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REVIEW

Neurocognitive mechanisms of real-world autobiographical memory retrieval: insights from studies using wearable camera technology

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In recent years, investigation into the cognitive and neural mechanisms of autobiographical memory has been aided by the use of experimental paradigms incorporating wearable camera technology. By effortlessly capturing first-person images of one's life events, these cameras provide a rich set of naturalistic stimuli that can later be used to trigger the recall of specific episodes. Here, we chronicle the development and progression of such studies in behavioral and neuroimaging examinations of both clinical and nonclinical adult populations. Experiments examining the effects of periodic review of first-person images of life events have documented enhancements of autobiographical memory retrieval. Such benefits are most pronounced in patients with memory impairments, but there is mounting evidence that cognitively healthy individuals may benefit as well. Findings from functional magnetic resonance imaging experiments using wearable camera stimuli as retrieval probes have produced results that, although largely consistent with the broader episodic memory literature, have significantly extended prior findings concerning the underlying mnemonic processes and the neural representation of autobiographical information. Taken together, wearable camera technology provides a unique opportunity for studies of autobiographical memory to more closely approximate real-world conditions, thus offering enhanced ecological validity and opening up new avenues for experimental work.

Keywords: episodic memory; recollection; life-logging; SenseCam; fMRI

Introduction

The ability to recollect detailed information about past events is a hallmark of episodic memory.[1] The vast majority of behavioral and neuroimaging studies of episodic retrieval have used laboratory-encoded stimuli, such as words or pictures, as memory probes. While such stimuli provide researchers with tight experimental control over the perceptual qualities, exposure duration, and retention interval of the events being probed, laboratory stimuli lack the richness of most real-world experiences. When events are encoded in a naturalistic setting, it is more likely that the details will have personal relevance, including information about the visuospatial context (event location), temporal context (timing of the event along with its relation to other life occurrences), cognitive context (what one was thinking about and/or trying to accomplish at the time), social context (who one was with), and emotional context (how one was feeling). Thus, it is perhaps unsurprising that neuroimaging studies comparing the profile of brain activity during the retrieval of stimuli learned in a laboratory context to that associated with the retrieval of autobiographical memories (i.e., memories for one's own life events) typically find marked differences. For instance, autobiographical memory retrieval evokes much greater activation of default mode network regions implicated in introspective cognition and self-referential processing—such as the medial prefrontal cortex (mPFC)—as well as medial temporal lobe (MTL) regions associated with recollection of

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visuospatial contextual details, such as the hippocampus and parahippocampal cortex.[2–4] Indeed, a meta-analysis of functional magnetic resonance imaging (fMRI) studies of episodic retrieval revealed only limited anatomical overlap in the neural correlates associated with the retrieval of laboratory-encoded and autobiographical memories.[5] Moreover, performance on standard laboratory-based memory tasks can be largely unrelated to one's autobiographical retrieval abilities, as demonstrated by individuals with either "highly superior autobiographical memory" or "severely deficient autobiographical memory."[6–9] Dissociations like these have led some to propose that retrieving autobiographical event knowledge is fundamentally different from other forms of episodic retrieval.[3,10]

Efforts to understand the neural mechanisms of real-world autobiographical memory retrieval have utilized a variety of experimental techniques to evoke recall. These include prospective methods, which document life events as they occur and thus allow for increased experimental control.[11] Such studies have benefited from the use of naturalistic stimuli, particularly photographs, to probe participants' memories.[2,12] While photographs can serve as effective retrieval cues that allow individuals to recollect experiences, the use of handheld cameras in autobiographical memory retrieval research presents potential methodological concerns as well. This is primarily due to participant involvement in the act of documenting personal events, which may result in modifications or biases in the resultant memories.[13] This same limitation applies to studies in which written diary entries[14,15] or voice recordings[16,17] are used to log daily experiences. However, recent technological advancements have facilitated the development of camera-based memory paradigms that avoid the need for participants' explicit input. Namely, studies have begun to incorporate the use of wearable digital camera devices to automatically capture images of the wearer's life events, which can later be used as probes to assess behavioral and neural processes related to the retrieval of these real-world autobiographical memories. This novel, nonintrusive approach provides objective measures of autobiographical details and occurrences while increasing the ecological validity of experimental tasks.

The goal of this review is to summarize and evaluate the growing set of behavioral and fMRI studies published in peer-reviewed journals that have incorporated wearable cameras as a tool to assess memories encoded in naturalistic contexts. This includes detailing how such camera devices have been used in experimental paradigms on clinical and nonclinical adult populations, with an emphasis on what this work has revealed about the mechanisms of autobiographical memory retrieval.

Wearable digital cameras

The first notable wearable camera device to be adopted by memory researchers was the SenseCam from Microsoft Research Cambridge (http://research.microsoft.com/en-us/um/cambridge/projects/sensecam), developed in 2003 as a tool for keeping a visual record of one's life experiences without the need for user intervention.[18] The SenseCam is most commonly worn on a lanyard around the neck and automatically takes relatively low-resolution (0.3 megapixel), wide-angle photographs from the wearer's perspective every 30 s (although the user can configure this interval to be shorter or longer). Moreover, the camera will capture additional photographs when its electronic sensors detect salient variations in the wearer's external environment, including changes in ambient temperature, light intensity and color, infrared (to detect body heat), and acceleration. The SenseCam was designed to operate for long periods of time without recharging or uploading photographs to the computer for review and storage. These characteristics allow the SenseCam to unobtrusively capture a large number of time-stamped images of its wearer's life events, providing a wealth of content that researchers can use in autobiographical memory experiments.

A commercial version of the SenseCam, marketed as the Vicon Revue®, became available in 2010 owing to increasing public interest in life-logging devices,[19] and the technology was later licensed to OMG Life, who released a higher-resolution and global positioning system (GPS)-enabled wearable camera product in 2012 called the Autographer® (Fig. 1). While memory researchers have benefitted from these newer iterations of the original SenseCam,[20–22] these products have struggled to achieve commercial success, and, as of 2016, all manufacturing and sales operations have ceased. Given recent technological advances, the market for life-logging devices has since shifted toward wearable

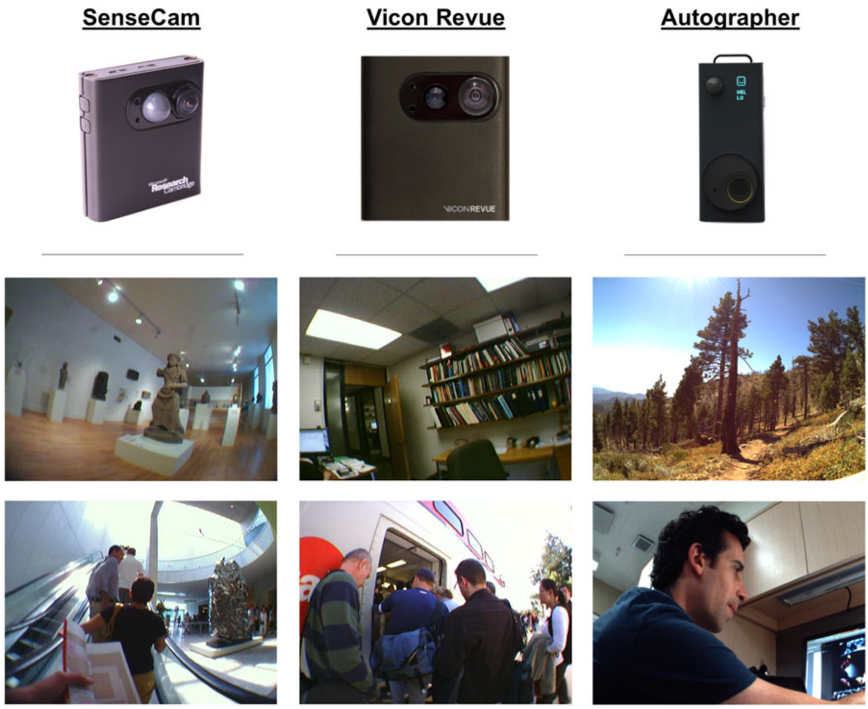

Figure 1. The SenseCam wearable camera device and its commercial successors, the Vicon Revue and the Autographer, with example photographs from each product. Images adapted from Microsoft Research, Vicon Motion Systems Ltd., and OMG Life. SenseCam photographs provided courtesy of Peggy St. Jacques; Vicon Revue and Autographer photographs provided by the authors.

