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Does memory research have a realistic future?

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How do we remember our past experiences? This question remains stubbornly resistant to resolution. The next 25 years may see significant traction on this and other outstanding issues if memory researchers capitalise on exciting technological developments that allow embodied cognition to be studied in ways that closely approximate real life.

When asked to look forward to what the next 25 years of cognitive research might bring, as befits a memory researcher, I immediately looked backwards, in fact to more than 25 years ago. A pandemic-afforded clear-out unearthed my younger self's musings about the key outstanding questions in cognitive research. My prime candidate seems to have been 'Remembering things that happen to us – HOW ON EARTH DO WE DO THIS?!!' (Figure 1). A Venn diagram accompanied this vexed question showing two components 'The World' (containing a question mark) and 'The Lab'. Nothing if not consistent, my main interest in the decades since has been in natural cognition and behaviour, the sort that occurs in everyday life even, or especially, when cognitive scientists are not around [1,2].

Specifically, I and others seek to understand how we learn to find our way around in the world – spatial navigation – and remember the experiences that happen to us along the way – autobiographical memories – both of which are critical for survival and independent living. Those of us additionally interested in how memory and related behaviours arise from the brain – cognitive neuroscience – deploy paradigms involving virtual reality and autobiographical memory recall with healthy volunteers and patients with brain lesions that compromise memory. We also adapt these tasks for confined environments such as MRI and magnetoencephalography (MEG) scanners. Much progress has been made, and yet, frustratingly, the aforementioned vexed memory question remains essentially unanswered.

Two barriers, in particular, have impeded progress. The first involves the dominant ethos in the memory field, which prescribes the use of simplified, highly controlled stimuli and paradigms. Data are acquired under these restricted conditions, they inform a simple model of a memory computation, process, or related behaviour, which then generates predictions about performance on similar memory tasks. This reductionist approach has been abetted by MRI and MEG which, with their requirement for head-restrained participants, are well suited to hosting highly controlled memory tasks. The relative ease with which these memory experiments can be conducted is appealing, and their elegance, rigor, and reliability epitomise the traditional scientific method.

Findings from these experiments are also often used to make inferences about real-world memory, for example, generalising from learning and retrieval of object or word pairs to how autobiographical memories of our life experiences are formed and recollected. However, the assumption that simplified memory tasks have direct relevance for understanding memory processing in the real world may be fundamentally flawed [3–6]. A meta-analysis of functional MRI studies, for instance, showed that laboratory-based and autobiographical memory retrieval tasks differ substantially in terms of their neural substrates [7], suggesting that some of the associated cognitive processes may also diverge. Why might this be the case? As noted by Nastase *et al.* [3], back in 1966, Bannister [8] identified a likely reason: '…[memory researchers]…construct situations in which our subjects are totally controlled, manipulated, and measured. We must cut our subjects down to size. We construct situations in which they can behave as little like human beings as possible and we do this in order to allow ourselves to make statements about the nature of their humanity.'

By contrast, the day-to-day experiences that are captured in autobiographical memories, and which inform our future behaviour, occur in rich, dynamic, multisensory, multidimensional, nonlinear, ever-changing contexts, where incoming stimulation is unrelenting [1–5]. We actively engage with the environment and other people, we move, we participate, our cognition is situated and embodied. Our lived experiences, and hence our autobiographical memories, span milliseconds to decades, crisscross multiple settings, involve repeated episodes and singular unique events. These are the normal parameters of the brain's operation and likely have a profound influence on neural responses, memory processes, and behaviour [3,4]. Yet these features, which are the very essence of autobiographical memories, are rarely considered in highly controlled laboratory-based memory experiments, instead being treated as 'noise' to be filtered out [4]. Consequently, a reductionist approach to memory research risks throwing the mnemonic baby out with the bathwater, rendering current models of memory impoverished at best and misleading at worst.

It is understandable why this reductionist approach has been overly dominant [3], leaving much less space for studies of real-world memory. It is because of the second barrier to establishing how we remember our past experiences, namely, the challenge associated with incorporating the key components of the brain's

