - \beta = .8$) and significance level ($\alpha = .05$) for a multiple linear model with a fixed effect of attentional state (preceding RT slope = .18; Wakeland-Hart et al., 2022) on memory, that is, 46 participants.

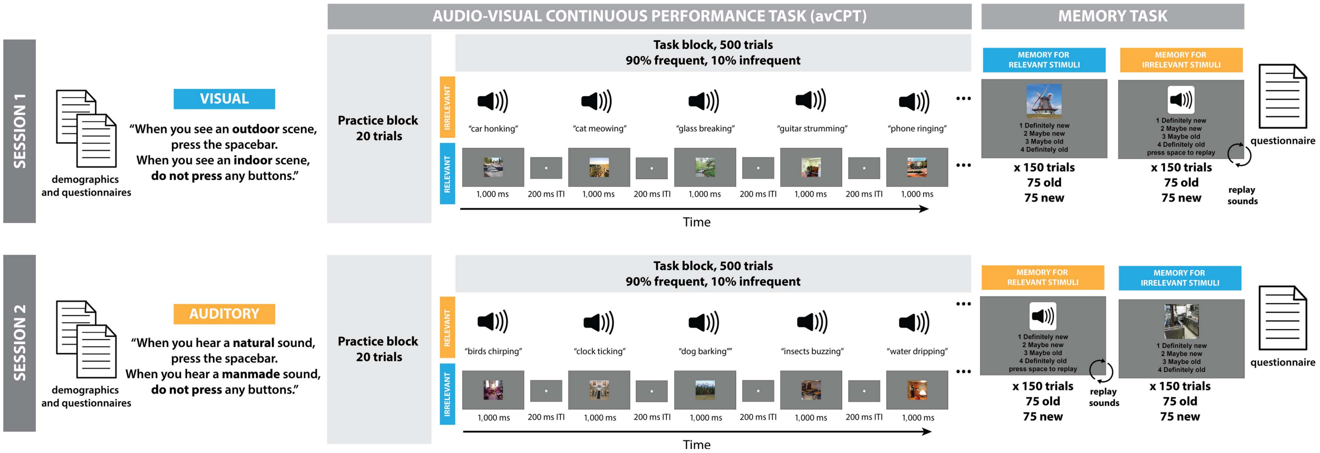
avCPT

To measure sustained attention performance in both auditory and visual domains, participants performed an avCPT (Figure 1). During the task, images and sounds were presented simultaneously for 1,000 ms, followed by a 200 ms intertrial interval. Participants were instructed to respond to either images or sounds. They were told that the stimuli in the task-irrelevant modality would not be important for the task but that computer volume should remain on and eyes should remain open to receive compensation.

The task-relevant modality was counterbalanced across sessions, such that participants were randomly assigned to either the auditory or visual condition during Session 1 and the opposite condition during Session 2. To familiarize participants with the task, a 20-trial practice task was provided at the start of each session, followed by performance feedback. Participants then completed the full 10-min task (500 trials). After the avCPT, as an attention check, participants were asked to indicate the types of stimuli they were presented throughout the task (e.g., indoor and outdoor scenes) in a multiple-choice format.

Both auditory and visual stimuli contained a frequent category (indoor or outdoor scene images for visual stimuli, natural or manmade sounds for auditory stimuli) that was presented on 90% of trials. Infrequent-category stimuli were presented on the remaining 10% of trials. During the auditory session, participants were instructed to respond to sounds and ignore the images. During the visual session, participants were instructed to respond to images and ignore the sounds. Participants were told to press the spacebar for every stimulus in the frequent category of the task-relevant modality and withhold a button press for infrequent-category stimuli. Each stimulus presentation contained a black fixation dot, which turned gray when the spacebar was pressed to indicate a response had been

Figure 1
Study Design



Note. Participants were invited to complete two online behavioral sessions, each consisting of an auditory–visual continuous performance task followed by a recognition memory task. During the avCPT, participants were randomly assigned to respond to auditory stimuli during Session 1 and visual stimuli during Session 2 or vice versa. Participants were then tested on recognition memory for both task-relevant and task-irrelevant stimuli presented during the avCPT using a 4-point scale. ITI = intertrial interval; avCPT = audio–visual continuous performance task. See the online article for the color version of this figure.

made. Frequent and infrequent categories were counterbalanced between sessions such that frequent categories during Session 1 served as infrequent categories during Session 2. Additionally, stimuli were trial-unique across both sessions, such that no image or sound was repeated across either session.

Stimulus Set Creation

Visual stimuli were naturalistic scene images drawn from the SUN397 image database (Xiao et al., 2010). Images belonged to one of two scene categories—indoor or outdoor scenes. To create a rich and diverse image stimulus set, images were drawn from 50 subcategories for both indoor (e.g., auditorium, kitchen) and outdoor (e.g., gazebo, skatepark) categories. Scene images were cropped to be square. Images were excluded if they included human figures, unusual borders, obvious photograph enhancement or editing, or category ambiguity (i.e., did not clearly belong to either the indoor or outdoor category). The resulting visual stimulus set included 1,481 indoor images and 1,420 outdoor images.

Auditory stimuli were drawn from online data sets for sounds (https://animal.memozee.com/; ESC-50, Piczak, 2015; https://www.freesoundeffects.com/; Google AudioSet; https://mixkit.co/; https://www.zapsplat.com/) and curated to belong to one of two categories—natural or manmade. The natural category consisted of 21 experimenter-determined subcategories (e.g., dogs barking, water flowing), while the manmade category was made up of 35 subcategories (e.g., musical instruments, car revving). Sound clips were cropped to be 1,000 ms in length. Sounds were curated to be unique from other sounds, nonhuman, and easily distinguishable as natural or manmade. A total of 600 natural and 605 manmade sounds were included in the final auditory stimulus set.

For stimuli to be trial-unique across sessions, a minimum of 593 stimuli were required per modality (auditory and visual) and category (natural/manmade, indoor/outdoor). This number corresponds to the number of stimuli required when a category was the frequent category (450 CPT trials, 50 memory foil images), stimuli for when the category was the infrequent category (50 CPT trials, 25 memory foil images), and an additional 20 stimuli (18 when the category was frequent and two when the category was infrequent) for a 20-trial practice CPT at the start of both sessions. Visual stimuli were curated from a large existing database, and, therefore, as many images as possible were used from the image categories selected. Auditory stimuli were curated by hand so stimulus collection stopped when enough unique sounds were found. As a result, there is an imbalance in the probability that an individual was presented with any given stimulus between visual and auditory stimulus sets. We do not expect this imbalance to affect current results. However, stimulus culling could be performed to balance presentation probability for future studies.

Recognition Memory Task

Following the avCPT, participants were tested for recognition memory of the stimuli presented. Recognition for stimuli in the task-relevant modality (i.e., visual or auditory) was tested first, followed by recognition for the task-irrelevant modality. The memory tasks for task-relevant and irrelevant stimuli included 150 trials each (75 old, 75 new). For each task, memory stimuli consisted of 25 old (i.e., previously seen/heard) stimuli from the frequent category, 25 old stimuli from the infrequent category, 25 stimuli that had been paired with the infrequent category of the opposite modality (always from the frequent category of the modality being tested), and 75 foil stimuli.

Participants reported confidence in their recognition memory on a scale of 1 to 4 (1 = *definitely new*, 2 = *maybe new*, 3 = *maybe old*, 4 = *definitely old*). The memory task was self-paced such that trials ended after a memory judgment was made. However, memory trials timed out if no response was made within 20 s to prevent participants from pausing the task and resuming after an extended period of time. Timed-out trials were not included in analyses.

Images remained on the screen until a memory judgment was made. Sounds were presented at the onset of the trial, and participants were able to replay sounds as many times as needed before making a memory judgment. On average, participants replayed a small number of relevant ($M = 2.38$; $SD = 5.01$) and irrelevant sounds ($M = 2.95$; $SD = 6.10$), and replay was not related to memory for sounds.

Questionnaires

After consenting to participate in each session, participants also completed two surveys, the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) and 10-item Perceived Stress Scale (S. Cohen & Williamson, 1988). The PANAS asks participants to report their mood in the current moment by rating a series of 10 positive and 10 negative affect items on a 5-point scale ranging from *very little or not at all* to *extremely*. PANAS results reflect both positive and negative affect state-level scores for each participant. The Perceived Stress Scale survey quantifies trait-level stress and asks about participants' thoughts and experiences over the month prior to completing the survey. Finally, to measure potential changes in affect following the task, participants completed a second, identical PANAS survey at the end of each session. These data are not analyzed here.