video cameras, such as the GoPro HERO®, Narrative Clip®, MeCam HD®, iON SnapCam®, and Snapchat Spectacles®. To our knowledge, no scientific studies of human memory have yet incorporated these latest video-enabled devices, but we anticipate that they will soon become a valuable research tool. Additionally, several memory studies have used necklace-mounted smartphones to document the lives of research participants.[23,24] Although the overall number of published memory studies utilizing wearable camera technology is still quite limited, the SenseCam and its immediate successor, the Vicon Revue, remain the most prevalent devices in the literature. The majority of studies have used this technology for behavioral experiments, particularly in clinical contexts, but an increasing number of fMRI studies examining real-world autobiographical event recall in healthy individuals have emerged in recent years.

Research in clinical contexts

External memory aids can be effective tools for assisting individuals with memory impairments.[25] Although patients with memory deficits can experience difficulties with the retrieval of personal memories, there are few external memory aids intended to bolster memory for such autobiographical events. Wearable digital camera devices offer a promising method to help compensate for mnemonic difficulties owing to their automaticity in capturing photographs of one's day-to-day activities.[26] A number of experiments, many conducted as case studies on individual patients, have evaluated the SenseCam's efficacy in supporting autobiographical memory retrieval.

The first such study to appear in a peer-reviewed journal was a behavioral experiment by Berry *et al.*[26] on a 63-year-old patient with limbic encephalitis. This patient's bilateral hippocampal lesions, although relatively mild, resulted in difficulty retrieving both recent and remote autobiographical events. The researchers sought to evaluate whether the patient's ability to recall details about her life experiences could be improved by having her wear a SenseCam and periodically review the photographic record of any notable (i.e., nonroutine) events. Of particular interest was whether SenseCam-based rehearsal could outperform a more traditional written diary–based approach; these two life-logging methods were employed sequentially, each for at least a month. Throughout the study, the patient's husband periodically tested her ability to recall the details of recent life events, with each recall test followed by an opportunity to review the SenseCam photographs or diary entries that recorded these events. Although these two forms of life-logging are impossible to equate on all attributes, an effort was made to match the review procedure and manner of testing. Relative to the diary entries, rehearsal of SenseCam photographs was associated with substantial improvements in the patient's ability to recall the recorded events, even over long durations of time (e.g., 3 months) without the patient reviewing photographs between testing sessions. Moreover, her memory for events significantly increased with successive viewings of SenseCam photographs, but no such progressive benefit was observed in the diary condition. Despite a number of methodological shortcomings, this proof-of-concept case study provided support for the notion that the photographs captured by wearable cameras might be particularly efficacious as cues for triggering recall of autobiographical event details and bolstering the long-term retention of these memories. When fMRI data were later collected from this same patient,[27] greater activity was observed across a network of brain regions typically associated with autobiographical retrieval when the patient reported recognition of photographs of an event that she had previously rehearsed using the SenseCam reviewing procedure relative to recognition of SenseCam photographs for an event that had been exclusively rehearsed using the written diary procedure. Although such results cannot prove that SenseCam photographs helped this memory-impaired patient recollect her actual life events as originally experienced, rather than remembering the repeatedly viewed photographs of the events, these encouraging demonstrations of mnemonic benefits and heightened retrieval-related brain activity motivated a series of follow-up investigations.

Similarly encouraging results were obtained in another research team's case study of an amnesic patient with a large right-lateralized MTL lesion caused by herpes simplex viral encephalitis.[28] SenseCam cues were found to promote the recollection of significantly more contextual details for autobiographical events relative to cues derived from written diary entries. Importantly, these memory improvements were observed even when the SenseCam photographs were only used as cues for prompting episodic recall and not also used as opportunities for rehearsal. This suggests that the beneficial effects can extend beyond the strengthening of autobiographical memory traces through repeated study and retrieval practice. SenseCam-induced memory improvements were also apparent in a contemporaneous case study of a patient with mild cognitive impairment.[29] While this study provided the patient with opportunities to review the photographs captured by her camera (or, in the control condition, to review diary entries written by her husband) during the first 2 weeks, the advantages of the SenseCam procedure were well apparent even after 6 months had elapsed since her last event review session, with a twofold increase in the number of event features recalled. Relatedly, a study of six older patients diagnosed with mild-to-moderate Alzheimer's disease found that review of events through SenseCam images, in comparison with a written diary, resulted in the majority of patients being able to recall more event details in both the short term (2 weeks after the event) and long term (1 and 3 months afterward)[30] (Fig. 2). It is notable that all of the aforementioned studies reported that SenseCam photographs led patients to recall event details that were not themselves apparent in the images. This suggests that these automatically captured first-person snapshots might be particularly effective at triggering mnemonic pattern-completion processes,[31,32] perhaps by harnessing the functional contribution of any intact portions of the patients' hippocampi to bring associated event details back to mind. Indeed, Loveday and Conway[28] reported that their amnesic patient would occasionally experience a "Proustian moment"—a powerful flood of recollected details—when encountering her SenseCam photographs.

By virtue of enhancing patients' ability to remember events from their daily lives, use of the SenseCam may potentially bestow additional quality-of-life benefits. For example, rehearsal of events using SenseCam photographs resulted in diminished anxiety and stress as well as increased confidence for a patient with mild cognitive impairment.[29]

