Current controversies in the cognitive science of short-term memory

ABSTRACT. Short-term memory is critically implicated in most human cognitive capacities and has been the object of study for more than a century, yet many questions remain unsettled and new controversies have emerged. This paper provides an overview of some current debates within the field. These include (i) the issue of how many short-term memory systems there are, (ii) whether working memory is best understood as having domain-specific resources, (iii) how information is encoded in working memory, (iv) how sensory memory and working memory are related to attention, and (v) the relationship between short-term memory and consciousness.

Memory, in the popular sense of the term, is associated with our capacity for recalling events minutes, hours, or years in the past. However, to use information we must represent or store it somewhere in our minds, even if only fleetingly. Hence some form of short-term memory is involved in capacities such as recognising an object [1], reading a text [2], or detecting changes in presented information [3].

Despite more than a century of research into the different forms of short-term memory, a number of major unsettled questions remain. This brief review will examine some of the most pressing current debates, with particular focus on those relevant to theoretical debates in cognitive science. As a result, it will largely pass over other valuable discussions concerning, for example, memory and intelligence and issues relating to development and aging.

1. How many short-term memory systems?

The dominant historical approach to short-term memory has involved positing different short-term memory systems. Atkinson and Shiffrin famously drew a distinction between sensory memory and short-term memory proper. While this model is now recognised to be overly simplistic, it has served as a basis for more nuanced frameworks for carving up the space of short-term memory systems.

Most contemporary memory researchers recognise at the very least a distinction between the various forms of sensory memory – such as iconic memory [4] and echoic memory [5] – and working memory [6] (however, see [7] for a dissenting view). The status of other posited memory systems is more controversial. There is some evidence, for example, for a form of visual sensory memory with somewhat smaller capacity but greater duration (up to several seconds) than iconic memory dubbed Fragile Visual Short-Term Memory (fVSTM) [8]). Some have suggested that this apparent new store can be explained away via a more complex account of differences in attentional processing of items in iconic memory [9], while others have suggested that fVSTM and sensory memory should be considered parts of an integrated system of ‘perceptual memory’ [10].

A second recently mooted memory store is Conceptual Short-Term Memory (CSTM) [11,12]. CSTM is invoked to explain our ability to seemingly effortlessly understand the conceptual significance of perceptual stimuli. It is conjectured to have a larger capacity but shorter duration than working memory, while differing from iconic memory insofar as it encodes not merely sensory but semantic features of objects. Evidence for CSTM comes from a variety of experiments, perhaps most notably Rapid Serial Visual Presentation (RSVP) tasks that show subjects can retain basic gist information of up to twelve very rapidly serially presented stimuli [13]. If true, these results would suggest (in light of the very brief presentation times of as little as 13ms per image) that feedforward processes alone can result in conceptualisation of visually presented information, a conclusion that remains controversial [14,15].

2. The structure of working memory

In addition to debates about the number of basic short-term memory systems, there are longstanding questions concerning the number of subsystems present in working memory specifically. An influential account of working memory due to Baddeley and Hitch [16] posits a multi-component store in which visuospatial and auditory-verbal information are retained in separate buffers of a single system. This model is supported by evidence that working memory tasks in separate modalities do not generate interference [17].

An alternative approach sees working memory as a central capacity-limited mechanism shared across multiple sensory modalities [18]. Some recent evidence for this alternative proposal comes from a review suggesting that patients displaying working memory deficits for one kind of information typically possess deficits in other domains and sensory modalities [24]. Moreover, one experimental assessment of between-domain interference in different working memory domains found that while a probe recognition task was not subject to cross-domain interference, there was such interference in the recall of verbal and visuospatial information [21].

Complicating matters, however, and contradicting earlier results [22], multiple findings now suggest that working memory training in one domain does not exhibit ‘far transfer’ effects to other domains [23]. Hence despite the apparently straightforward nature of the question as to whether or not working memory involves separate non-interfering components, the matter remains frustratingly contested.