Analysis

Overall avCPT performance in each session was quantified using the signal detection theory measure of sensitivity, A′, calculated using the following formula (Equation 1; Grier, 1971):

$$\begin{aligned} &\text{if hit} > fa,\ \text{A}' = \frac{1}{2} + \frac{(\text{hit} - fa) \times (1 + \text{hit} - fa)}{4 \times \text{hit} \times (1 - fa)} \\ &\text{if} f\,a > \text{hit},\ \text{A}' = \frac{1}{2} - \frac{(fa - \text{hit}) \times (1 + fa - \text{hit})}{4 \times fa \times (1 - \text{hit})} \end{aligned} . \quad (1)$$

A′ provides a nonparametric measure of sensitivity that can be compared against chance-level performance, where chance is 0.5. The change in sustained attention over the course of the avCPT in each session, or the vigilance decrement, was measured as the linear slope of the RT time course across a session. This measure quantifies RT speeding over the CPT, indicating the extent to which pressing became faster and less deliberate.

Higher frequency changes in sustained attentional state were characterized using two RT measures: RT speed (deBettencourt et al., 2018) and variance (Esterman et al., 2013). RT speed was calculated over three preceding correct frequent-category trials, with faster RTs indicating more automatic, less deliberate, and less attentive responses. If any of the three preceding trials was a commission or omission error, that trial was not included in the calculation of the average pretrial RT and RT variance. In some cases, this led to the pretrial RT measures being calculated as the average of two preceding trials or a single trial. However, reanalysis of the data using only trials with three preceding correct frequent-category trials confirmed that effects are largely unaffected by this analytical decision. Model results from this alternative analysis are included in Supplemental Table 1.

RT variance was calculated from each session's variance time course (VTC; Esterman et al., 2013; Rosenberg et al., 2013) values of the three preceding correct frequent-category trials. The VTC is calculated as the absolute difference of each RT from the median RT divided by the standard deviation of the RT time course. Only RTs from correct, frequent-category trials were used to calculate the VTC. It quantifies periods of low RT variability, indicating "in-the-zone" attentional states and periods of highly variable, "out-of-the-zone" attentional states. Both measures were calculated using the detrended RT time course for correct presses to account for linear drift in RT over each run.

Recognition memory for old stimuli was tested using a confidence rating from 1 to 4. In line with previous work, memory was considered correct when participants reported a stimulus was "definitely old" (i.e., a rating of 4; Corriveau et al., 2024; deBettencourt et al., 2018; Decker et al., 2022; Kim, 2013; Wagner et al., 1998; Wakeland-Hart et al., 2022) based on work showing that guessing constitutes a large proportion of low-confidence memory reports (Turk-Browne et al., 2006). For new stimuli, a report that the stimulus was "definitely old" was considered incorrect, while any other response was considered correct. Thus, a confident memory judgment is required to make both a hit and a false alarm. Overall performance on the recognition memory tasks was also measured as sensitivity, or A′. In rare cases wherein hit rates and false alarm rates during a memory task were both zero, values were adjusted to the equivalent of a hit and false alarm to a half trial to ensure the resulting A′ is a real number. In the current context, this always resulted in an A′ of 0.5, or chance. All main analyses were determined a priori. However, alternative analyses are included to confirm that results are robust to analysis decisions.

For all correlation analyses, Spearman's rank correlation values are used to minimize the potential effects of outliers in the data. Statistical models were constructed using the *lme4* package in R (Bates et al., 2015). For analyses comparing individual differences between auditory and visual sessions, the sample ($N = 105$) of participants who completed both sessions is used. For all other analyses, full samples (visual $N = 177$; auditory $N = 143$) are used to maximize power.

Transparency and Openness

Data, experiment code, and analysis code are publicly available on the Open Science Framework at https://osf.io/mjy7a/. This study was not preregistered.

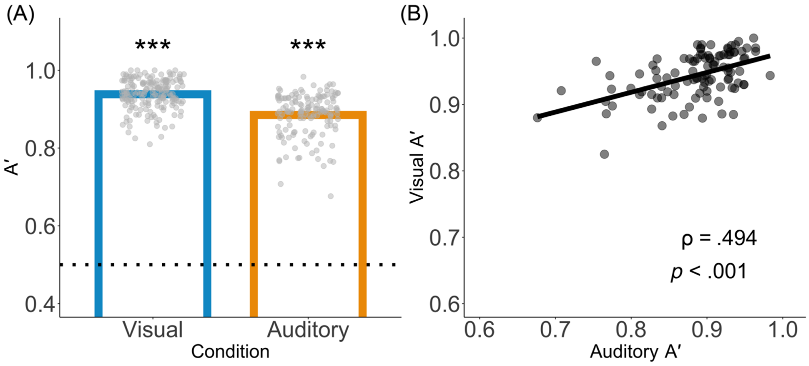
Results

CPT Performance and Attention Signatures Are Consistent Across Perceptual Modalities

We first tested whether the avCPT is a valid test of sustained attention and can therefore be used to explore the consequences of sustained attention on memory across perceptual modalities. Demonstrating compliance, mean avCPT A′ was significantly above chance for both auditory, $M = 0.885$, $SD = 0.056$, 95% confidence interval (CI) [.876, .894], $t(142) = 82.83$, $p < .001$, Cohen's $d = 6.93$, and visual, $M = 0.938$, $SD = 0.039$, 95% CI [.933, .944], $t(176) = 147.99$, $p < .001$, Cohen's $d = 11.12$, task sessions (Figure 2A). Although these values are inflated based on exclusion criteria requiring participants' avCPT A′ values fall within 2.5 *SD* from mean performance, mean avCPT A′ values were still above

Figure 2

Sustained Attention Performance



Note. (A) Average session-level continuous performance task (CPT) performance across participants was above chance (0.5). (B) Run-wise memory accuracy related across participants for auditory and visual runs. Translucent gray points reflect individual participants' memory performance quantified as sensitivity (A′). See the online article for the color version of this figure.

*** $p < .001$.

chance prior to removal of low-performing participants, auditory: $M = 0.869$, $SD = 0.085$, 95% CI [.857, .882], $t(175) = 57.20$, $p < .001$; visual: $M = 0.931$, $SD = 0.053$, 95% CI [.923, .939], $t(186) = 110.27$, $p < .001$. We next tested within-task reliability by correlating A′ on odd and even trials within auditory and visual sessions in participants who completed both sessions. Performance was reliable in both auditory (Spearman's $\rho = .738$, $p < .001$) and visual (Spearman's $\rho = .683$, $p < .001$) sessions. A linear model revealed that avCPT performance was higher during visual sessions ($\beta = .055$, $SE = 4.31 \times 10^{-3}$, $p < .001$), even after controlling for session number that did not predict avCPT performance in this model ($\beta = -4.79 \times 10^{-3}$, $SE = 4.40 \times 10^{-3}$, $p = .278$). Hit rates on the avCPT were high for both auditory ($M = 0.938$, $SD = 0.055$, 95% CI [.929, .948]) and visual ($M = 0.990$, $SD = 0.022$, 95% CI [.987, .994]) sessions, and false alarm rates were within the typical range for both auditory ($M = 0.336$, $SD = 0.145$, 95% CI [.312, .360]) and visual ($M = 0.229$, $SD = 0.139$, 95% CI [.208, .249]) sessions, based on previous work (Esterman et al., 2013; Rosenberg et al., 2013).

Next, to test whether sustained attention performance was consistent between auditory and visual sessions, we calculated Spearman's rank correlation of A′ values between sessions across participants. For participants who completed both sessions ($n = 105$), auditory and visual A′ was significantly related (Spearman's $\rho = .494$, $p < .001$; Figure 2B), aligning with prior work suggesting that sustained attention ability is consistent across auditory and visual modalities (Seli et al., 2012; Terashima et al., 2021). Hit rates (Spearman's $\rho = .282$, $p = 3.56 \times 10^{-3}$) and false alarm rates (Spearman's $\rho = .468$, $p < .001$) were significantly correlated between sessions, suggesting that pressing tendency is consistent within individuals.