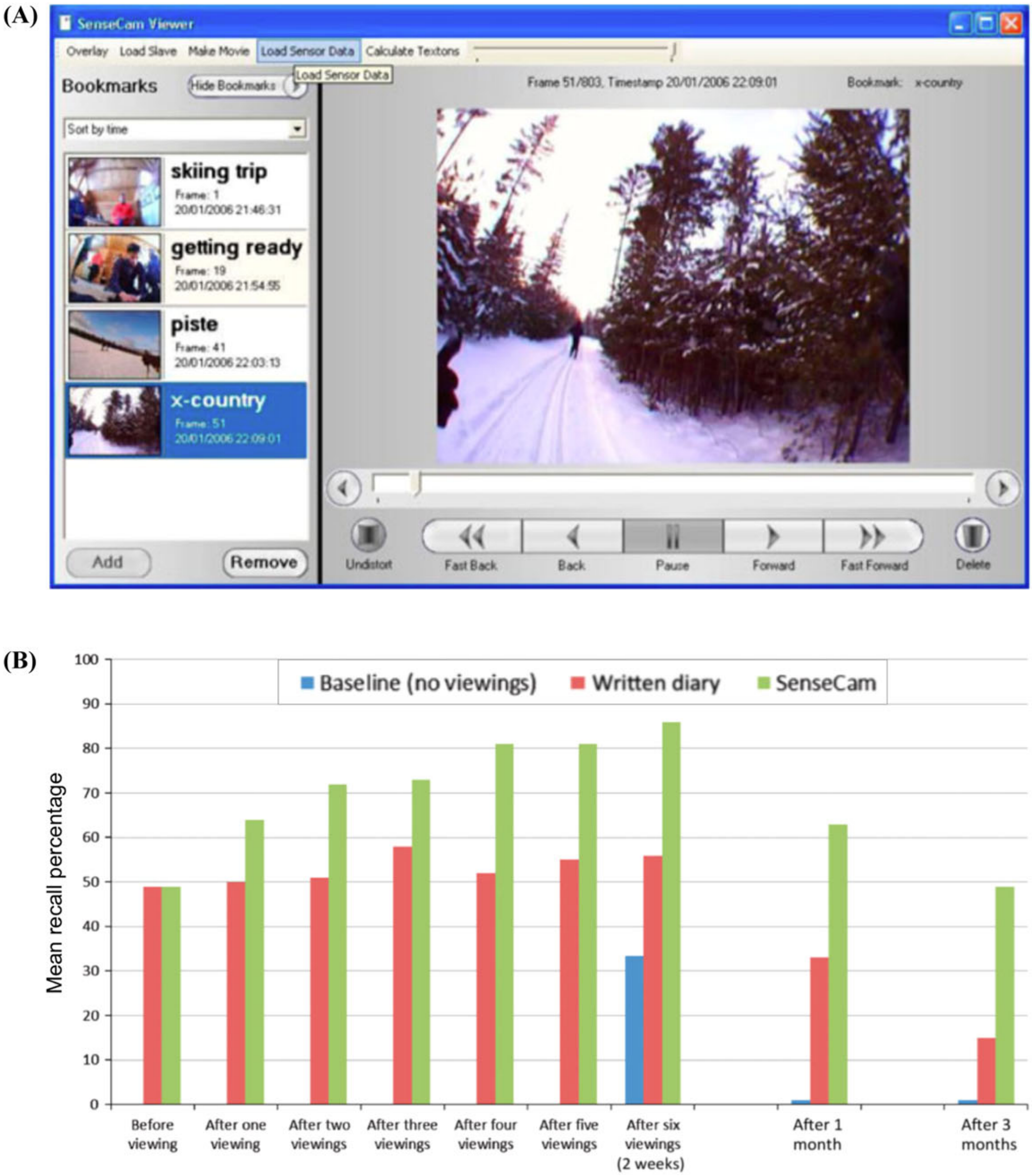

Figure 2. A comparison of autobiographical recall in patients with Alzheimer's disease when using different forms of external memory aids to review events. (A) Multiple experiments, particularly clinical ones, have included the process of revisiting event photographs captured by wearable camera devices. This study, in particular, allowed participants to review images using a software program called the SenseCam Viewer (Microsoft Research Cambridge). (B) Over the course of several months, participants with Alzheimer's disease were tested on their recall for experienced events. Their performance, in terms of mean recall percentage, is shown for the SenseCam condition, written diary condition, and the baseline condition (in which no review of the events was conducted). Memory for events rehearsed with the SenseCam review method steadily improved across successive viewings and outperformed diary-based rehearsal, with lasting improvements even after several months had elapsed since the last review opportunity. Figure adapted, with permission, from Ref. 30.

Relatedly, the SenseCam can be used within the context of psychotherapy for emotional events: for a patient with memory deficits and an anxiety disorder following acquired brain injury, the SenseCam was superior in evoking autobiographical memory retrieval, including the specific recall of anxiety-producing events and internal state information critical for cognitive–behavioral therapeutic intervention.[33] SenseCam review also decreased apathy and increased sense of self in an older patient with moderate Alzheimer's disease.[34,35] Similarly, a patient with memory impairment stemming from Korsakoff's syndrome demonstrated better recall for events captured and reviewed with the SenseCam, along with improved subjective ratings of identity.[21] In a larger study of 51 patients with mild Alzheimer's disease who were randomly assigned to one of three cognitive training programs, including a written diary and a SenseCam intervention, the SenseCam group showed significantly improved functional capacity and reduced depressive symptomology when measures were compared before the program and 1 week afterward.[36] However, these beneficial effects were transient and decreased when measured 6 months later, suggesting that continued SenseCam use might be necessary to maintain these subjective quality-of-life enhancements. In comparison with the SenseCam, anecdotal reports from patients and caregivers suggest that the written diary method was not as rewarding or effective and could even cause stress or tension with its use.[26,29,30,36]

It is important to consider what qualities of the photographs captured by wearable cameras make them so effective at cuing episodic recall and strengthening the later accessibility of event details. One advantage of photographs over verbal diary entries is the fact that pictorial stimuli are known to be associated with better memory than verbal stimuli.[37,38] Even if the people, objects, or landmarks depicted within a given photograph are insufficient to elicit recall of the specific episode, the high degree of perceptual correspondence between a first-person perspective photograph and the visuospatial context in which the event was encoded may facilitate recollection. Ample research has shown that mental reinstatement of a context, typically through the use of visual imagery, aids in the recovery of information that had been acquired in that context.[39,40] By providing potent visual cues to promote context visualization, photographs may accelerate the initial phase of the mental time travel process that is considered to be the hallmark of autobiographical recollection.[1,41,42] Furthermore, camera-based studies typically present participants with multiple images depicting the temporal unfolding of an event, which provides additional contextual information and increases the likelihood of there being sufficient cues for retrieval[43] while easing the demands on the executive system to engage in self-initiated episodic search processes. Indeed, it has been suggested that the viewing of brief, ordered sequences of photographs captured by wearable cameras may roughly approximate the time-compressed and fragmentary characteristics of actual endogenously retrieved autobiographical memories.[28] That said, a recent study that probed participants' memories with sequences of SenseCam photographs depicting events unfolding in either their original forward order or in a random order found only a small advantage in recall for the forward-order condition.[44] This could suggest that the overall amount of detail contained within the set of images is more consequential than the temporal dynamics conveyed in the sequence.

When SenseCam photographs are periodically shown to memory-impaired patients to help them remember recent events, the accessibility of these memory traces may be progressively strengthened through the well-documented memory-enhancing effects of spaced retrieval practice.[45–47] It is also possible, if not likely, that the details of the event memories will be altered to some degree by each viewing of the photographs. Reminder cues are thought to return stored memories to a labile state in which they are briefly amenable to updating—and distortion—before reconsolidation mechanisms act to stabilize the trace.[48] Although some efforts have been made to understand the mechanisms and long-term consequences of memory reactivation and updating in wearable camera paradigms,[49–51] more work will be needed to evaluate the contributions of retrieval practice and reconsolidation in memory-impaired patients using photographic review procedures as an external memory aid.

One significant limitation of studies comparing SenseCam-based review to diary-based review is the inherent difficulty of equating the event-logging and review procedures. Diary entries can differ wildly in composition, ranging from basic outlines or notes of important details[26,30] to more expansive entries recording event information in addition to associated emotions and thoughts.[29,36] While cameras are worn by the patient, diary entries are typically (although not always[28,36]) written by someone else—such as the patient's spouse[26,27,29,30] or the experimenter[30]—owing to concerns that memory-impaired patients would be unable to accurately log their daily events or that their efforts to do so would potentially alter their memories and bias the results. In an apparent trade-off between ease of implementation and precise experimental control, many experimenters have opted to involve patients' spouses in reviewing or testing procedures.[26–30] One study even had the experimenter assist some patients while other patients were assisted by their spouses.[28] Future camera studies incorporating diary review as a comparison condition should require that the same individual, preferably an experimenter, record diary entries to ensure consistency and should also limit spousal involvement in testing procedures to prevent potential subjectivity. Furthermore, most of the case studies reviewed above have probed patients' memories with a relatively limited number of life events. It would be useful for future studies to record and test a larger number of unique events to better understand wearable cameras' potential to cue retrieval for a broader range of memories.