A related controversy concerns whether representations in working memory are simply those portions of working memory activated by a "focus of attention" or instead constitute separate copies held in a dedicated short-term store (see Fig. 1). Put another way, we might ask whether short-term memory stores information or instead simply stores pointers to information encoded elsewhere.

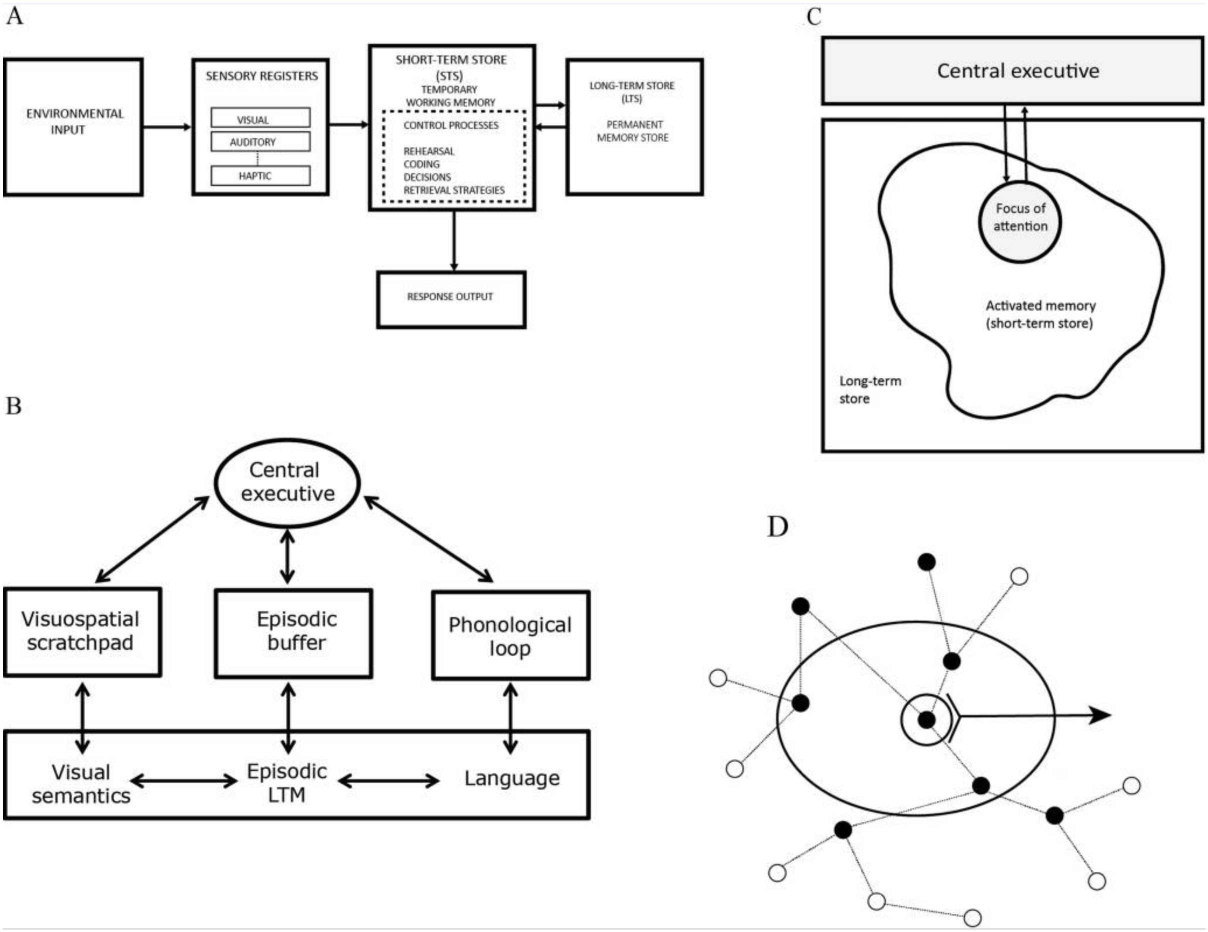

Fig. 1- a comparison of different models of long- and short-term memory. (A) and (B) depict separate store models, respectively those of Atkinson & Shiffrin [24] and Baddeley & Hitch [6]. (C) depicts the model of Cowan [25] in which information in long-term memory is activated via attentional processes. (D) depicts the related model of Oberauer [26] in which lines and circle represent nodes in long term memory, with black nodes indicating activated portions. The larger oval represents the 'direct access region' and the smaller circle represents the focus of attention. From Norris [27].

While some neuroimaging data has been brought to bear on the question, many recent moves in this debate have focused part on theoretical rather than experimental considerations. For example, while the activated long-term memory (aLTM) view may have the advantage of allowing for more efficient encoding of information, it has been questioned whether it can adequately capture our ability to recall wholly novel or information and to recall information about the order in which stimuli are presented [27]. Nelson Cowan in defending the aLTM view suggests that information can be encoded rapidly in LTM, and that sequence information can be represented via a structured system of pointers [25], a move that one critic has claimed is “simply an exercise in relabelling” [28]. As in the case of the debate concerning whether working memory involves a single domain general or multiple domain-specific stores, the question of the relationship between long-term memory and working memory remains unresolved.

3. How many slots in working memory?