We finally tested whether participants' vigilance decrement during the avCPT was related between auditory and visual sessions. Vigilance decrement was quantified as the slope of the RT time course over each avCPT session. RT time course slopes were positively related (Spearman's $\rho = .232$, $p = .017$) such that individuals with a smaller decrement in the visual run were likely to have a smaller decrement in the auditory run. This suggests that individuals' decreases in sustained attention is traitlike, regardless of sensory modality. However, vigilance decrements were not related to overall A′ in auditory (Spearman's $\rho = .124$, $p = .141$) or visual (Spearman's $\rho = -.038$, $p = .613$) runs, suggesting that the rate of RT speeding is not reflective of overall performance.

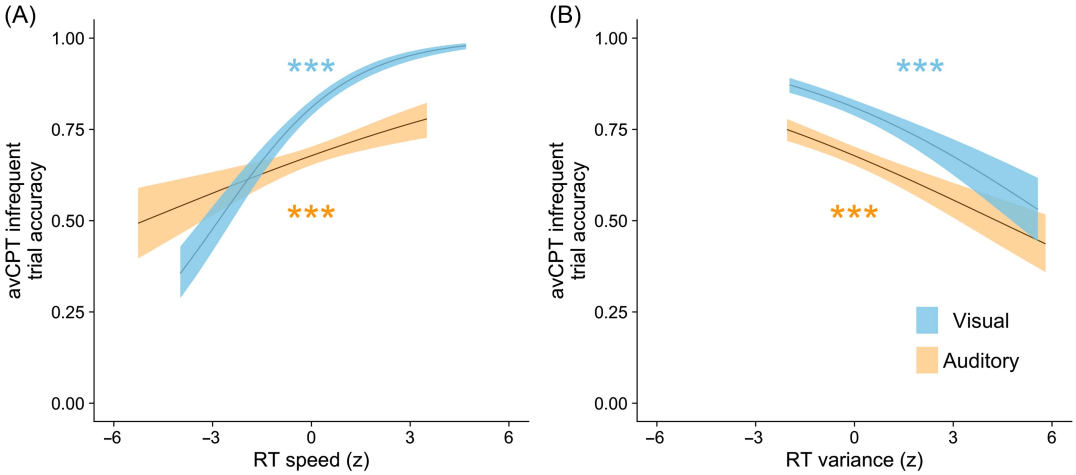
RT Measures Predict Lapses in Sustained Attention

While these results suggest that aspects of overall sustained attention performance are stable, we know that attentional state fluctuates within an individual over time and is reliably indexed by transient changes in RT during visual CPTs (deBettencourt et al., 2018; Decker et al., 2022; Esterman et al., 2013; Rosenberg et al., 2013; Wakeland-Hart et al., 2022). Do these indicators of attentional state predict lapses during both auditory and visual CPTs? We tested whether RT speed and variance during the three trials preceding infrequent stimuli predicted correctly withheld responses. RT speed was calculated from the linearly detrended RT time course using the three trials preceding infrequent, task-relevant stimuli. RT variance was calculated using the unsmoothed VTC for these three preceding trials. On average, within-subject pretrial RT speed and variance were positively, but not perfectly, correlated in auditory sessions (mean Spearman's $\rho = .097$, $SD = 0.233$, 95% CI [.058, .135]) and visual sessions (mean Spearman's $\rho = .247$, $SD = 0.231$, 95% CI [.213, .281]), suggesting that they are not redundant and thus may explain unique variance in sustained attentional state. For both auditory and visual sessions, we constructed a model of performance on infrequent, task-relevant CPT stimuli with fixed effects for RT, RT variance, and their interaction. We included subject-level random intercepts in all models, replicating previous work (Wakeland-Hart et al., 2022). However, results are similar if models include random slope effects. The fixed effects of RT and RT variance are visualized in Figure 3.

Replicating previous work in the visual domain (deBettencourt et al., 2018; Wakeland-Hart et al., 2022), RT during the three trials

Figure 3

Fixed Effects of Pretrial RT Speed (A) and Variance (B) on Continuous Performance Task Performance



Note. This model included predictors for pretrial RT, pretrial RT variance, and their interaction, as well as a random intercept term for individual subjects. Slower and less variable RTs were related to better performance on infrequent avCPT trials. Shaded areas reflect 95% confidence intervals. avCPT = audio–visual continuous performance task; RT = reaction time. See the online article for the color version of this figure.
$^{***}p < .001$.

preceding infrequent, task-relevant stimuli predicted whether a response was correctly withheld in both visual ($\beta = .513$, $SE = .038$, $p < .001$) and auditory ($\beta = .147$, $SE = .036$, $p < .001$) sessions, such that lapses were preceded by faster RTs in both. RT variance also predicted correctly withheld presses in both visual ($\beta = -.238$, $SE = .030$, $p < .001$) and auditory ($\beta = -.172$, $SE = .027$, $p < .001$) runs, with lower variance preceding correctly withheld responses and higher variance preceding lapses. The interaction of pretrial RT speed and variance was significant in visual sessions ($\beta = -.065$, $SE = .020$, $p = 1.01 \times 10^{-3}$), but not auditory sessions ($\beta = -.016$, $SE = .021$, $p = .430$). In combination, these results demonstrate that behavioral signatures of sustained attention previously characterized in visual CPTs explain unique variance in both visual and auditory sustained attention performance.

No Evidence of a Memory Trade-Off for Relevant and Irrelevant Items

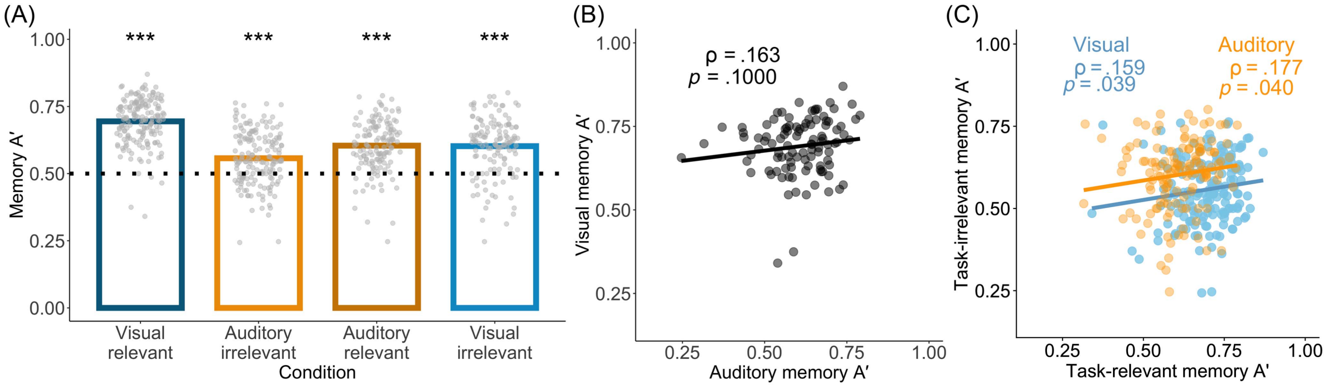
We next evaluated recognition memory performance for task-relevant and task-irrelevant stimuli in both sessions. Mean performance (A′) on the memory task was above chance for images and sounds, regardless of whether stimuli belonged to the task-relevant modality, auditory: $M = 0.603$, $SD = 0.095$, 95% CI [.587, .618], $t(142) = 12.87$, $p < .001$, Cohen's $d = 1.08$; visual: $M = 0.690$, $SD = 0.089$, 95% CI [.677, .703], $t(176) = 28.41$, $p < .001$, Cohen's $d = 2.14$, or the task-irrelevant modality, auditory: $M = 0.555$, $SD = 0.098$, 95% CI [.541, .570], $t(176) = 7.48$, $p < .001$, Cohen's $d = 0.56$; visual: $M = 0.597$, $SD = 0.108$, 95% CI [.579, .614], $t(142) = 10.69$, $p < .001$, Cohen's $d = 0.89$ of a session (Figure 4A). Hit rates and false alarm rates for task-relevant and task-irrelevant stimuli are visualized in Supplemental Figure 1. While the main analysis was conducted considering the confident memory judgments to old stimuli are correct, it is reasonable that less confident memory judgments may reflect true memory. Therefore, we recalculated A′ such that memory reports to old stimuli of "definitely old" or "maybe old" were considered correct. Memory performance was above chance using this less stringent threshold (Supplemental Figure 2), suggesting that results were not largely influenced by this analytical decision.