In summary, studies examining the consequences of SenseCam use in memory-impaired patients have reported promising benefits for the accessibility and vividness of memories for personal events, often with concomitant improvements in subjective well-being. However, given that many of the results were derived from case studies on individual patients with heterogeneous memory disorders, caution is warranted in evaluating the robustness and generalizability of these effects. It is our hope that, as wearable cameras become more widely adopted as a tool for patient rehabilitation, psychologists and clinicians will continue to collaborate on larger-scale studies aimed at evaluating the factors that maximally affect the efficacy of this approach.

Behavioral research in nonclinical populations

Although wearable camera studies have demonstrated marked improvements in autobiographical recall for memory-impaired patients, an important question is whether this technology would also offer benefits to cognitively healthy individuals. Relatively few studies have examined unimpaired participants, but those that have done so have largely reported positive outcomes. One early study assessed whether young adults would show enhanced long-term retention of events that they rehearsed using an end-of-day SenseCam photograph review procedure.[52] Although substantial forgetting occurred across the 8-week interval of the experiment, participants' memories for reviewed events were more accurate in comparison with non-reviewed events, even when no explicit instructions were given to memorize the images.

Another study compared SenseCam and diary review protocols in groups of healthy younger and older adults and found that the SenseCam method enhanced autobiographical memory performance in both age groups.[53] Intriguingly, this study also found that the SenseCam condition was associated with broader enrichment of participants' cognitive function, as assessed by a battery of neuropsychological tests. The largest effects were observed for both memory and executive function tasks, including measures of semantic, verbal, and working memory. Participants' subjective reports indicated that reviewing photographs not only cued more memories than reviewing diary entries, but also produced a better sense of reliving. This is in line with previous SenseCam studies of clinical populations.[26,27,29] To explain the performance gains on neuropsychological measures, the researchers speculated that SenseCam-based rehearsal may serve as a short-term cognitive stimulant, potentially by virtue of the photographs being interesting and pleasurable to look at, which, in turn, can heighten alertness.[53] While potentially promising, these findings of generalized cognitive enhancement should be replicated to confirm whether the benefits of SenseCam use are as far-reaching as these researchers have claimed. A more recent study also compared the effects of SenseCam use in younger and older adults to examine the benefits of SenseCam images as retrieval cues.[44] Relative to cuing memories with participant-generated event titles, cuing with SenseCam photographs led to improved recall (including of details not apparent in the images) in both age groups, with no significant effects of aging. The apparent lack of age differences in these two studies is surprising, given other work showing age-related changes in behavioral performance and neural engagement during autobiographical recall.[54] Further exploration will be helpful to evaluate what experimental design considerations might affect the degree to which younger versus older adults' memories benefit from photographic rehearsal and cuing. Indeed, the data indicating memory improvements in younger adults are somewhat mixed. Although others have reported a similar benefit of SenseCam-based memory cuing over verbal cuing in younger adults,[55] one large study examining the effects of SenseCam review procedures—versus diary review or no review—found no improvements in memory recall when participants were tested 1 week later.[56] Given the methodological differences in these various experiments, more research is needed to delineate the boundary conditions that determine the utility of wearable cameras as a memory aid for cognitively healthy individuals.

Neuroimaging research in nonclinical populations

The integration of wearable cameras into fMRI studies has helped to elucidate the neural mechanisms underlying autobiographical memory retrieval by incorporating naturalistic stimuli to assess participants' memories for real-world events. After briefly reviewing the neuroimaging literature on autobiographical memory, we will discuss the insights that have emerged from the seven fMRI experiments published to date that have used wearable cameras photographs as memory probes in cognitively healthy adults. With the exception of the case study by Berry *et al.*[27] discussed above, wearable cameras have yet to be incorporated into neuroimaging studies of memory-impaired patients or other clinical populations.

Autobiographical memory retrieval involves recruiting a predominately left-lateralized network of distributed brain regions.[11,57] These include MTL areas such as the hippocampus and parahippocampal cortex, which are critically important for recollection processes, as well as regions of the temporoparietal junction, lateral temporal cortex, and posterior parietal cortex.[11,57] Medial regions of the prefrontal cortex (PFC) contribute to the representation of one's self as an agent in the memory, as well as the broader schema of the event, while more lateral PFC regions mediate episodic search processes and the selection and maintenance of search results.[11,57–59] Additionally, occipital regions, the precuneus, and the amygdala contribute to the retrieval of mnemonic representations through processes involving visual imagery and emotion.[5] The posterior cingulate cortex and retrosplenial cortex are also thought to support recollection by facilitating mental reconstruction of the visuospatial reference frame.[57,60,61] This set of regions has been consistently associated with autobiographical memory retrieval throughout the neuroimaging literature,[3,5,11,57–59] although some studies have suggested more bilateral[62,63] or right-lateralized involvement.[64,65]

Neuroimaging studies have used photographic stimuli derived from the SenseCam to assess the neural correlates of recollection and familiarity during autobiographical recall of real-world events. Milton *et al.*[66,67] evaluated these processes as a function of memory remoteness. The researchers first studied recent memories,[66] where participants were scanned approximately 36 h after photograph acquisition. A modified remember/know paradigm was used during the fMRI scan session to assess recall as participants were shown SenseCam images generated from their own lives as well as the lives of other participants. Recollected and familiar events evoked activity in overlapping brain regions previously associated with autobiographical retrieval, including the posterior cingulate, right inferior parietal lobe, and right dorsolateral PFC. However, recollection elicited greater activity in the right posterior and anterior parahippocampal gyrus as well as the mPFC, whereas familiarity elicited greater activity in the right ventrolateral PFC and bilateral cingulate gyrus. These findings are broadly consistent with previous studies of recollection and familiarity.[68,69] Moreover, the activity of the right hippocampus and posterior parahippocampal gyrus increased parametrically as participants' retrieval experiences increased from weakly familiar to strongly recollected. It is unclear whether these effects should be attributed to quantitative differences in memory strength or qualitative differences in the subjective attributes of retrieval (e.g., the degree of contextual reinstatement). However, the fact that these regions' activity increased between weak recollection and strong recollection trials supports the notion that recollection may not be an all-or-none phenomenon, but rather may operate as a continuously varying or graded retrieval process.[70,71]

Milton *et al.*[67] then scanned the same participants 5 months after last wearing the SenseCam in the original study[66] while they performed the same recognition memory task in order to evaluate the neural mechanisms of recollection and familiarity for remote autobiographical memories. Compared with the previous 36-h retention interval, photographs depicting events that had transpired approximately 5 months earlier showed decreased neural activation related to both recollection and familiarity in the right hippocampus and parahippocampal gyrus. Indeed, for these remote memories, recollection-related MTL activity no longer exceeded that observed during familiarity-based responses or correctly rejected novel images. Consistent with the standard consolidation model, which predicts reduced MTL involvement and increased neocortical involvement as memories become more temporally remote,[72] the researchers only found recollection-related activity for 5-month-old memories in neocortical regions, such as the mPFC. However, it should be noted that the second fMRI experiment from Milton *et al.*[67] had a relatively small sample ($n = 10$), limiting their experimental power. Additionally, owing to the small number of unique events captured by the cameras, they opted to use the same stimuli for both the short-delay and long-delay scanning sessions, so the neural representations of the remote memories may have been somewhat altered by this retrieval practice. Fortunately, more work is underway to investigate the effects of both temporal remoteness and retrieval practice on the neural correlates of real-world memories.[73]