One robust finding in the science of short-term memory has been the observation that humans are strikingly limited in the number of discrete items that can be recalled from a given dataset when appropriate constraints are in place to safeguard against the use of mnemonic devices and rehearsal. In one of the most widely cited papers in all of psychology, George Miller estimated a limit of around “seven, plus or minus two” [29], though later work reduced this to around 3-5 items [30].

The idea that working memory involves a discrete number of slots has however been challenged by the idea that working memory involves a continuous ‘mnemonic resource’ that can be allocated variably to different items in accordance with task demands [31,32]. Evidence for this model comes from multiple experiments whose results are seemingly at odds with earlier slot-based approaches. For example, in one experiment subjects were presented with an array of coloured squares and after stimulus removal were tasked with matching the colour of a probed item using a colour wheel (see Fig.2). According to a slots-based approach, one might expect a rapid dropoff in performance once the number of items in the initially presented array exceeded the number of slots in working memory. What was found, however, was a continuous decline in performance proportionate to the number of items presented.

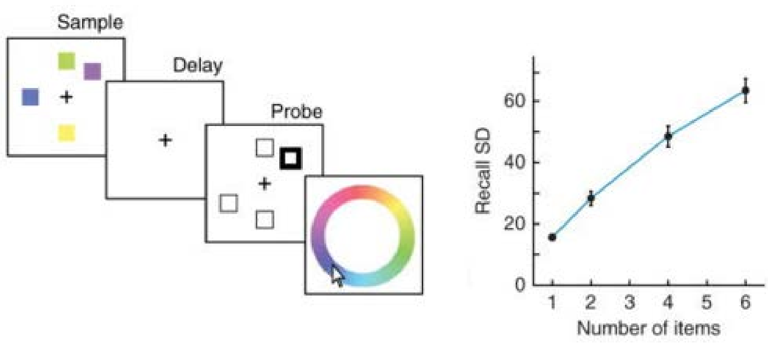

Fig. 2. A colour delayed-estimation task (from Ma et al. [31], summarizing [33]). Subjects are presented with variable numbers of coloured squares and given a cue following a short delay. The task was to indicate via a colour wheel the exact colour of the square that had been cued. Subject's accuracy as indicated by recall variability decreased smoothly in proportion to the quantity of squares in the initial stimulus. This conflicts with predictions of a slot-based model, which might be expected to anticipate smooth performance up to around four items followed by a rapid degrading thereafter.