Recognition memory performance for task-relevant stimuli was marginally related across perceptual modality in participants who completed both sessions (Spearman's $\rho = .192$, $p = .0499$; Figure 4B). Memory performance for task-relevant and task-irrelevant sounds (Spearman's $\rho = .322$, $p < .001$) and task-relevant and task-irrelevant images (Spearman's $\rho = .262$, $p = 6.83 \times 10^{-3}$) was positively related. This suggests that the ability to remember stimuli from a perceptual modality is consistent, regardless of whether the modality is task relevant or not. To assess the reliability of memory A′, we calculated the split-half reliability of memory performance within task-relevant modality by correlating A′ between even and odd trials for both auditory and visual memory performance. Memory performance was reliable for both visual (Spearman's $\rho = .447$, $p < .001$) and auditory (Spearman's $\rho = .280$, $p = 3.87 \times 10^{-3}$) sessions. However, the correlation coefficient of memory performance across modalities approaches the auditory within-task reliability, which provides a theoretical ceiling for possible relationships with other measures.

We also tested whether memory performance for task-relevant and task-irrelevant stimuli was related within a session. A negative relationship between within-session memory performance would suggest a trade-off between task-relevant and task-irrelevant stimuli, such that one may be prioritized at the expense of the other. However, within-session memory performance was not related when collapsing across perceptual modality (Spearman's $\rho = .063$, $p = .262$) and positively related when considering auditory and visual sessions separately (auditory Spearman's $\rho = .200$, $p = .017$;

Figure 4

Recognition Memory Performance



Note. (A) Memory performance, quantified as sensitivity (A′), was above chance for both relevant and irrelevant auditory and visual stimuli. (B) Within-subject memory performance was marginally related between auditory and visual sessions. (C) Within-session memory for task-relevant and irrelevant stimuli was positively related within a modality. Points represent individual participants' memory performance in a given session. See the online article for the color version of this figure.

*** $p < .001$.

visual Spearman's $\rho = .167$, $p = .027$; Figure 4C), providing no evidence of a trade-off in memory between task-relevant and task-irrelevant stimuli.

Within sessions, avCPT performance was significantly correlated with memory performance for the task-relevant modality in both auditory (Spearman's $\rho = .223$, $p = 7.40 \times 10^{-3}$) and visual (Spearman's $\rho = .344$, $p < .001$) sessions, suggesting that better performers in the avCPT also showed higher recognition memory for task-relevant stimuli. Overall avCPT performance during the auditory session was positively correlated with recognition memory for task-irrelevant images (Spearman's $\rho = .165$, $p = .049$), but visual avCPT performance was not related to memory for task-irrelevant sounds (Spearman's $\rho = .084$, $p = .264$).

Task-Relevant and Infrequent Stimuli Are Best Remembered

What factors influence whether a stimulus is remembered? For example, is memory performance higher in the second session, when participants might expect a subsequent recognition memory task? Are infrequent-category stimuli more salient and therefore better remembered? To test these questions, we next investigated memory performance for sounds and images presented during the avCPT. We constructed a comprehensive model that took into account session number, perceptual modality, task relevance, and stimulus frequency (Equation 2). Further, we included RT predictors of sustained attentional state—pretrial RT speed and variance—to determine whether attentional state predicted memory above and beyond these other variables. Finally, we included a random effect of subject.

$$\begin{aligned}\text{memory accuracy} \sim\ & \text{session} + \text{perceptual modality}\\ & + \text{task-relevance} + \text{stimulus frequency}\\ & + \text{RT speed} + \text{RT variance} + (1|\text{subject}). \quad (2)\end{aligned}$$

We observed the expected selective attention effect, such that belonging to the task-relevant modality was the strongest predictor of subsequent memory (Table 1). Stimuli from the infrequent category were better remembered than stimuli from the frequent category, showing evidence for the von Restorff effect, which predicts that unique stimuli will be remembered better than homogenous stimuli (Wallace, 1965). Stimuli presented in the first session were better remembered, suggesting that anticipation of a subsequent memory task did not improve memory performance. Images and stimuli preceded by slower RTs were also better recognized.

Behavioral Correlates of Sustained Attention Predict Subsequently Forgotten Task-Relevant Images

We next tested whether measures of sustained attention predicted memory. For these analyses we focus on memory for infrequent, task-relevant stimuli, which have traditionally provided key assays of attention lapses (deBettencourt et al., 2018; Wakeland-Hart et al., 2022). We first tested whether lapses in sustained attention predict recognition memory by constructing logistic models predicting memory from trial accuracy during the avCPT (Equation 3). Models were fit for auditory and visual sessions separately:

$$\text{memory accuracy} \sim \text{avCPT accuracy} + (1|\text{subject}). \quad (3)$$

Performance during the avCPT significantly predicted recognition memory for both auditory ($\beta = .094$, $SE = .039$, $p = .017$) and visual ($\beta = .168$, $SE = .036$, $p < .001$) stimuli, suggesting that sustained attention lapses predict the mnemonic fate of stimuli in both auditory and visual modalities.

Next, we constructed logistic models with predictors of pretrial RT speed, RT variance, and their interaction to determine whether these indices of sustained attentional state uniquely predicted memory for individual stimuli (Equation 4). Models were constructed for visual and auditory sessions separately and included a random intercept for individual subjects:

Table 1

Fixed Effects of Trial-Level Recognition Memory Performance

Predictor	Coefficient	*SE*	Significance
Session number: *1 versus 2*	.265	.027	<.001***
Perceptual modality: *Visual versus auditory*	.083	.027	2.37×10^{-3}**
Task relevance: *Task relevant versus task irrelevant*	.481	.022	<.001***
Stimulus frequency: *Infrequent versus frequent*	.205	.025	<.001***
RT speed	.033	.011	3.52×10^{-3}**
RT variance	−.016	.011	.150

Note. *SE* = standard error; RT = reaction time.
** $p < .01$. *** $p < .001$.

$$\text{memory accuracy} \sim \text{RT speed} \times \text{RT variance} + (1|\text{subject}). \tag{4}$$

RT variance significantly predicted subsequent memory for infrequent, task-relevant images, suggesting that sustained attentional state during encoding affects memory for images (Table 2 and Figure 5). However, we did not observe a significant relationship between RT speed and memory for infrequent, task-relevant images nor did RT measures predict memory for sounds. While RT measures predicted lapses in sustained attention, as well as memory in a larger model, RT speed and variability may be noisy measures of sustained attentional state itself and therefore may not capture the effect of attentional state on memory for infrequent, task-relevant images. However, we hypothesized that a more reliable measure of momentary attentional state may be memory itself. To investigate this, we next tested whether memory for a task-relevant stimulus predicted memory for its task-irrelevant pair, which was presented in the same avCPT trial.

Memory for Task-Relevant Stimuli Predicts Memory for Paired Task-Irrelevant Stimuli

Images and sounds in the avCPT were paired randomly and were therefore unrelated. In this context, does sustained attentional state enhance selective attention's spotlight, increasing encoding for relevant stimuli and filtering irrelevant stimuli? Or, does it act more like a floodlight—boosting processing for all information, even information outside of selective attention's spotlight? To test this, we asked whether task-irrelevant stimuli presented with a successfully remembered stimulus were more or less likely to be remembered than those paired with forgotten stimuli. A "spotlight" model assuming target–distractor competition would predict that accurate memory for task-relevant stimulus would *decrease* the likelihood that its task-irrelevant pair would be remembered. A "floodlight" model, on the other hand, would predict that accurate memory for a relevant stimulus (presumably indicating a more engaged attentional state overall) would *increase* the likelihood that its irrelevant pair would be remembered.