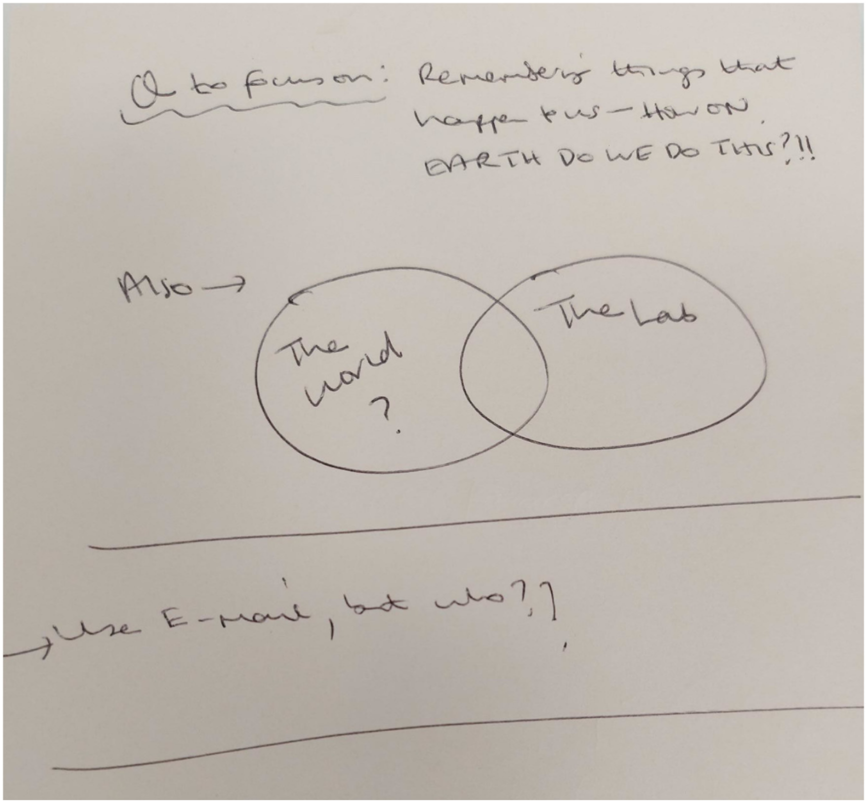

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Figure 1. A reality check from the early 1990s. A note about the key issue that I felt needed resolution in cognitive research. My fellow course mates and I had also just been given our first ever email addresses. However, other than each other, no one else we knew had email (those were the days!), hence the second question.

everyday milieu into our memory research. This is particularly difficult for neuroimaging experiments, where the participant must remain as still as possible, precluding truly embodied experiences.

However, technological developments are starting to enable memory neuroscience experiments at the scale of real life. In particular, the participant can be unshackled from head-fixed brain scanners and instead can move freely while neural responses are recorded. Current examples of this include intracranial electroencephalography (EEG) in patients with epilepsy [9], functional near-infrared spectroscopy [10], mobile EEG [11], and, most recently, optically pumped magnetometer (OPM)-based MEG [12] (Figure 2). The latter is particularly exciting for memory research because it permits noninvasive, millisecond recordings from the whole brain with good spatial resolution, including for deep brain structures such as the memory-critical hippocampus, all while a participant can move. These techniques can be combined with interactive and multisensory actual, augmented, or virtual reality to permit a more direct examination of how memory representations of truly embodied everyday experiences are formed, stored, and recollected by the brain. Another advantage of wearable neuroimaging is that an individual participant can be studied for several hours at a time, allowing detailed neural characterization of their memory processes over realistic timescales. This type of 'smart data' could offer a perspective on memory neuroscience that typically eludes current 'big data' approaches.

Related challenges are also being tackled, not least of which is how to analyse the rich, complex, dynamic, and continuous data generated by wearable neuroimaging technologies. For example, how do we tell brain signals from artifacts, how do we define windows of analysis, how do we robustly analyse neural signatures associated with the one-off autobiographical experiences that characterise much of our daily lives, and which brace the entire memory system? Machine and deep learning methods [3–5] are among some of the approaches being explored, but further innovations are required.

These wearable brain scanners and related tools mean that technology is finally starting to catch up with memory researchers' ambitions. Consequently, I predict that the next 25 years will see many more of us stepping outside the traditional mode of inquiry and a burgeoning of studies sampling brain activity, memory, and behaviour in contexts more closely approximating the real world. We will be able to study how new autobiographical memories of embodied experiences in everyday contexts are first formed, which currently eludes direct neuroscientific scrutiny. We could also test whether popular computations and processes identified in laboratory memory experiments, such as pattern separation, pattern completion, neural replay, event segmentation, and even the most long-standing of dichotomies – encoding and retrieval – are at all meaningful or recognizable during the ceaseless stream of stimulation that is real life. In a similar vein, learning and memory do not occur in a vacuum. They are intertwined with perception, social interactions, emotional processing, planning, decision-making, metacognition, and more. The study of embodied cognition over the next 25 years will, I predict, further emphasise the artificiality of these separate functional categories and instead situate memory within more integrated models of cognition and brain function.

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Figure 2. A participant wearing an OPM-based MEG scanner. The OPM sensors have been placed in a 3D-printed scanner-cast with cables fixed into a backpack. Several infrared markers have been attached to the scanner-cast for motion tracking purposes. The participant is within a magnetically shielded room and can move freely while standing and performing tasks [12]. Abbreviations: MEG, magnetoencephalography; OPM, optically pumped magnetometer.

Does this mean we should eschew highly controlled laboratory-based memory experiments? Not at all. But I hope that the next 25 years will see a rebalancing whereby more memory studies will deploy naturalistic paradigms. Arguably, these experiments should be the starting point, the nursery for hypotheses and theories [3,6] that then shape and guide specific laboratory-based experiments where the relationship with everyday memory is more direct, the provenance is clearer, and assumptions are fewer. Overall, this approach could yield richer and more relevant models of memory, and its dysfunction, possessed of greater predictive power. It is interesting to note that a similar move toward studying natural behaviours in non-humans is also gathering momentum [4,5], which could provide further mnemonic insights.

To conclude what is essentially my updated Venn diagram, I believe that memory research not only will, but must, have a realistic future in order to flourish and truly inform, and in so doing, also hasten an answer to the important question of how we remember our past experiences.

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Declaration of interests

No interests are declared.

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