In light of experiments such as these [34], a view has emerged even among prior defenders of a purely slot-based approach that a more fine-grained approach to the retention and encoding of information in working memory is required [43; however, see 44]. Correspondingly, greater emphasis is now placed by many prominent memory researchers on computational and information-theoretic measures of memory. Rather than a simple picture of activating and encoding information in discrete slots, then, many researchers now recognise that short-term memory should be understood in terms of the demands of extracting signals from noisy data by selective and continuous attentional amplification and restoration of information [37,38].

4. Short-term memory and attention

The relationship between short-term memory and attention is also highly vexed, no doubt in part because of the wide variety of forms of attention and the various functions it might play in the encoding, retention, and access of information in memory [39], as well as the still unresolved controversies about the architecture of memory already discussed. A detailed review of the relevant literature is beyond the scope of the present paper, but a few notable results can be reported.

First, it has long been recognised that attention in some sense facilitates working memory, but its exact role in unclear. Thus the initiation of the consolidation of visually presented information into working memory seems to require attention [40]. On the assumption that attention is in some sense is a limited-capacity mechanism or 'bottleneck' in processing, this would explain the phenomenon of the ‘attentional blink’ in which subjects often fail to see a stimulus presented immediately after a target [41]. By contrast, evidence for a role for attention in the maintenance of previously presented information is much more contested. For example, as children enter adolescence, their ability to manage distinct stores information relevant to different tasks seems to increase, despite no concomitant improvement in core attentional capabilities [42]. Evidence such as this has led some to suggest that information once consolidated into working memory can be “offloaded”, allowing maintenance to occur without the need for the allocation of attention [43]. An alternate influential model known as time-based resource sharing holds the role of attention in maintenance to involve not continual retention of individual items but rather the periodic and serial ‘refreshing’ of items to prevent decay [44].

A second ongoing debate concerns the relationship between perceptual attention and memory-directed attention. One reason to think these mechanisms are closely linked comes from the finding that many of the properties of objects that facilitate or impair the selection of items in perceptual tasks – such as target-distractor similarity effects – also do so for working-memory tasks [52; see also 53]. Likewise, there is some reason to think that performance in tasks that place heavy demands on perceptual attention is related to measures of cognitive performance, specifically fluid IQ [47]. This is somewhat supported by neuroimaging results that show considerable overlap in brain regions recruited for visual and memory-based forms of attention [48]. Evidence for interference between cognitive load and perceptual performance (and vice-versa) however is more mixed. For example, while there is evidence that cognitive load may influence even early perceptual processing [49], it seems to do so in ways quite different from perceptual load. One study using realistic advertisements placed around a browser game, for example, found that perceptual load reduced recognition of the adverts, while cognitive load made participants *more* likely to notice them [50], a finding supported by a similar experiment involving distraction by billboards while driving [51]. One possible explanation is that perceptual attention is best understood as involving distinct mechanisms for spatial tracking and feature tracking [57].

A final debate worth briefly noting concerns the relationship between attention and sensory memory. While it has long been assumed that sensory memory operates effortlessly and thus does not require attention, some doubt has been cast on this by recent findings. In one experiment, subjects were shown either letter-matrices or coloured circles and instructed to perform either a letter recall task or a colour-circle task respectively. After initial separate training on these two tasks, the displays were combined with subjects performing one or another task as instructed by a cue. The striking finding of the experiment was that subjects entirely failed to notice when in one colour-circle cue the background letter display was absent entirely, leading them to conclude that inattention prevents the encoding of sensory information in iconic memory [54]. While these findings are not uncontested [55], they highlight an intriguing and underexplored area for research on short-term memory and attention.