We tested whether the proportion of correctly remembered task-irrelevant stimuli differed depending on whether stimuli were presented alongside remembered or forgotten task-relevant stimuli. To maximize power, all stimulus pairs tested for memory—whether stimuli were frequent or infrequent—were used in this analysis. Proportions were calculated by dividing the number of remembered, task-irrelevant stimuli paired with remembered (or forgotten) task-relevant stimuli by the total number of remembered (or forgotten) task-relevant stimuli. Individuals who did not correctly remember any task-relevant stimuli, for whom the denominator of this equation would equal zero, were excluded from this analysis. Figure 6A and 6B visualizes memory performance for task-irrelevant stimuli relative to memory for their task-relevant pairs. Task-irrelevant sounds that were paired with remembered, task-relevant images were more likely to be remembered (memory accuracy, $M = 0.281$, $SD = 0.209$, 95% CI [.250, .313]) than those paired with forgotten images (memory accuracy, $M = 0.259$, $SD = 0.190$, 95% CI [.231, .288]), $t(172) = 2.34$, $p = .021$, Cohen's $d = 0.178$. The relationship between the proportion of remembered task-irrelevant images paired with correctly recognized sounds ($M = 0.218$, $SD = 0.194$, 95% CI [.185, .250]) versus forgotten sounds ($M = 0.202$, $SD = 0.191$, 95% CI [.170, .234]) was similar but nonsignificant, $t(139) = 1.85$, $p = .066$, Cohen's $d = 0.156$. A mixed-effects modeling approach

Table 2

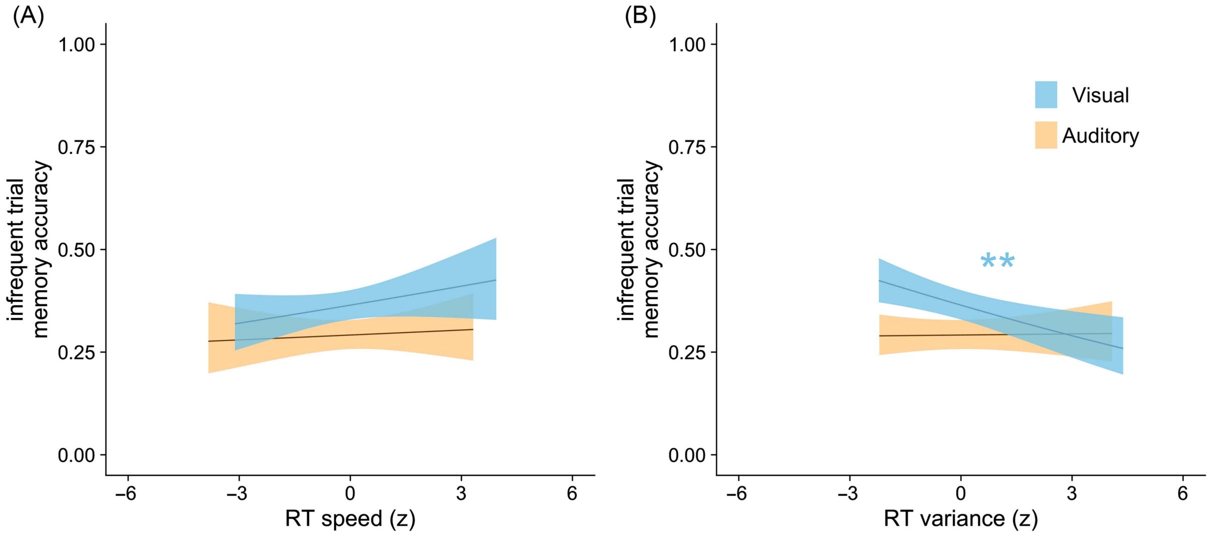
Fixed Effects for Sustained Attention Measures on Recognition Memory for Infrequent Task-Relevant Items From Joint Model

Modality	Predictor	Coefficient	*SE*	Significance
Auditory	RT speed	.019	.054	.718
	RT variance	4.44×10^{-3}	.039	.909
	RT speed: RT variance	4.33×10^{-3}	.034	.899
Visual	RT speed	.065	.048	.176
	RT variance	−.113	.038	2.66×10^{-3}**
	RT speed: RT variance	−.035	.030	.239

Note. *SE* = standard error; RT = reaction time.
** $p < .01$.

Figure 5

Fixed Effects of RT Speed (A) and Variance (B) on Recognition Memory for Task-Relevant Stimuli



Note. Model predictors were pretrial RT, pretrial RT variance, and their interaction, as well as a random intercept term for individual subjects. Less variable pretrial RTs were related to better memory for images. Shaded areas reflect 95% confidence intervals. RT = reaction time. See the online article for the color version of this figure.
** $p < .01$.

revealed the same pattern: Recognition memory for a relevant stimulus positively predicted memory for its paired, irrelevant stimulus (auditory: $\beta = .054$, $SE = .026$, $p = .041$; visual: $\beta = .055$, $SE = .021$, $p = .011$; Figure 6C and 6D). This suggests that correctly recognizing a task-relevant stimulus increases the likelihood of recognizing a paired but irrelevant stimulus presented at the same time, lending support for the floodlight hypothesis of sustained attention.

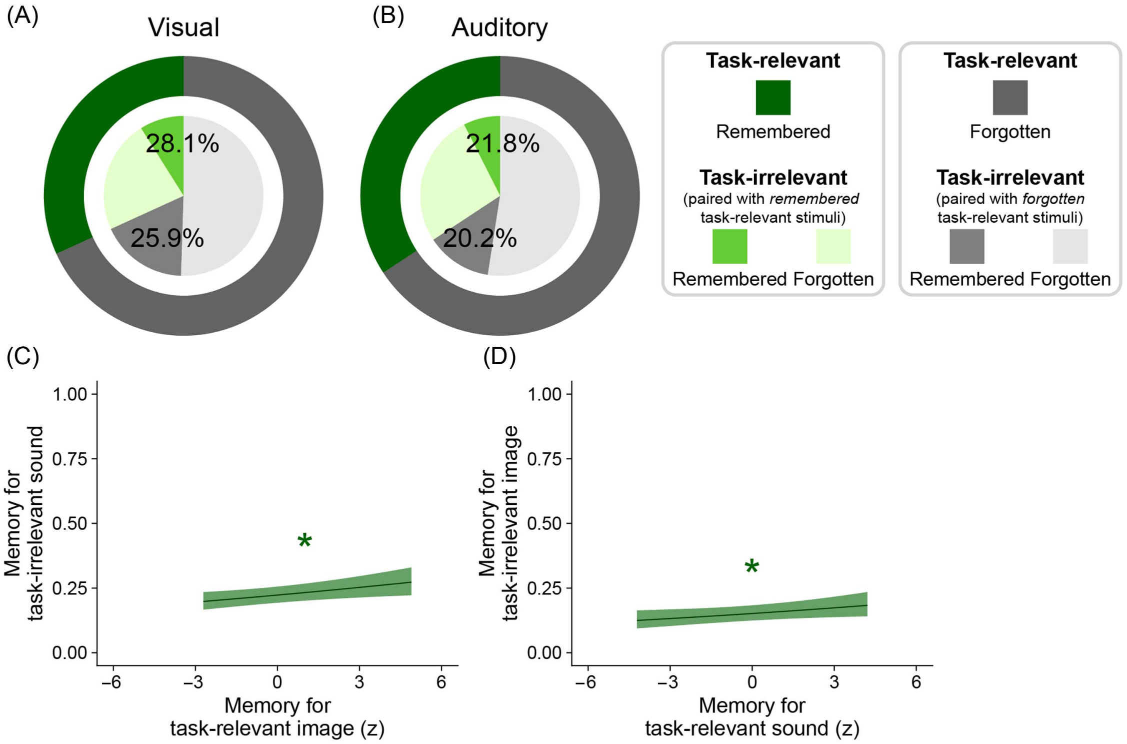
Perhaps this effect is driven by the attentional boost theory, which suggests that, during a target-detection task, the salience of a rare target detected among a stream of frequent stimuli boosts processing and memory for task-irrelevant stimuli presented with the target (Lin et al., 2010; Swallow & Jiang, 2010). If this is the case, we would expect to observe high memory performance for task-irrelevant stimuli that were paired with infrequent, task-relevant stimuli in our data. To test this, we constructed mixed-effects models testing whether the frequency of task-relevant items predicted memory for task-irrelevant pairs. We found evidence for the attentional boost theory during visual sessions, such that task-irrelevant sounds paired with task-relevant, infrequent images were better remembered ($\beta = .260$, $SE = .045$, $p < .001$). However, we found no evidence of this effect for task-irrelevant images paired with task-relevant, infrequent sounds ($\beta = 3.36 \times 10^{-4}$, $SE = .056$, $p = .995$). These results suggest that increased processing during infrequent, task-relevant trials may contribute to the floodlight effect of sustained attention during the visual session. However, the lack of this effect during auditory sessions suggests that the attentional boost theory does not fully explain the memory benefit for task-relevant and task-irrelevant stimuli presented in engaged attentional states.