St. Jacques and her collaborators have also used wearable cameras to conduct a set of fMRI studies assessing the neural mechanisms of autobiographical memory retrieval for real-world events. Their first study[74] investigated how the processes associated with mentally projecting oneself into specific events from one's past differ from those supporting the simulation of another individual's perspective. Participants wore the SenseCam while concurrently keeping a written record of daily activities. One week after last wearing the SenseCam, participants underwent fMRI scanning and were presented with photographs from their own lives as well as from the lives of other individuals and instructed to either retrieve the depicted events or comprehend the depicted event from another individual's perspective. Overall, SenseCam photographs allowed participants to strongly re-experience their personal past as well as understand another individual's perspective. Not surprisingly, projection into one's own past evoked greater activity in areas previously implicated in autobiographical memory retrieval, including the bilateral ventrolateral PFC, left hippocampus, posterior midline regions, and lateral temporal regions. However, an interesting dissociation was observed within the mPFC, such that projection into one's own past preferentially recruited a ventral component of the mPFC, whereas projection into someone else's past preferentially recruited a more dorsal component of the mPFC.[59,74] Task-related functional connectivity further established the different contributions of dorsal and ventral mPFC regions: the ventral mPFC showed greater connectivity with regions of the hippocampus and precuneus associated with episodic retrieval memory processes, whereas the dorsal mPFC demonstrated greater connectivity with areas of the frontoparietal network associated with control processes. These results provided novel evidence that ventral and dorsal mPFC regions support dissociable forms of self-projection.

Data collected from the aforementioned study were also used to examine putative gender differences in autobiographical recall evoked by visual versus verbal retrieval cues.[55] During the fMRI scanning session, memories were cued by either a sequence of SenseCam photographs (dynamic visual cue) or a short textual description (verbal cue). Men demonstrated greater neural activity during the reliving of memories elicited by the visual cues, relative to the verbal ones, in regions associated with autobiographical memory, including the left hippocampus, left interior frontal gyrus, right occipital cortex, and retrosplenial cortex. In comparison, women were equally sensitive to both types of cues, such that neural activity did not differ significantly in response to reliving prompted by verbal or visual stimuli. These results could have important implications for studies using camera-based life-logging procedures to bolster autobiographical retrieval in patient populations, as males and females may experience differences in the relative efficacy of photographs versus diary entries as memory prompts.

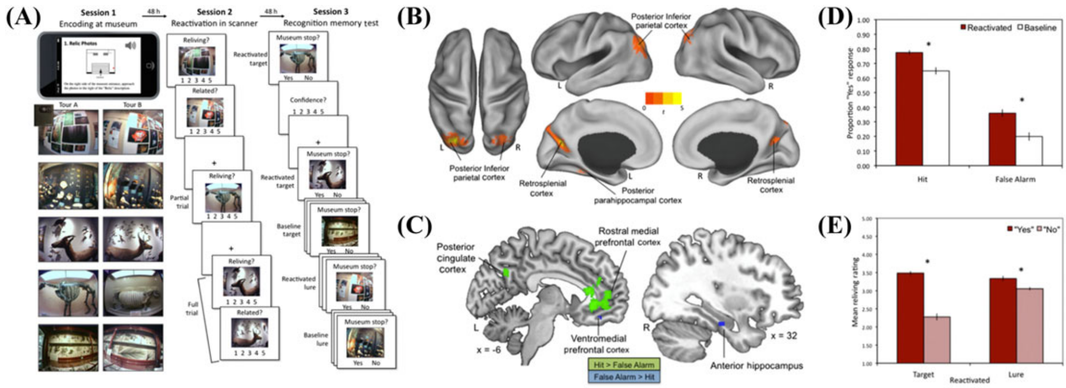

Figure 3. Common and distinct neural areas associated with subsequent true and false autobiographical memories. (A) The experimental design included three phases. Session 1 involved the encoding task, where participants engaged in a museum tour. Session 2 involved reactivation during the fMRI scan session, where participants were presented with images from museum stops they had visited ("targets") and prompted to make ratings of their sense of reliving ("partial trial"). A subset of trials in the second session ("full trial") also presented an image from an alternate museum tour ("lure") and prompted participants to rate the relatedness of the two images. Session 3 involved the recognition memory test: participants were presented with targets and lures that were either from the second session or were completely novel ("baseline") and were prompted to indicate whether the images contained a museum stop that had been visited. (B) Subsequent true memories (target images that were later recognized) and subsequent false memories (lure images that were later reported as recognized) were associated with activation in several common brain areas, including the left parahippocampal cortex, bilateral retrosplenial cortex, and bilateral posterior inferior parietal cortex. (C) However, different brain regions were associated with reactivation quality for subsequent hits and false alarms. For memories with high reliving ratings during target presentation relative to lure presentation, subsequent hits showed greater reactivation-related activity in regions like the rostral mPFC and posterior cingulate cortex, while subsequent false alarms showed greater reactivation-related activation in the right hippocampus and ventral mPFC. (D) Behavioral results from the recognition memory test demonstrated increased rates for hits and false alarms for reactivated images relative to baseline ones. (E) Behavioral results indicated that the quality of memory reactivation differed on the basis of recognition memory performance. Mean reliving ratings were greater for hits (responding "yes" to a target) relative to misses (responding "no" to a target). Mean reliving ratings were also greater for false alarms (responding "yes" to a lure) in comparison to correct rejections (responding "no" to a lure). Figure adapted, with permission, from Ref. 50.

In another cleverly designed fMRI experiment incorporating wearable cameras, St. Jacques *et al.*[50] investigated how the neural mechanisms associated with the cued reactivation of event memories can contribute not only to the subsequent strengthening of these memories but also, under certain circumstances, to their distortion. Participants in their study were given Vicon Revue cameras to wear as they completed a self-guided museum tour (Fig. 3). Two days later, participants underwent fMRI scanning while they were presented with photographs from their own cameras to trigger memory reactivation for events they had experienced during their museum tour, with a subset of these images followed by a new lure photograph derived from an alternative version of the museum tour that participants had not actually experienced. Then, 2 days after the scan, participants completed a recognition memory task where they were presented with photographs of reactivated targets and lures that had been previously encountered in addition to novel photographs of targets and lures. Not surprisingly, events that had been reactivated received a boost in subsequent memory. However, participants also reported increased recognition of photographs depicting event elements that they had not actually experienced in real life but which had become falsely woven into their memories of real events through the presentation of lure images during the reactivation session. This reactivation-induced memory distortion was consistent with the findings of the researchers' previous behavioral experiment,[51] setting the stage for their investigation into the neural correlates of this robust and putatively adaptive[75] quirk of episodic memory.

When these researchers examined the fMRI activity associated with photographs that participants would subsequently claim to remember, they found a number of regions that showed increases in activation (relative to subsequently forgotten events), regardless of whether these memories were true or false. These regions—which included the bilateral posterior inferior parietal cortex, left posterior parahippocampal cortex, and bilateral retrosplenial cortex—also showed sensitivity to the degree of reliving reported by participants during the scanning session. Further examination of these regions' responses during lure trials revealed that the lure photographs that went on to later be correctly rejected by participants (indicating that they were not falsely integrated into the original memory trace) were associated with low activity levels at the time the lure appeared on the screen, whereas the lure photographs that went on to be falsely remembered as real experiences were associated with sustained involvement of these areas during both initial reactivation and lure presentation. In addition to finding that these regions' activity predicted both true and false subsequent memories, the analyses also identified regions that were uniquely associated with true or false subsequent memories. For trials with high reliving ratings, comparing target presentation relative to lure presentation demonstrated that subsequently true memories evoked greater activity in the posterior cingulate and rostromedial PFC, whereas subsequently false memories evoked greater activity in the ventrolateral PFC, ventral mPFC, lateral temporal cortex, and right anterior hippocampus. Taken together, these findings help to clarify the neural processes at work when revisiting photographs of a past event, showcasing how some of the same regions involved in strengthening the representation of a true memory can also contribute toward the creation of a (at least partially) false one because of the inherent malleability of memory traces immediately following reactivation.