5. Short-term memory and consciousness

A final vexed issue in the philosophy and science of short-term memory research concerns its relationship to consciousness. Two particular ongoing discussions are worth noting. The first is the so-called ‘overflow’ debate developed by philosopher Ned Block, and it concerns whether the contents of sensory memory might themselves be conscious independent of encoding in working memory [56]. Multiple experiments spanning several decades have indicated that items in iconic memory can be recruited via postcues for the performance of tasks, with subjects having an impression of having seen these items all along and thus (perhaps) consciously perceived them. More recent work has provided further evidence to this effect, with the finding that subjects are able to access information about the diversity of colours in an array via a postcue [57]. Interpretation of the results is complex, to say the least, with some suggesting, for example, that subjects’ impression of ‘phenomenal richness’ can be better explained via an illusory process of interpretation subsequent to cueing [58].

Other support for the overflow hypothesis has come from the use of ‘no-report paradigms’ [59]. These involve trials that do not require subjects to make reports of their experience, but instead use third-personal measures such as eye-movement monitoring during binocular rivalry combined with neuroimaging to track changes in neural activation during changes in conscious experience. In principle, these might allow us to identify and compensate for the specific contributions to neural activation in perceptual tasks made by requirements of report. Some results of this kind have suggested a far smaller role than traditionally assumed for prefrontal regions involved in executive control and working memory in comparison with occipital areas associated with sensory processing. Pushback to such claims has come from authors who suggest, for example, that no-report paradigms introduce distinctive confounds of their own [59], and should not overrule existing evidence for a critical role for the prefrontal cortex in conscious perception [60].

A second debate has arisen concerning whether working memory itself is always conscious. While it has long been assumed that working memory “should contain what we think of as the conscious mind" [35], recent experiments have put this in doubt. For example, it has been demonstrated that masked and unreportable Gabor patches can still be used after a delay of several seconds for the purposes of an orientation-matching task [61]. In light of these relatively long delays and the use of pattern masks, an explanation for this capacity in terms of sensory memory seems unlikely, while a working memory interpretation is supported by the presence of accompanying signal changes in the prefrontal cortex [62]. Against this interpretation, some have suggested the possibility of accompanying conscious experience below the threshold required for confident report [63], as well as the worry that, absent evidence for active maintenance of the relevant information, so-called unconscious working memory might merely involve a priming effect that facilitated subsequent guessing [64].

6. Conclusion

It is easy to feel despondent about the state of short-term memory research: how can we have so much evidence yet so few firm conclusions? In light of this, there are grounds for thinking that a move away from a narrow systems-based approach to short-term memory may offer at the very least some new avenues of investigation, whether in the form of active inference frameworks [65], computational approaches [66], or simply better theory-neutral benchmarks for assessing competing models [67]. Likewise, while neuroscientific data has long played an important role in informing and constraining theoretical debates about short-term memory, one might hope that by identifying or modelling specific memory mechanisms – such as the oscillatory properties of neurons encoding working memory information [68] – new light may be shed on longstanding debates, especially in light of ongoing progress in neuroimaging techniques. Broader progress in neuroscience towards understanding the biological basis of different cognitive capacities may also make important contributions to our understanding of short-term memory, as demonstrated for example by the growing interest in the contribution of white matter to working memory function [69].

On a separate note, there may be grounds for paying closer attention to cultural differences in constructing models of short-term memory. In one important recent study [70], subjects' spatialization of even non-verbal information in working memory was shown to be heavily influenced by language and literacy, with literate Arabic speakers encoding information about sequentially presented Gabor patches in a right-to-left direction, in contrast both to Western readers (who encoded information in a left-to-right direction) and illiterate Arabic speakers (who showed no systematic spatial organisation).

As a final counsel against despair, we should not forget that cognitive science is a relatively young field and one that present immense challenges. Aside from a few spectacular successes in fields such as early visual processing, the norm of the field has been tentative progress dogged by continued debate about concepts and methods. Rather than anticipating that answers will emerge spontaneously from data, then, we should expect insights to emerge in fits and starts from a background of lively theoretical disagreement.

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