A significant relationship between memory for task-relevant and task-irrelevant stimuli presented at the same time suggests that the strength of processing varies with sustained attentional fluctuations at encoding. However, other factors may have contributed to this relationship. For example, reactivation of a task-relevant stimulus during the memory task may strengthen memory for other information presented at encoding, as has been demonstrated in previous work (Gardner-Medwin, 1976; Horner & Burgess, 2013, 2014; Starns & Hicks, 2005). To test whether behavioral signatures of sustained attentional state indeed influenced task-irrelevant memory, we fit separate logistic models testing the relationship between RT speed and task-irrelevant stimulus memory, as well as RT variance as irrelevant-item memory. RT variance did not predict irrelevant-item memory in either auditory ($b = -.082$, $SE = .058$, $p = .157$) or visual sessions ($b = .025$, $SE = .043$, $p = .569$). However, RT speed positively predicted irrelevant-item memory in both auditory ($b = .65$, $SE = .035$, $p = .064$) and visual sessions ($b = .081$, $SE = .028$, $p = 3.81 \times 10^{-3}$), although this relationship was not significant in the auditory session. This suggests that higher attentional state, measured by longer RTs, was associated with better memory for task-irrelevant stimuli, as predicted by a floodlight view of sustained attentional state.

Further, we tested whether including RT speed as an additional behavioral index of sustained attention state affected the relationship between relevant and irrelevant stimulus memory. A floodlight view of sustained attention could make multiple plausible predictions. One possibility is that irrelevant item memory is positively related to relevant item memory in engaged attentional states when attention is directed to the task. When attention is disengaged, however, irrelevant and relevant item memory may be negatively related (because there are fewer resources to allocate the display overall, inducing competition) or independent of each other (if the breadth and focus of attention is essentially random).

Figure 6

Relevant Memory Predicts Memory for Irrelevant Pairs



Note. In both visual (A) and auditory (B) conditions, more task-irrelevant stimuli paired with correctly recognized relevant stimuli were successfully recognized, relative to the proportion of stimuli paired with forgotten relevant stimuli that were successfully recognized. In the inner circle, the darker green wedge constitutes a relatively larger portion than the darker gray wedge, suggesting that remembering task-relevant stimuli was associated with remembering their paired task-irrelevant stimuli, more so than when task-relevant stimuli were forgotten. Percentages represent the percentage of task-irrelevant stimuli paired with remembered (green) or forgotten (gray) task-relevant stimuli. Memory for task-irrelevant sound (C) and task-irrelevant image (D) pairs was predicted by memory for task-relevant stimuli presented at the same time. Shaded areas reflect 95% confidence intervals. See the online article for the color version of this figure.

$^{*}p < .05$.

This possibility would be reflected in a significant interaction term between attentional state and relevant-item memory such that relevant-item memory should predict irrelevant memory more strongly when stimuli were presented under engaged attentional states. An alternative possibility is that irrelevant and relevant item memory are positively related in both engaged and disengaged states: In engaged states both are processed simultaneously, whereas in disengaged states, neither is successfully encoded in memory. We did not have an a priori hypothesis about which relationship we would observe.

To address this question, we fit logistic models predicting irrelevant stimulus memory with effects of relevant stimulus memory, RT speed, and their interaction. Effects of relevant-item memory remained significant in both auditory ($b = .058$, $SE = .0286$, $p = .029$) and visual sessions ($b = .054$, $SE = .022$, $p = .013$). Additionally, RT speed effects were again positive in auditory ($b = .064$, $SE = .035$, $p = .068$) and visual ($b = .080$, $SE = .028$, $p = 4.21 \times 10^{-3}$)sessions, although again this effect did not reach significance in the auditory session. This suggests that irrelevant stimuli presented during moments of high sustained attention are not better filtered. Interaction effects were not significant in either session (auditory: $b = .037$, $SE = .034$, $p = .281$; visual: $b = -.025$, $SE = .029$, $p = .383$). These results suggest that both sustained attentional and mnemonic effects contribute to successful memory for task-irrelevant stimuli. The lack of an interaction effect would suggest that the relationship between relevant and irrelevant-item memory is not a function of attentional state but, rather, that these effects contribute separately to the successful recognition of irrelevant stimuli.

Discussion

The present study investigated the consequences of fluctuations in sustained attention on the mnemonic fate of auditory and visual stimuli using the novel avCPT. Results support a perceptual modality-general mechanism of sustained attention indexed by behavioral RT measures. Further, rather than a trade-off of attention to task-relevant versus task-irrelevant stimuli, we find that better memory for a relevant image or sound predicts better memory for its simultaneously presented pair. These findings provide insights into the relationship between sustained attention and recognition memory across perceptual modalities.

Despite the potential for distraction, online participants performed auditory and visual sessions of the avCPT successfully. Across modalities, we observed stable individual differences in both overall sustained attention performance and vigilance decrements over time, replicating previous work (Seli et al., 2012; Terashima et al., 2021). RT indices previously shown to predict lapses in visual sustained attention (deBettencourt et al., 2018; Esterman et al., 2013; Rosenberg et al., 2013; Wakeland-Hart et al., 2022) also predict lapses in auditory attention. Furthermore, these measures explain unique variance in lapses, suggesting they may index separable aspects of sustained attentional state. Our results add to accumulating evidence of a modality-general mechanism underlying sustained attention and validate the use of the avCPT for investigating auditory and visual attention.

Memory was above chance for both visual and auditory stimuli, demonstrating that participants successfully encoded images and sounds when they were task relevant and task irrelevant. Unsurprisingly, memory was better for task-relevant than task-irrelevant stimuli, providing evidence that selective attention leads to better memory for stimuli in the focus of attention. Memory was also better for images than for sounds, replicating previous work showing poor memory for sounds (M. A. Cohen et al., 2009). Infrequent-category stimuli were remembered better than frequent-category stimuli, in line with the von Restorff effect (Wallace, 1965), which predicts better memory for unique items. Finally, recognition memory was better for infrequent images encoded in engaged sustained attentional states, indexed by low RT variance. However, neither RT speed nor variance predicted memory for infrequent sounds, suggesting that RT measures may be noisy signatures of sustained attention.

There was a trending relationship between memory performance across perceptual modalities, such that individuals who remembered more images also remembered more sounds. Importantly, individual differences analyses also revealed no evidence for a trade-off between memory for task-relevant and task-irrelevant stimuli within a session. Better memory for task-relevant stimuli did not predict worse memory for task-irrelevant stimuli or vice versa. Thus, contrary to predictions of "spotlight" models of sustained attention, participants who perform well on the memory task for relevant stimuli do not appear to do so at the expense of task-irrelevant stimuli.

To further investigate how moment-to-moment changes in sustained attentional state influence memory, we asked whether memory for a task-relevant stimulus predicted memory for its task-irrelevant pair. In both auditory and visual sessions, memory for the task-relevant stimulus predicted memory for the irrelevant stimulus presented at the same time. When an additional effect of attentional state, RT speed, was included in the model, we observed that both higher sustained attentional state and successful recognition of a paired task-relevant image predicted memory for task-irrelevant sounds. These findings provide additional support for the floodlight view of sustained attentional state, such that moments of higher sustained attentional state enhance processing of task-irrelevant information.

Given the pervasive metaphor of attention as a spotlight, this result may seem counterintuitive. Previous work has argued against a clean spotlight analogy for other forms of attention, such as selective visuospatial attention (Cave & Bichot, 1999). Our results further demonstrate that sustained attention is not well-characterized by a spotlight. They correspond, however, with previous findings of increased—rather than decreased—processing of distractors during in-the-zone sustained attentional states (Esterman et al., 2014). In other words, good performance on a sustained attention task was characterized not by distractor filtering but by a broad attentional state in which distractors were processed *more*. Results also align with observations of greater distractor processing during tasks with low perceptual load (Rees et al., 1997; Yi et al., 2004), consistent with the perceptual load hypothesis of distractor processing, which predicts increased processing of task-irrelevant information due to spare attentional capacity in low load conditions. Increases in sustained attentional state may be analogous here to low perceptual load conditions, such that additional attentional capacity is available to process distractors. Further, results are congruent with the attentional boost effect, which proposes that salient moments boost processing of both task-relevant and task-irrelevant information (Lin et al., 2010; Swallow & Jiang, 2010). However, while this effect might suggest that infrequent stimuli drive moments of high attentional state and therefore fully explain the relationship between memory for relevant and irrelevant stimuli, we only saw evidence of this effect during visual sessions and not auditory sessions. Instead, moments of increased processing fluctuate throughout the task, both during salient, infrequent-category trials and repetitive frequent-category trials, shining the "floodlight" of sustained attention on stimuli regardless of task relevance.