On the basis of the success of this experimental paradigm, it was later adapted in a behavioral study to assess differences in reactivation processes between healthy younger and older adults.[49] Consistent with prior findings,[50,51] reactivation quality affected subsequent memory such that photographs that evoked greater reliving ratings during the reactivation phase were more likely to lead to subsequent hits or, in the case of lure stimuli, subsequent false alarms during the recognition phase. Furthermore, in line with the broader literature on age-related increases in the frequency of false remembering,[76] older adults exhibited significantly more false alarms than younger adults. But despite this overall increase in false memories, older adults showed a smaller impact of reactivation on subsequent recognition performance. Accordingly, aging appears to diminish the ease with which episodic memories can be updated. Although this property likely has negative consequences in many circumstances in which it is desirable to update one's memory on the basis of new information, it also has the somewhat counterintuitive positive consequence of making the memories of older adults less vulnerable to reactivation-induced distortions. These data thus help to advance our understanding of how the critical process of memory updating changes over the life span.

In another innovative investigation into the brain mechanisms that support memory for real-world events, Nielson *et al.*[24] gave their participants customized neck strap–mounted smartphones to record photographs, along with corresponding GPS coordinates, of their experiences over a period of roughly one month (Fig. 4). The participants then underwent fMRI scanning, during which each was presented with individual photographs from their smartphone's camera and instructed to mentally relive each experience. The resulting fMRI data were analyzed using multivoxel pattern analysis (MVPA), a methodological technique that differs from traditional univariate analyses by assessing the spatial pattern of brain activation, rather than the peak of activation, which can allow for greater sensitivity.[77–79] Using a variant of MVPA known as representational similarity analysis, the fMRI activity patterns from individual trials were compared with one another and their dissimilarity (i.e., "neural distance") was computed. When the researchers attempted to relate the neural distance between pairs of events to the spatial distance between them (i.e., how much geographic distance separated the locations where the probe photographs were captured), they found that activity patterns within the left anterior hippocampus could be used to predict spatial distances between events, ranging from 100 m to 30 km. Strikingly, this same region was found to also carry information about the temporal distance between events, such that events that took place further apart in time (e.g., 1 month) showed greater neural distance than events that occurred closer together in time (e.g., 15 h). These results demonstrate lateralization in the hippocampal computations

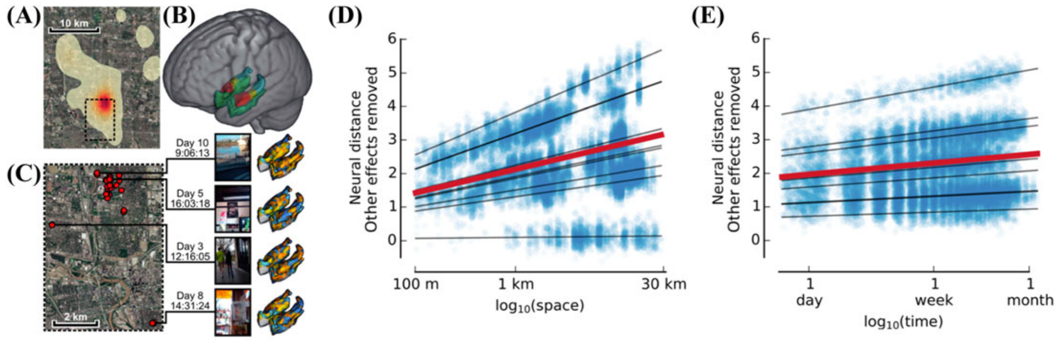

Figure 4. The spatial and temporal distance between autobiographical events scales with the dissimilarity of neural activity patterns ("neural distance") in the left anterior hippocampus. (A) A heat map representing locations in Columbus, Ohio where participants' images were captured by wearable GPS-enabled smartphones. (B) Regions of interest in the medial temporal lobe: anterior hippocampus (red), intermediate hippocampus (yellow), posterior hippocampus (blue), and parahippocampal cortex (green). (C) Select event locations for a single participant, where each red marker indicates a photograph that was presented during the scan session. The time and corresponding location of four sample photographs are included, along with the associated heat maps of the single-trial activation parameter estimates in the right and left hippocampus. (D and E) When the effects of other factors were eliminated from the model, neural distance within the left anterior hippocampus was correlated with both spatial distance (D) and temporal distance (E). Each blue marker indicates a pair of photographs shown to participants, with the black lines representing the estimated neural distance from each participant's regression results and the red lines indicating the averaged estimated neural distance across all participants. Figure adapted, with permission, from Ref. 24.

supporting the recall of autobiographical event details, with the left anterior hippocampus playing a particularly important role in representing and integrating the spatiotemporal characteristics of personal episodes. This study nicely illustrates the potential for wearable camera technology to provide valuable information, such as geographical and temporal tagging of real-world experiences over many weeks, which could not be easily ascertained through other methods. This in turn allows for an enriched understanding of how the spatial and temporal features of event knowledge are represented in the brain.

Most recently, Rissman *et al.*[20] examined the degree to which an individual's level of memory for personally experienced events can be decoded on the basis of distributed fMRI activity patterns measured in response to wearable camera photographs (Fig. 5). After wearing a Vicon Revue camera for 3 weeks, participants were scanned while viewing brief sequences of photographs depicting events from their own lives or from other participants' lives. Participants indicated their subjective retrieval experience with one of eight response options, which included varying levels of novelty, familiarity, and recollection. Using MVPA methodology, the neural activation patterns associated with individual trials were used to train a logistic regression classifier algorithm, which learned the distributed patterns of activity most capable of distinguishing between each of the subjective retrieval outcomes. The classifiers were then used to predict the mnemonic state of trials on which the model had not been trained. The results revealed extraordinarily accurate classification (>90% correct) of whether each probed memory was from one's own life or someone else's life. Classifiers could also decode more nuanced information about the subjective qualities of one's remembrance, such as whether the photographs evoked a strong or moderate sense of recollection, familiarity, or novelty. These neural signatures of autobiographical retrieval were found to be stable across retention intervals of up to 1 month, as well as highly consistent across participants. Assessment of the classifier-based "importance maps" provided insights into which brain regions provided diagnostic signals for each mnemonic classification scheme. For instance, when classifying hits versus correct rejections, an extensive set of lateral frontoparietal regions were highly predictive of participants' own events, whereas activity in visual regions, such as occipital and inferior temporal areas, tended to be predictive of novel photographs from someone else's life. When classifying between trials where participants reported recollection of contextual details versus trials associated with only familiarity-based