It should be noted that while task-irrelevant stimuli may have had the potential for distraction in the present study, they did not directly interfere with task goals during the avCPT. The task was designed to test selective attention to images and sounds separately while controlling for potential confounds of presenting images or sounds in isolation. Therefore, selection demand for task-relevant stimuli was low such that accurate performance on the avCPT could be achieved without any need for selective attentional filtering of task-irrelevant information. This may have enabled processing of task-irrelevant stimuli to occur without real detriment to task performance. It is possible that increasing selection demands, that is, interference between task-relevant and task-irrelevant stimuli, would impact how stimuli are remembered and how memory changes as a function of sustained attentional state. Future work will test this question by varying the extent to which task-irrelevant stimuli compete with task-relevant goals.

Although the spotlight metaphor does not apply to sustained attention, it may remain appropriate for describing other forms of attention, such as selective spatial attention. The current findings underscore the fact that attention is not a single process (Amengual et al., 2022; Chun et al., 2011) and highlight the importance of disambiguating sustained attention from other attentional components. The floodlight metaphor may also not extend to tasks in which distractor stimuli directly compete with task-relevant goals. That is, in the avCPT, task-irrelevant stimuli were presented in a different perceptual modality and therefore were not in direct competition with task-relevant stimuli for the focus of attention. Further, long trial durations, chosen to allow for clear discrimination of sounds, may have allowed time for encoding of both task-relevant and task-irrelevant information during a single trial. If the task design were such that processing of irrelevant stimuli interfered with task goals, for example, if relevant and irrelevant stimuli came from the same perceptual modality or if stimulus presentation time was shortened, we might expect a different pattern of results. For example, work by

Decker et al. (2023) found evidence for increased distractor processing during attentional lapses when distractors competed with task-relevant stimuli. Further, the avCPT was intentionally designed to have low perceptual load to ensure that errors in category judgments are the result of lapses in sustained attention and not due to difficulty of category discrimination itself. Therefore, it is an open question whether the floodlight metaphor would apply in a more perceptually difficult task of sustained attention. Future work may seek to characterize the extent and limitations of the floodlight metaphor of sustained attention.

Because this study is behavioral in nature, we use behavioral measures of sustained attentional state and memory performance to investigate changes in stimulus processing throughout the sustained attention task. As a result, it is difficult to disentangle attentional and memory mechanisms in the current results. For example, our results align with previous work demonstrating that paired association memory for a cue and contextual information was dependent, such that memory for a cue-pair association predicts memory for another cue-pair from the same context (Gardner-Medwin, 1976; Horner & Burgess, 2013, 2014; Starns & Hicks, 2005). Indeed, we saw evidence for contributions from both sustained attentional and memory mechanisms in successful memory for task-irrelevant stimuli. Previous work differs from the present study by testing memory using cued retrieval for learned pairs, that is, participants were explicitly instructed to imagine and memorize associated items. Therefore, all stimuli were task relevant to some extent. It is also worth noting that previous work tested memory using a cue (Horner & Burgess, 2013, 2014) or tested memory pairs concurrently (Starns & Hicks, 2005), which may have increased the likelihood of observing dependent memory between associated pairs, whereas in the present study, recognition memory was tested using an old–new judgment, and tests for relevant and irrelevant stimuli were separated across time (the first half of the memory task contained only relevant-category stimuli, followed by irrelevant-category stimuli in the second half). Therefore, while the effects observed in the present study may be due to similar memory dependence mechanisms, this effect has not been tested with the current methods.

One benefit of the present study design is to provide one explanation for why a relevant stimulus is remembered in the first place, that is, the sustained attentional state at encoding. We showed that sustained attentional state predicts recognition memory for task-relevant stimuli, and retrieval of a memory strengthens retention of contextual information presented at encoding (Jonker et al., 2018). Therefore, it may be that the effect of sustained attentional state on task-irrelevant stimulus memory is twofold. Higher sustained attentional state at encoding may lead to stronger memory for a task-irrelevant stimulus itself. Further, task-relevant stimuli presented during higher sustained attentional state are more likely to be remembered, reactivating memory for irrelevant stimuli presented at the same time. Future work using neural methods such as fMRI may be better equipped to inform what mechanisms underlie this relationship.

Our current results challenge the notion that all forms of attention act as a spotlight, enhancing processing for only goal-relevant information. Instead, fluctuations in sustained attention led to similarly increased (or decreased) processing for all stimuli regardless of task relevance. Future work can interrogate the boundaries of the sustained attentional floodlight within and across perceptual modalities and contexts. Further, consequences of sustained attentional state may extend to other cognitive processes impacted by fluctuations in attention, such as learning. Fully characterizing the extent and effects of sustained attention's floodlight may provide insights into processes involved in sustained attention and its interaction with other forms of attention and cognition.

Constraints on Generality

Participants in the present study were adults aged 18–35. While the effects observed may generalize to populations outside this age range, we cannot conclude that results would replicate in all age groups.

References

Amengual, J. L., Di Bello, F., Ben Hadj Hassen, S., & Ben Hamed, S. (2022). Distractibility and impulsivity neural states are distinct from selective attention and modulate the implementation of spatial attention. *Nature Communications*, *13*(1), Article 4796. https://doi.org/10.1038/s41467-022-32385-y

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Butler, B. C., & Klein, R. (2009). Inattentional blindness for ignored words: Comparison of explicit and implicit memory tasks. *Consciousness and Cognition*, *18*(3), 811–819. https://doi.org/10.1016/j.concog.2009.02.009

Cave, K. R., & Bichot, N. P. (1999). Visuospatial attention: Beyond a spotlight model. *Psychonomic Bulletin & Review*, *6*(2), 204–223. https://doi.org/10.3758/BF03212327

Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, *62*(1), 73–101. https://doi.org/10.1146/annurev.psych.093008.100427

Cohen, M. A., Horowitz, T. S., & Wolfe, J. M. (2009). Auditory recognition memory is inferior to visual recognition memory. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(14), 6008–6010. https://doi.org/10.1073/pnas.0811884106

Cohen, S., & Williamson, G. (1988). Perceived stress in a probability sample of the United States. In S. Spacapan & S. Oskamp (Eds.), *The social psychology of health: Claremont Symposium on applied social psychology* (pp. 31–67). Sage Publications.

Corriveau, A., Chao, A. F., deBettencourt, M. T., & Rosenberg, M. D. (2024). Recognition memory fluctuates with sustained attention regardless of task relevance. *Psychonomic Bulletin & Review*, *32*, 714–728. https://doi.org/10.3758/s13423-024-02560-x

de Leeuw, J. R. (2015). jsPsych: A JavaScript library for creating behavioral experiments in a Web browser. *Behavior Research Methods*, *47*(1), 1–12. https://doi.org/10.3758/s13428-014-0458-y

deBettencourt, M. T., Norman, K. A., & Turk-Browne, N. B. (2018). Forgetting from lapses of sustained attention. *Psychonomic Bulletin & Review*, *25*(2), 605–611. https://doi.org/10.3758/s13423-017-1309-5

Decker, A., Dubois, M., Duncan, K., & Finn, A. S. (2023). Pay attention and you might miss it: Greater learning during attentional lapses. *Psychonomic Bulletin & Review*, *30*(3), 1041–1052. https://doi.org/10.3758/s13423-022-02226-6

Decker, A., Duncan, K., & Finn, A. (2022). *Fluctuations in sustained attention explain moment-to-moment shifts in children's memory formation*. PsyArXiv. https://doi.org/10.31234/osf.io/gzkuc

Eargle, D., Gureckis, T., Rich, A. S., McDonnell, J., & Martin, J. B. (2020). *psiTurk: An open platform for science on Amazon Mechanical Turk* (Version 3.2.1) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.3598652

Esterman, M., Noonan, S. K., Rosenberg, M., & Degutis, J. (2013). In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. *Cerebral Cortex*, *23*(11), 2712–2723. https://doi.org/10.1093/cercor/bhs261

Esterman, M., Rosenberg, M. D., & Noonan, S. K. (2014). Intrinsic fluctuations in sustained attention and distractor processing. *The Journal of Neuroscience*, *34*(5), 1724–1730. https://doi.org/10.1523/JNEUROSCI.2658-13.2014

Gardner-Medwin, A. R. (1976). The recall of events through the learning of associations between their parts. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, *194*(1116), 375–402. https://doi.org/10.1098/rspb.1976.0084

Grier, J. B. (1971). Nonparametric indexes for sensitivity and bias: Computing formulas. *Psychological Bulletin*, *75*(6), 424–429. https://doi.org/10.1037/h0031246