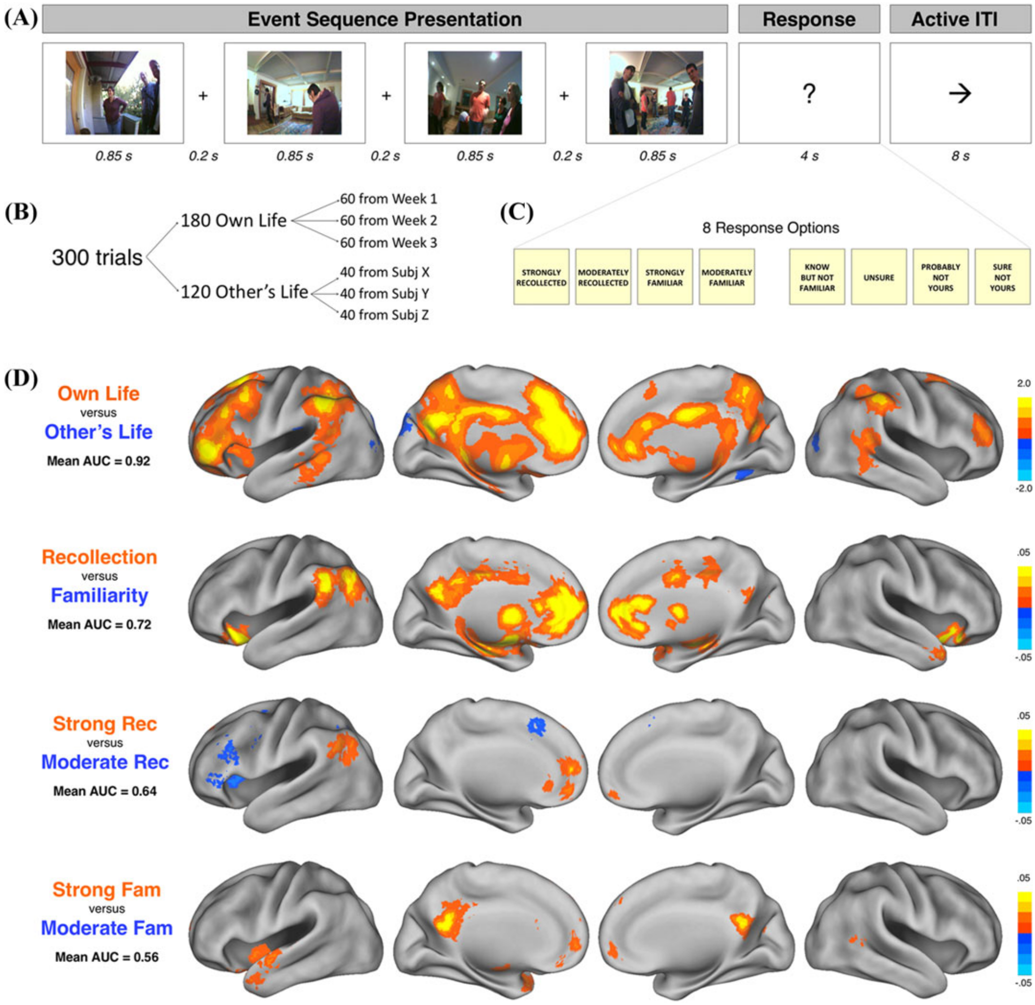

Figure 5. Decoding neural signatures of autobiographical event retrieval. (A) On each trial of the fMRI session, participants viewed a sequence of four photographs depicting the temporal unfolding of an event and then made a judgment indicating their level of memory for the event. (B) For each participant, experimental trials included photographic sequences from their own life, across the span of the 3 weeks they wore their camera device, as well as sequences from the lives of three other participants. (C) The response options for participants during the scan session range from reporting strong recollection of the depicted event to expressing high confidence that the event was not from one's own life. (D) Maps of classifier importance values, associated with four different binary classification analyses, averaged across participants. Warm colors depict voxels where increased activation biased the classifier to predict that a trial was associated with the condition listed in orange print, whereas cool colors depict voxels where increased activation biased the classifier to predict that a trial was associated with the condition listed in blue print. For each classification, decoding performance is reported as the mean area under the receiver operating characteristic curve (AUC). Rec, recollection; Fam, familiarity. Figure adapted, with permission, from Ref. 20.

recognition, regions most diagnostic of recollection included the hippocampus and parahippocampal cortex, as well as medial frontal areas and parietal regions, such as the retrosplenial cortex and posterior cingulate cortex, along with the left angular gyrus. These results build upon earlier efforts to decode memory-retrieval states associated with laboratory-encoded visual stimuli[80] by extending such effects to real-world events and showcase the ability of fMRI to differentiate between subtle gradations in the strength and subjective quality of one's memory.

Taken together, wearable cameras have been utilized by memory researchers to capture photographs of real-world experiences that can later be presented in the fMRI scanner to probe various aspects of autobiographical memory (the main findings of these fMRI studies are summarized in

Table 1. Neuroimaging research in nonclinical populations

Experiment	Camera protocol	Memory protocol	Main findings
Milton *et al.*[65]	• 15 healthy participants (18–25 years old) • 2-day SenseCam capture of daily events	• fMRI scan occurred ∼36 h after camera was worn. • Modified remember/know paradigm used to test recognition memory in response to presentations of participants' own photos or photos from other individuals.	• Recollection elicited greater activity in the mPFC and right parahippocampal gyrus. • Familiarity elicited greater activity in the right ventrolateral PFC and bilateral cingulate gyrus. • Regions including the right hippocampus, right parahippocampal gyrus, and mPFC were parametrically modulated by the subjective strength of recollection.
Milton *et al.*[67]	• 10 healthy participants (18–25 years old) • 2-day SenseCam capture of daily events	• fMRI scan occurred ∼5 months after camera was worn. • Extension of Milton *et al.*[66] using the same memory protocol with identical photos presented in both scan sessions.	• Relative to recently encoded memories, remote memories showed decreased recollection and familiarity-related activity in the right hippocampus and parahippocampal gyrus. • Neocortical regions, including the mPFC, continued to be recruited during retrieval of remote memories.
St. Jacques *et al.*[74]	• 23 healthy participants (18–35 years old) • 6-day SenseCam capture of daily events	• fMRI scan occurred ∼1 week after the last day the camera was worn. • Each trial presented a dynamic sequence of 40 photos depicting an event from the participant's life or someone else's life. • Participants were instructed to mentally project themselves into each event, rating either reliving for their own life events or understanding for other's life events.	• Self-projection preferentially engaged the ventral mPFC, while projection into another's perspective preferentially engaged the dorsal mPFC. • The ventral mPFC showed greater task-related functional connectivity with regions of the MTL network associated with memory processes. • The dorsal mPFC demonstrated greater task-related functional connectivity with areas of the frontoparietal network associated with control processes.
St. Jacques *et al.*[55]	• 23 healthy participants (18–35 years old) • 6-day SenseCam capture of daily events	• fMRI data collected at the same time as St. Jacques *et al.*[74] • Trials comprised either photo sequences or verbal retrieval cues describing events from the participants' lives. • Participants were given instructions to recall each event and rate their reliving.	• Women were sensitive to both visual and verbal cues, with no significantly different activity. • Men were more sensitive to visual cues, which evoked greater activity in areas associated with autobiographical memory retrieval, including the left hippocampus.

Continued

Table 1. ***Continued***

Experiment	Camera protocol	Memory protocol	Main findings
St. Jacques *et al.*[50]	• 35 healthy participants (18–30 years old); 26 included in the fMRI analysis • ∼4- to 5-h Vicon Revue capture of a self-guided museum tour	• The experiment included 3 sessions with 48 h between each: (1) museum tour while wearing camera, (2) fMRI scan session (reactivation phase), and (3) recognition test. • During fMRI scan, participants' camera photos were used to cue recall of museum tour stops and participants rated their reliving. • On some fMRI trials, after a participant's own photo was shown, a lure photo from an alternate version of the museum tour was presented, and the participant judged how related the depicted exhibit was to the one in their own photo.	• Reactivated events increased both true and false subsequent memories, depending on reactivation quality. • Common regions associated with true and false subsequent memories included the left posterior parahippocampal cortex, bilateral posterior parietal cortex, and retrosplenial cortex. • Subsequently true memories were associated with greater activation in regions such as the rostromedial PFC, while subsequently false memories were associated with greater activation in areas including the ventrolateral PFC, ventral mPFC, and right hippocampus.
Nielson *et al.*[24]	• 9 healthy female participants (19–26 years old) • Participants wore smartphones for ∼1 month to record daily events as well as their time and GPS coordinates	• fMRI scan took place 1-3 weeks after the camera-wearing period concluded. • Photos from participant's camera were presented one at a time to cue retrieval, with participants indicating whether they recalled the depicted event, and how vividly.	• Representational similarity analysis searched for MTL areas where the "neural distance" between pairs of events was related to the spatial or temporal distances between pairs. • The left anterior hippocampus was found to represent recalled autobiographical events' spatial features for distances ranging from 100 m to 30 km. • The left anterior hippocampus was also found to represent the temporal features of recalled autobiographical events for times ranging from 15 h to 1 month.
Rissman *et al.*[20]	• 16 healthy participants (18–22 years old) • 3-week Vicon Revue capture of daily events	• fMRI scan occurred 6–9 days after the camera-wearing phase concluded. • Participants were presented with sequences of four photos depicting events from their own life or from other participants' lives. • Participants used one of eight response options—which included levels of recollection, familiarity, and novelty—to indicate their retrieval experience.	• Participants' subjective retrieval experience could be reliably decoded from fMRI activity patterns. • The neural signatures associated with autobiographical retrieval were highly consistent across participants and were stable up to a 1-month retention interval. • Regions most diagnostic of recollection (vs. familiarity) included the hippocampus, parahippocampal cortex, left angular gyrus, medial frontal areas, and parietal regions.