Gureckis, T. M., Martin, J., McDonnell, J., Rich, A. S., Markant, D., Coenen, A., Halpern, D., Hamrick, J. B., & Chan, P. (2016). psiTurk: An open-source framework for conducting replicable behavioral experiments online. *Behavior Research Methods*, *48*(3), 829–842. https://doi.org/10.3758/s13428-015-0642-8

Horner, A. J., & Burgess, N. (2013). The associative structure of memory for multi-element events. *Journal of Experimental Psychology: General*, *142*(4), 1370–1383. https://doi.org/10.1037/a0033626

Horner, A. J., & Burgess, N. (2014). Pattern completion in multielement event engrams. *Current Biology*, *24*(9), 988–992. https://doi.org/10.1016/j.cub.2014.03.012

Hutmacher, F., & Kuhbandner, C. (2020). Detailed long-term memory for unattended, irrelevant, and incidentally encoded auditory information. *Journal of Experimental Psychology: General*, *149*(2), 222–229. https://doi.org/10.1037/xge0000650

Jonker, T. R., Dimsdale-Zucker, H., Ritchey, M., Clarke, A., & Ranganath, C. (2018). Neural reactivation in parietal cortex enhances memory for episodically linked information. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(43), 11084–11089. https://doi.org/10.1073/pnas.1800006115

Katayama, J., & Polich, J. (1999). Auditory and visual P300 topography from a 3 stimulus paradigm. *Clinical Neurophysiology*, *110*(3), 463–468. https://doi.org/10.1016/S1388-2457(98)00035-2

Kim, H. (2013). Differential neural activity in the recognition of old versus new events: An activation likelihood estimation meta-analysis. *Human Brain Mapping*, *34*(4), 814–836. https://doi.org/10.1002/hbm.21474

Kuhbandner, C., Rosas-Corona, E. A., & Spachtholz, P. (2017). High-fidelity visual long-term memory within an unattended blink of an eye. *Frontiers in Psychology*, *8*, Article 1859. https://doi.org/10.3389/fpsyg.2017.01859

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(3), 451–468. https://doi.org/10.1037/0096-1523.21.3.451

Lavie, N., Lin, Z., Zokaei, N., & Thoma, V. (2009). The role of perceptual load in object recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1346–1358. https://doi.org/10.1037/a0016454

Lin, J. Y., Pype, A. D., Murray, S. O., & Boynton, G. M. (2010). Enhanced memory for scenes presented at behaviorally relevant points in time. *PLOS Biology*, *8*(3), Article e1000337. https://doi.org/10.1371/journal.pbio.1000337

Linden, D. E. J., Prvulovic, D., Formisano, E., Völlinger, M., Zanella, F. E., Goebel, R., & Dierks, T. (1999). The functional neuroanatomy of target detection: An fMRI study of visual and auditory oddball tasks. *Cerebral Cortex*, *9*(8), 815–823. https://doi.org/10.1093/cercor/9.8.815

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology*, *1*(1), 6–21. https://doi.org/10.1080/17470214808416738

Mandal, A., Liesefeld, A. M., & Liesefeld, H. R. (2022). *The surprising robustness of visual attention against concurrent auditory distraction*. PsyArXiv. https://doi.org/10.31234/osf.io/hnvdm

Norman, D. A. (1968). Toward a theory of memory and attention. *Psychological Review*, *75*(6), 522–536. https://doi.org/10.1037/h0026699

Parmentier, F. B. R., Elford, G., Escera, C., Andrés, P., & San Miguel, I. (2008). The cognitive locus of distraction by acoustic novelty in the cross-modal oddball task. *Cognition*, *106*(1), 408–432. https://doi.org/10.1016/j.cognition.2007.03.008

Piczak, K. J. (2015). *ESC: Dataset for environmental sound classification* (Version 2) [Dataset]. Harvard Dataverse. https://doi.org/10.7910/DVN/YDEPUT

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science*, *278*(5343), 1616–1619. https://doi.org/10.1126/science.278.5343.1616

Rees, G., Russell, C., Frith, C. D., & Driver, J. (1999). Inattentional blindness versus inattentional amnesia for fixated but ignored words. *Science*, *286*(5449), 2504–2507. https://doi.org/10.1126/science.286.5449.2504

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). "Oops!": Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, *35*(6), 747–758. https://doi.org/10.1016/S0028-3932(97)00015-8

Rosenberg, M., Noonan, S., DeGutis, J., & Esterman, M. (2013). Sustaining visual attention in the face of distraction: A novel gradual-onset continuous performance task. *Attention, Perception, & Psychophysics*, *75*(3), 426–439. https://doi.org/10.3758/s13414-012-0413-x

Ruz, M., Wolmetz, M. E., Tudela, P., & McCandliss, B. D. (2005). Two brain pathways for attended and ignored words. *NeuroImage*, *27*(4), 852–861. https://doi.org/10.1016/j.neuroimage.2005.05.031

Ruz, M., Worden, M. S., Tudela, P., & McCandliss, B. D. (2005). Inattentional amnesia to words in a high attentional load task. *Journal of Cognitive Neuroscience*, *17*(5), 768–776. https://doi.org/10.1162/0898929053747685

Seli, P., Cheyne, J. A., Barton, K. R., & Smilek, D. (2012). Consistency of sustained attention across modalities: Comparing visual and auditory versions of the SART. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *66*(1), 44–50. https://doi.org/10.1037/a0025111

Starns, J. J., & Hicks, J. L. (2005). Source dimensions are retrieved independently in multidimensional monitoring tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(6), 1213–1220. https://doi.org/10.1037/0278-7393.31.6.1213

Stevens, A. A., Skudlarski, P., Gatenby, J. C., & Gore, J. C. (2000). Event-related fMRI of auditory and visual oddball tasks. *Magnetic Resonance Imaging*, *18*(5), 495–502. https://doi.org/10.1016/S0730-725X(00)00128-4

Swallow, K. M., & Jiang, Y. V. (2010). The attentional boost effect: Transient increases in attention to one task enhance performance in a second task. *Cognition*, *115*(1), 118–132. https://doi.org/10.1016/j.cognition.2009.12.003

Terashima, H., Kihara, K., Kawahara, J. I., & Kondo, H. M. (2021). Common principles underlie the fluctuation of auditory and visual sustained attention. *Quarterly Journal of Experimental Psychology*, *74*(4), 705–715. https://doi.org/10.1177/1747021820972255

Turk-Browne, N. B., Yi, D.-J., & Chun, M. M. (2006). Linking implicit and explicit memory: common encoding factors and shared representations. *Neuron*, *49*(6), 917–927. https://doi.org/10.1016/j.neuron.2006.01.030

Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., Dale, A. M., Rosen, B. R., & Buckner, R. L. (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. *Science*, *281*(5380), 1188–1191. https://doi.org/10.1126/science.281.5380.1188

Wakeland-Hart, C. D., Cao, S. A., deBettencourt, M. T., Bainbridge, W. A., & Rosenberg, M. D. (2022). Predicting visual memory across images and within individuals. *Cognition*, *227*, Article 105201. https://doi.org/10.1016/j.cognition.2022.105201

Wallace, W. P. (1965). Review of the historical, empirical, and theoretical status of the von Restorff phenomenon. *Psychological Bulletin*, *63*(6), 410–424. https://doi.org/10.1037/h0022001

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*(6), 1063–1070. https://doi.org/10.1037/0022-3514.54.6.1063

Xiao, J., Hays, J., Ehinger, K. A., Oliva, A., & Torralba, A. (2010). SUN database: Large-scale scene recognition from abbey to zoo. *2010 IEEE Computer Society conference on computer vision and pattern recognition* (pp. 3485–3492). https://doi.org/10.1109/CVPR.2010.5539970

Yamashita, A., Rothlein, D., Kucyi, A., Valera, E. M., Germine, L., Wilmer, J., DeGutis, J., & Esterman, M. (2021). Variable rather than extreme slow reaction times distinguish brain states during sustained attention. *Scientific Reports*, *11*(1), Article 14883. https://doi.org/10.1038/s41598-021-94161-0

Yi, D.-J., Woodman, G. F., Widders, D., Marois, R., & Chun, M. M. (2004). Neural fate of ignored stimuli: Dissociable effects of perceptual and working memory load. *Nature Neuroscience*, *7*(9), Article 9. https://doi.org/10.1038/nn1294

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