Table 1). The results have largely corroborated the field's prior characterization of the neural substrates of autobiographical recall, as derived from studies using laboratory-based techniques for probing participants' memories for past events. In this sense, rather than upending our understanding of the core cortical and MTL brain systems that support event retrieval, camera-based fMRI paradigms have helped confirm that these mechanisms can generalize to the retrieval of real-world memories encoded in naturalistic settings. That said, this emerging literature contains a number of novel findings, including the dissociation between ventral and dorsal mPFC contributions to the reliving of a personally experienced event memory versus projecting oneself into an event experienced by someone else,[74] the graded nature of neural representations of episodic recollection and familiarity,[20,66,67] hippocampal lateralization in the representation of spatiotemporal information associated with personal events,[24] the differential sensitivity of men and women to verbal versus visual retrieval cues,[55] and the mechanisms of reactivation-induced distortion of real-world event memories.[50] Although there are certainly circumstances in which the enhanced experimental control over exposure duration, attentional allocation, and event content provided by laboratory stimuli can outweigh the enhanced ecological validity provided by wearable camera stimuli, we believe that the fMRI studies reviewed above have provided an important first step toward showcasing the viability of more naturalistic paradigms for cataloging people's day-to-day experiences and characterizing the brain processes evoked during their retrieval.

Discussion

Wearable camera technology has not only been used to enhance individuals' memories, but has also been instrumental as a tool for studying the cognitive and neural processes that support autobiographical memory. The integration of wearable camera technology into behavioral and fMRI experiments permits more ecologically valid assessments of autobiographical memory retrieval by providing detail-rich, personally relevant cues that evoke specific experiences. As such, wearable camera photographs may better capture the complex phenomenological properties of real-world memories than laboratory-based stimuli. Like other prospective experimental methods for logging one's day-to-day experiences, these nonintrusive camera devices allow for some degree of experimental control, but critically avoid other techniques' potential for interfering with the encoding process.[11] Although integration of wearable camera technology with neuroimaging approaches to assess healthy adult populations has only occurred recently, these techniques have been effectively used to evaluate the contributions of various cortical and MTL regions to the recollection of events from one's personal past. While several other review articles on wearable cameras have recently appeared, they predominantly focus on the devices' rehabilitative applications and do not comprehensively cover extant neuroimaging experiments.[81–83] The combination of wearable camera technology and neuroimaging methods may prove to be a powerful approach that helps further elucidate the complexities of autobiographical recall for real-world events.

Despite the many promising findings highlighted in our review, this still-small body of research suffers from a number of limitations that will be important to address as the field moves forward. Many of the clinical studies investigating the use of wearable cameras as a therapeutic tool for bolstering retention of autobiographical memories in memory-impaired patients have derived their results from single cases or very small cohorts. Given the heterogeneity of these patients, as well as of the experimental procedures of individual studies, it is hard to specify which types of patients will be most amenable to the benefits of wearable cameras and which protocol for photographic review will be most effective. These limitations could begin to be addressed by larger-scale clinical trials featuring more careful control over the procedures for selecting photographs for patients to review, as well as the structure and timing of the memory rehearsal and testing sessions. Efforts should also be made to address the demographic disparity in the wearable camera literature. The majority of clinical experiments have focused on older adults with memory impairments, whereas nonclinical experiments have primarily assessed healthy, younger adults. In order to evaluate the generalizability of extant findings, it would be helpful to know whether memory-impaired younger adults could benefit from wearable cameras, and more behavioral and neuroimaging studies should be done using wearable cameras in cognitively healthy older adults.

On the basis of our own experiences, as well as those described in other studies, there are many practical challenges inherent in the implementation of camera-based experimental paradigms. One difficulty is participant compliance: even with careful instructions, participants may not wear their cameras in the "on" mode for long enough to generate a sufficient number of photographs or to capture enough unique events. Even if cameras were worn as instructed, it is possible to capture repetitive and generic daily events that may not be memorable or personally relevant.[20,23,66] Given the variability of life experiences across participants, or even variability within participants across days, it can be hard to adopt universally applicable guidelines for selecting photographs for use as memory probes. Furthermore, in some experimental paradigms, participants' cameras can generate several thousand photographs,[20,52,84] so combing through these images in search of optimal stimuli can be an incredibly labor-intensive process. Other issues pertain to image quality. Despite ongoing improvements in wearable camera technology, it can be difficult to capture photographs under low-light conditions [23,24,26,44] or during periods of movement.[24,66] One study estimated that 93% of their smartphone images were unusable owing to image quality or repetitiveness,[23] but even uneventful photographs may be able to cue memory retrieval.[85] It is also hard to know whether a camera wearer was paying attention to his or her surroundings at the time that a given photograph was recorded; a seemingly interesting event could have been captured by a camera while its wearer was looking elsewhere or consumed by unrelated thoughts. Although these issues may make camera-based studies more challenging to implement than other memory experiments, the advantages provided by such paradigms in facilitating the study of real-world autobiographical memories—for which the details can be verified by photographs, timestamps, and sometimes even GPS coordinates—may outweigh the obstacles.

As video-enabled wearable camera devices achieve increasingly greater storage capacity and battery life, researchers should explore what added utility video might provide for clinical applications and cognitive neuroscience research studies. Furthermore, if audio recordings are also collected, then this combination may provide additional contextual details (e.g., recognizable voices, interpersonal dialogue, environmental sounds) to aid retrieval. Indeed, audiovisual stimuli typically evoke better recognition memory performance than either modality individually.[86] However, legal issues and privacy concerns pertaining to the surreptitious recording of conversations may ultimately limit the viability of audio and audiovisual life-logging technology. Future research efforts should remain mindful of such user-experience considerations.[87,88]

Since the literature regarding camera-based investigations of autobiographical memory retrieval is still nascent, the field is ripe with underexplored research questions that could be approached with this technology. For instance, it could be informative to deploy wearable cameras to examine how people's memories may be affected through social interactions with other individuals, including the effects of photo sharing (e.g., through social media applications) on memory accuracy and retention. Studies could also provide cameras to groups of individuals who experience the same events from different vantage points. The resulting photographs could provide a unique opportunity to assess the viewpoint specificity of real-world memories. This research direction may be of particular interest in applied settings concerned with the detection of autobiographical memories for specific past experiences.[20,89–92] In sum, although wearable camera technology has already been productively used to further our understanding of autobiographical memory retrieval—and in some circumstances, to rehabilitate its deficiencies—we hope that these devices will provide many exciting opportunities for future research into the recall of real-world events.

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Competing interests

The authors have no competing interests to report.

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